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English edition

Open foundry to spur open-innovation

Development of an advanced sewage sludge incinerator, "turbocharged fluidized bed incinerator"

A novel material design system method for on-demand material development

Towards large-capacity, energy-efficient, and sustainable communication networks

Synthesiology editorial board

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National Institute of Advanced Industrial Science and Technology (AIST)

MESSAGES FROM THE EDITORIAL BOARD

There has been a wide gap between science and society. The last three hundred years of the history of modern science indicates to us that many research results disappeared or took a long time to become useful to society. Due to the difficulties of bridging this gap, this stage has been recently called the valley of death or the nightmare stage (Note 1). Rather than passively waiting, therefore, researchers and engineers who understand the potential of the research should actively try to bridge the gap.

To bridge the gap, technology integration (i.e. *Type 2 Basic Research* – Note 2) of scientific findings for utilizing them in society, in addition to analytical research, has been one of the wheels of progress (i.e. *Full Research* – Note 3). Traditional journals, have been collecting much analytical type knowledge that is factual knowledge and establishing many scientific disciplines (i.e. *Type 1 Basic Research* – Note 4). Technology integration research activities, on the other hand, have been kept as personal know-how. They have not been formalized as universal knowledge of what ought to be done.

As there must be common theories, principles, and practices in the methodologies of technology integration, we regard it as basic research. This is the reason why we have decided to publish "*Synthesiology*", a new academic journal. *Synthesiology* is a coined word combining "synthesis" and "ology". Synthesis which has its origin in Greek means integration. Ology is a suffix attached to scientific disciplines.

Each paper in this journal will present scenarios selected for their societal value, identify elemental knowledge and/or technologies to be integrated, and describe the procedures and processes to achieve this goal. Through the publishing of papers in this journal, researchers and engineers can enhance the transformation of scientific outputs into the societal prosperity and make technical contributions to sustainable development. Efforts such as this will serve to increase the significance of research activities to society.

We look forward to your active contributions of papers on technology integration to the journal.

Addendum to Synthesiology-English edition,

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Synthesiology Editorial Board
(written in January, 2008)

Note 1 : The period was named "nightmare stage" by Hiroyuki Yoshikawa, the then President of AIST, and historical scientist Joseph Hatvany. The "valley of death" was used by Vernon Ehlers in 1998 when he was Vice Chairman of US Congress, Science and Technology Committee. Lewis Branscomb, Professor emeritus of Harvard University, called this gap as "Darwinian sea" where natural selection takes place.
Note 2 : *Type 2 Basic Research*
This is a research type where various known and new knowledge is combined and integrated in order to achieve the specific goal that has social value. It also includes research activities that develop common theories or principles in technology integration.
Note 3 : *Full Research*
This is a research type where the theme is placed within the scenario toward the future society, and where framework is developed in which researchers from wide range of research fields can participate in studying actual issues. This research is done continuously and concurrently from *Type 1 Basic Research* (Note 4) to *Product Realization Research* (Note 5), centered by *Type 2 Basic Research* (Note 2).
Note 4 : *Type 1 Basic Research*
This is an analytical research type where unknown phenomena are analyzed, by observation, experimentation, and theoretical calculation, to establish universal principles and theories.
Note 5 : *Product Realization Research*
This is a research where the results and knowledge from *Type 1 Basic Research* and *Type 2 Basic Research* are applied to embody use of a new technology in the society.

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Contents

Open foundry to spur open-innovation

— Establishment of a foundry to realize an innovative cooperation platform and development of its sustainable management strategy —

Hiro AKINAGA

[Translation from *Synthesiology*, Vol.7, No.1, p.16-26 (2014)]

Open foundries enable us to share cutting-edge equipment with global partners of industry-academia-government collaboration, and to promote interdisciplinary integration and job mobility among research personnel. Foundries have been established in many world-class public organizations, and are widely recognized as one of the most effective measures to spur R&D open-innovation. In this paper, the management strategy of the AIST open foundry, the Nano Processing Facility, is discussed. In this foundry, cooperation with users brings about the integration of R&D achievements and technologies. This paper also presents a scenario for sustainable development of the foundry as an eco-innovative cooperation system.

Keywords : User foundry, interdisciplinary integration, human resource development, open-innovation, global cooperation platform, eco-innovation

1 Introduction – What is an open foundry?

To promote R&D efficiently, a facility where researchers can share state-of-the-art devices and equipment and utilize its prototyping capabilities is important. In the 21st century when the economy is globalizing rapidly, the necessity has increased to progress from R&D to technological development to commercialization, or to quickly transfer the research topics from the site of production to the site of R&D.

Today, R&D that must be done by a corporation and the space in which businesses are conducted have increased. With such a background, an open foundry, or a common-use facility to share the state-of-the-art equipment, will function as an engine to shift the vector outward and open up space for the companies that harbor inward-pointing vectors, as they seek research and technological developments within themselves and spend effort to build a mechanism only in closed space. Since nanotechnology is a core technology that cuts through an extremely wide range of research disciplines, a foundry will contribute greatly to various industries. The foundry will allow the universities and public research institutions to avoid owning expensive state-of-the-art equipment, and thereby allowing them to efficiently manage their limited budget and to be able to promote interdisciplinary integration via the foundry.

The open foundry in nanotechnology R&D of the United States will be discussed. The National Nanotechnology Initiative (NNI) positions the R&D infrastructure of public institutions as the target of continuous budget allotment, and over 10 % of the total NNI investments are allotted to this target.[1] The characteristic infrastructures were built at the National Nanotechnology Infrastructure Network (NNIN) of the National Science Foundation (NSF), the Nanoscale Science Research Center (NSRC) of the Department of Energy (DOE), Center for Nanoscale Science and Technology (CNST) of the National Institute of Standards and Technology (NIST), and others. In the report that describes the policies and results of the NNI and the issues and guidelines for the year 2020, it is explained that "these facilities must be expanded to provide prototyping capabilities that will accelerate the transition of research discoveries into innovative technologies."[2] Also, further organization and advancement of the foundry function are positioned as one of the most important topics for the 2020. The reason for setting this as the most important topic is that "without (user facilities providing prototyping capabilities) facilitating the transition of science/engineering discovery into innovative technologies, continued support for nanoscale science and engineering may be jeopardized."[2]

In this paper, first, the types and functions of the foundries operated by the public institutions, and the dilemma in managing them are explained. Next, based on the analysis of the current status of the foundry managed by AIST, the scenario for the continuous growth of the foundry, and the scenario for realizing eco innovation (a sustainable innovation system) that continuously widens the space for innovation spurred by such foundry will be presented.

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2 Types, functions, and issues of the open foundry

2.1 Categorization of the open foundry[1]

There are a number of representative types of open foundries. The foundries are categorized from three viewpoints.

2.1.1 Type in which large equipment is shared and type which aggregates multiple equipment

The examples of foundries that share ultra large experimental equipment include the Super Photon Ring-8 GeV (SPring-8) and the Beam Line of the High Energy Accelerator Research Organization (KEK or Ko Energy Kasokuki Kenkyu Kiko) in Japan, and the Los Alamos National Laboratory in the United States. There are many relatively expensive equipment in the nanotechnology field, and the ultra high-voltage transmission electron microscope, for example, is shared in the similar managerial format as the foundry for large equipment. On the other hand, there are facilities that are very attractive to users because equipment, even if it consists of general-use, small/medium-sized equipment, is aggregated in one place. The foundries that are offered for open use by universities, such as the facilities participating in NNIN in the US, can be categorized as this type which aggregates multiple equipment. The centers with large exposure equipment along with the peripheral general-use equipment related to semiconductor technology, such as the Albany Nano Tech Complex in the US, IMEC (formerly, the Interuniversity Microelectronics Centre) in Belgium, MINATEC (formerly, the Micro and Nanotechnology Innovation Centre) in France, and the super clean room facilities at AIST can be positioned as the intermediate type of this category.

2.1.2 Central type and network type

The aforementioned large equipment sharing foundry, the National Nano Fab Center (NNFC) of Korea, Korea Advanced Nanofab Center (KANC) also of Korea, and Institute of Microelectronics (IME) of Singapore can be categorized as central facilities that attract users by aggregating large equipment within their compounds. On the other hand, the foundries participating in the NNIN of the US and the foundries of the public institutions participating in the Nanotechnology Platform Project[3] of the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan can be categorized into the network type that aims to provide complementary research support services.

2.1.3 Type for accumulating/integrating knowledge and type for strengthening industrial competitiveness

The Center for Integrated Nanotechnologies (CINT) that is part of NSRC is a facility established under the national policy to accumulate knowledge, to integrate accumulated knowledge, and then to create new knowledge. The users who publicize the results are not charged, and its primary index of evaluation is to gather as many users as possible. Compared to the facilities where users are charged because they are considered beneficiaries, it is categorized as being at the opposite end, from the perspective of the way in which the foundry is managed. On the other hand, the type of foundries for strengthening industrial competitiveness charges the users as they are deemed beneficiaries, and the results are unpublished in many cases. When a facility is established to solve a specific issue, it may be called a problem-solving foundry.

2.2 Functions and roles of the open foundry

The open foundries have functions and roles characteristic of the categories described in subchapter 2.1. In this subchapter, the roles and functions are broken down into five categories, and what are expected for each category is explained. In this paper, “science” and “technology” are separated, and “research” and “development,” are considered actions with different vectors. Of the open foundries, it will be easier to understand the functions, particularly for the type for strengthening industrial competitiveness, by clarifying the differences between research and development (Fig. 1).[4][5]

(1) Promote interdisciplinary integration

In the type that concentrates/integrates knowledge and the central type foundries, the interdisciplinary integration is promoted through the gathering of researchers with different specialties and through new relationships being built among them. The formation of new relationships is the origin of innovation, and is the primary function of a foundry where diverse people and knowledge gather.[Note)]

(2) Promote mobility of research results

For the production of knowledge, the involvement with various players is necessary, including not only researchers but also engineers, students, as well as salespeople who are not necessarily involved in R&D. Knowledge has a package-like characteristic that is born from such congregations.[6] In the foundry, the knowledge package is produced in the process of development where the research results are sifted and selected, as shown in Fig. 1. On the other hand, in the technological development phase shown on the right side of the figure, it is not easy to transfer the knowledge package outside for practical use, and it is important that a foundry where many types of players reside functions as a trading zone.

(3) Strengthen capacity to handle complexity and uncertainty

One of the purposes of NSRC of the United States is to strengthen R&D capabilities to handle a totally new issue, and it is equipped with the function to handle the complexity of R&D and the uncertainty of innovation. Particularly, the foundries that aggregate multiple equipment and those that concentrate/integrate knowledge are operated for the purpose of strengthening the capabilities to handle such complexity and uncertainty.

(4) Provide complementary technology

The universal role of the open foundry is to respond to the requests from diverse and wide-ranging users and speedily provide solutions. Particularly, an open foundry that is networking with multiple user foundries is expected to provide efficient research support by offering complementary technology in its field of specialty.

(5) Promote human resource mobility

When a researcher wishes to start up new research when moving from one workplace or section to another, there are major time and financial barriers. These can be reduced by using the open foundry, and the mobility of young researchers will be promoted. Therefore, in NNIN and the Nanotechnology Platform Project, the participating open foundries are selected with their locations also considered.

2.3 Dilemma of managing an open foundry

I shall introduce one of the major managerial dilemmas faced by many open foundries in Japan. For a public institution, financing the maintenance cost of the expensive state-of-the-art equipment is one of the major problems. Therefore, in many cases, idle time of the state-of-the-art equipment is loaned to R&D of external researchers, and the income from the charges collected are used for equipment maintenance. As a result, a user foundry that claims the efficient use of expensive equipment by using it for its own R&D as well as sharing with others is established. On the other hand, if the efficient use of idle time is thoroughly enforced, the priority of cost reduction increases excessively, and this may lead to (1) reduced cost of labor, (2) elimination of support for R&D with a large number of process steps, or (3) keeping away from difficult R&D topics. Moreover, in cases where the institution to which the foundry belongs or the institution that provides financial support considers the users as the beneficiaries, establishes and strongly enforces a charge system, the demand for cost reduction will increase on the side of the user. In an environment with strong cost reduction demand, the facilities and equipment that are used for a long time degenerates and aging is accelerated, and the “tragedy of the commons” occurs.[7][8] The users are less attracted to worn out facilities and equipment, and as a result, the idle time increases. Unless equipment sharing becomes the main business, a user foundry cannot gain profit from equipment sharing, and meets the dilemma that rational management does not lead to strengthened management. The share use of idle time is one of the choices for cost reduction, but it must be noted that such cost reduction possesses the aspect of depleting provided services.

3 Open foundry of AIST

3.1 Three open foundries and their collaborative system

At AIST, there are two open foundries in operation with over 10 years of history. They are the Super Clean Room (SCR) of Tsukuba West and the Nano Processing Facility (NPF) at Tsukuba Central 2. Also, as a problem-solving type foundry, the Platform for Green Functional-Oxide Nanotechnology (GreFON) stands next to NPF.

SCR is an open foundry with the characteristics of the type that shares large equipment and that which aggregates multiple equipment. It consists of a 3,000 m^2 super clean room (JIS Class 3) with a process line for 12-inch wafers, and a 1,500 m^2 research clean room (JIS Class 5) with a process line for mainly 4-inch wafers.

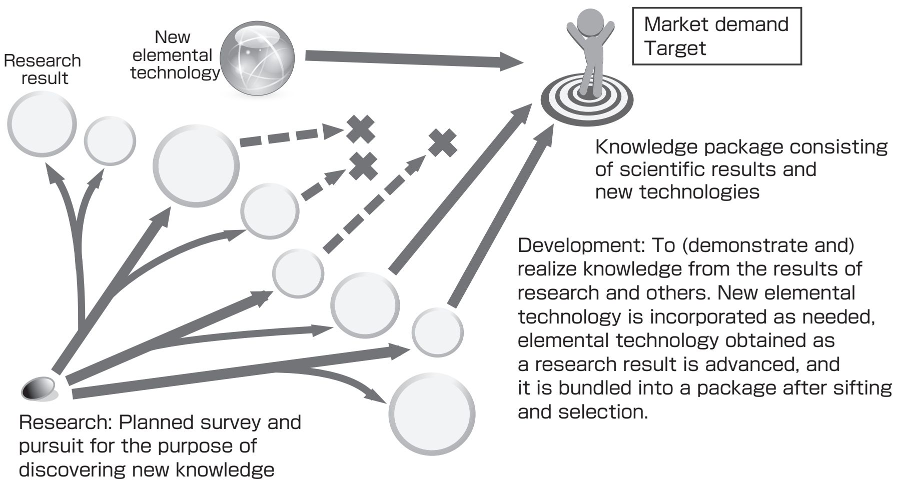

Fig. 1 Difference between research and development

A research has a divergent vector where all the circles may become results, including the arrows that were unexpected initially. On the other hand, a development has the vector of sifting and selecting the research results and then gathering them up as a knowledge package matched to the market demand. Previously, research and development were in a linear relationship with overlaps in several areas, and if a technology was good, it could be connected with a solid line. Currently, research and development must be clearly delineated to generate new values. Often, a totally new elemental technology is necessary.

NPF has the characteristics of the multiple equipment aggregating type and the network type. By collaborating with the Nanotechnology Platform Project and GreFON that were introduced earlier, it is managed for both the functions of the type that concentrates/integrates knowledge and the type for strengthening industrial competitiveness.

Recently, there has been a rapid increase of users who utilize these open foundries according to their R&D phases, such as using SCR for the application of new materials developed at NPF or GreFON to the large-scale integration process technology, or conducting elemental technology development at NPF to resolve the R&D bottleneck at SCR. Since pages are limited in this paper, focus will be placed on NPF for further discussions.

3.2 Nano Processing Facility

The Nano Processing Facility (NPF) was initiated as a user foundry for research units within AIST in April 2001. Initially, it consisted of a 231 m^2 clean room. In the press release for its launch, it is stated, “This is a facility to be shared by researchers of electronic engineering, optical engineering, molecular engineering, and biotechnology, under the motto of ‘expeditious realization of ideas.’ The objective is to pioneer new industries by integrating the creativity of the individual researchers and by producing nanotechnology products that is the hope of the 21st century, through the R&D of next-generation information devices, ultra high density optical recording, molecular devices, and sensors.” It was managed with the cooperation of seven research organizations mostly within AIST, led by the Nanotechnology Research Institute. Efforts were spent to organize and manage the facility and a support system that enabled the formation of structures at micro and nanometer level needed by the research organizations of AIST, at high throughput, with excellent reproducibility and uniformity, and without having the researchers of wide-ranging specialties to feel the barriers. As a result, there were over 100 users within AIST by April 2003. Although the Nanotechnology Research Institute took the lead for its management, the basic policy from the beginning was to serve as the crossroad of researchers while the institute devoted itself to be the supporter, and care was taken to make access to the state-of-the-art equipment at the foundry fair for all users.

Currently, NPF has developed into an open foundry with a 600 m^2 clean room from Class 100 to 10000 (US federal standard), a 300 m^2 of general experiment facility, and accommodation space for short-term stay of users. It has been commissioned to conduct MEXT research support projects from 2002 to present, and is now promoting operations as a foundry with the functions of accumulating/integrating knowledge and strengthening industrial competitiveness. As of the end of FY 2012, there were over 1,200 user registrations, and about two-thirds were people from outside of AIST. There are a total of about 50 instruments worth several million to several hundred million yen, and there are, on average, about 100 cases of project support conducted per year. It supports joint research with various private companies that are promoted by AIST, and also participates in the Tsukuba Innovation Arena Project.[9]

The NPF forms a user foundry network in Japan, using the subcontract projects of MEXT. For example, it halted operations for about four months after the Great East Japan Earthquake. During this downtime, the corporate users were referred to the foundries of the universities in Tokyo that had similar equipment as NPF, to minimize the delay in the users’ R&D schedule. Maintaining such resilient R&D operations by overlapping some of the functions of the foundries is an important role of the network type foundry that provides complementary technology.

At NPF, generous support is offered to each and every user, including the technological support to strengthen working examples for patent application and the support in creating documents in response to peer reviewers of academic papers. “Support for Success” is the NPF statement that states that action must be taken keeping in mind that the priority is the user’s success and that the success of the NPF personnel is the user’s success. As a result, compared to other user foundries in Japan of a similar scale, NPF has higher percentage of corporate users.[10] An example of R&D support for a private company actually done by NPF is shown in Fig. 2. A request for prototyping was received from a user, the process engineer of NPF developed a new process, and the know-how was accumulated at NPF. The corporate user may bring high-risk research topics to NPF, and in many cases, the results may be “the clarification that the issue cannot be solved by the initially planned process.” This is an example where the user handles the complexity and uncertainty of R&D with minimum investment.

4 Analysis of the current status of the open foundry NPF and the concept of global innovation platform

In this chapter, the current status of NPF that has the highest number of registered users among the open foundries managed by AIST is analyzed. Using the analysis result, the strategy for creating a global innovation platform where NPF can gain new users and continue to grow will be described.

4.1 Analysis of the current status of NPF and the management strategy

To understand the current status of NPF, we conducted the SWOT analysis. The reason for selecting the SWOT analysis is because it allows analysis under the clear strategy of presenting to the users the differentiated value for using NPF, on the boundary condition of not aiming for cost leadership where the base of competition is low cost. In the background is the situation where similar user foundries are increasing and commercial facilities that conduct foundry business are beginning to appear. The result of the SWOT analysis is shown in Fig. 3. The partition between the internal and the external environment was placed on the boundary line between the inside and the outside of AIST, and the categorization was based on whether AIST could directly control the content or not.

In an ordinary clean room, it is necessary to thoroughly reduce the presence of impurities and fine particles of alkali metals or heavy metals that may affect the performance of electronic devices. Therefore, the introduction of new materials that hold the danger of introducing such impurities into the clean room must be regarded with extreme care. However, as apparent in STRENGTHS, NPF greatly succeeds in lowering the barrier of introducing new materials by devising ways for equipment operation, thereby enabling both R&D of electronic devices and new materials. Also, looking at each item of the SWOT analysis based on the goal of differentiating the value of using NPF, it becomes clear from the cross analysis of STRENGTHS and OPPORTUNITIES that the conclusion implied is to select the strategy of gathering users particularly from the materials and equipment manufacturers and to aim to become a facility where users of more diverse industrial fields will gather.

Next, based on the SWOT analysis, we clarified the strategies that should be further taken by AIST. The SWOT analysis

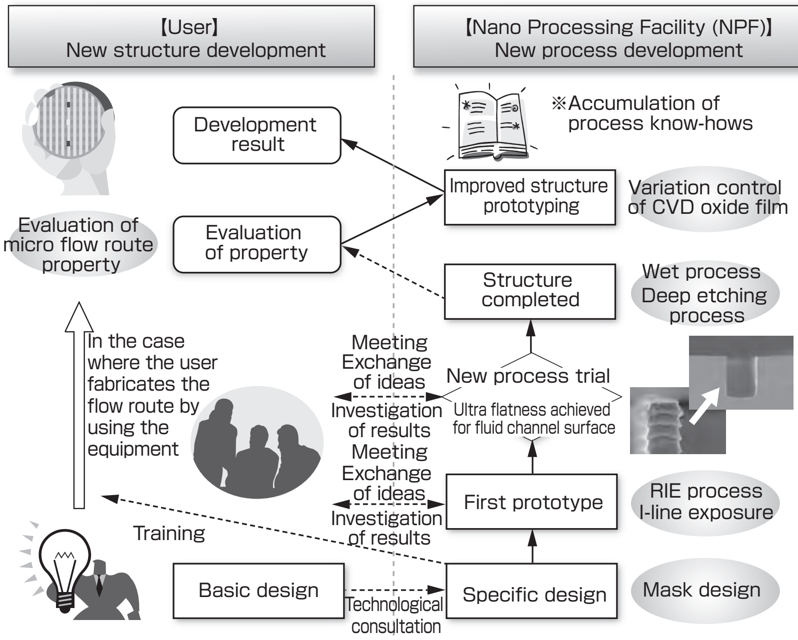

Fig. 2 Example of R&D actually conducted at NPF

NPF received a prototyping request from a user who wished to develop a microfluidic device, but the device with desired characteristics could not be fabricated using the standard process. Therefore, an etching process was developed. Prototyping was successfully done by developing an oxide film forming process that achieved both the variation control and the ultra flatness of the fluid channel surface.

Internal environment	STRENGTHS ・Accumulation of various R&D projects Over 1,000 registered users ・Globally advantaged research topics Technologies for functional oxides (GreFON) ・New materials can be introduced easily ・Excellent engineers ・Abundant technological training program ・Readily accessible to AIST resources	WEAKNESSES ・Limited operation time of clean room ・Lack of available space in clean room ・Aging of equipment for core processes ・Frequent equipment troubles ・Lack of machine time ・Facility operation/Regulated budget execution ・Technology accumulation system not built ・Technology succession system not built ・Technology transfer system not built
External environment	OPPOTUNITIES ・Multitude of collaborating foundries ・Increased consciousness for equal division of labor in managing the foundries and R&D ・Efficient use of research resources by sharing the facilities Increased consciousness for reducing the cost of facility maintenance and saving energy ・Presence of strong manufacturers of materials and equipment in Japan	THREATS ・Newly participating organizations and facilities to the nanotech foundry business ・Transfer of R&D centers overseas

Fig. 3 Result of the SWOT analysis for NPF

is done by placing a divider between the external and internal environments. Therefore, as a method for creating the strategy, we employed the competitive strategy theory where the strategy is considered by separating the origin of innovation into the internal and external areas.[11] The result is shown in Fig. 4. In the upper left corner, the resources within NPF were observed for the resource approach, and the strategy to strengthen the resource itself was proposed. In the SWOT analysis, of the WEAKNESSES, the need for building a technological succession system was derived. The WEAKNESSES are marked by "▼" in the figure. Similarly, in the learning approach in the upper right corner, the investigation shifts to the process of how to overcome the weaknesses. For this, from the perspective of utilizing the STRENGTHS, we obtained the action item of disclosing the information of the technological know-how accumulated by the process engineers to the users. On the other hand, in the positioning approach, the strategy to position NPF to bring out the strengths of NPF is considered. For this approach, a long-term consideration was necessary such as fortifying the linkage between NPF and the production centers. If NPF becomes attractive to the manufacturers of devices, materials, equipment, and fabless, it will become possible to lower the mobility barrier in the users' business as an open foundry.

The open foundry is a place where both the users and AIST create values. From the viewpoint of the user, the foundry should increase the total amount of value, and even so it will not be attractive unless the user can take the larger share. Therefore, the game approach that NPF must take is the strategy of obtaining new users by creating a good situation while appealing to the external environment including the users. While NPF does not have the facilities that allow semiconductor process development, it has many users of device manufacturers that conduct elemental technology development. Therefore, for example, if NPF can function as an R&D partner of a material manufacturer, the range of the stakeholders including NPF will expand, and the device manufacturer will be able to increase the options of ways to use NPF. Moreover, using the strength that many researchers from multiple companies are engaging in R&D at NPF, if the international standardization of the results obtained at NPF can be done actively, the usage of NPF in the role of a game changer can be proposed to the users.

4.2 Scenario for building a global innovation platform at NPF

Using the strategy established in the previous subchapter, a scenario for making NPF into a tool for promoting further advanced R&D will be explained. In constructing the scenario, we set up the hypothesis that a global innovation platform that will be explained below will grow if NPF employs the game approach. Seen from the viewpoint that the user foundry operation must be carried out while harboring the dilemma described in subchapter 2.3, it will be possible to write an *aufheben* type scenario.[12] At NPF, there are many instances of breakthrough type R&D.[13] However, due to the space limitations of the paper, we describe the scenario for building space for a global innovation platform with NPF at the core and for continuously expanding the space. The scenario for promoting eco innovation is shown in Fig. 5. What the authors have done in the past 10 years was to organize the rules of the foundry and research support, and this corresponds to the organization of the interior of the rectangle marked NPF in Fig. 5. NPF has become an innovative platform called the open foundry, and has built collaboration connected with other foundries in Japan and overseas. On the other hand, by promoting the game approach shown in Fig. 4, NPF creates new users by advancing the provided services and by strengthening the ability to provide services by utilizing its network. The

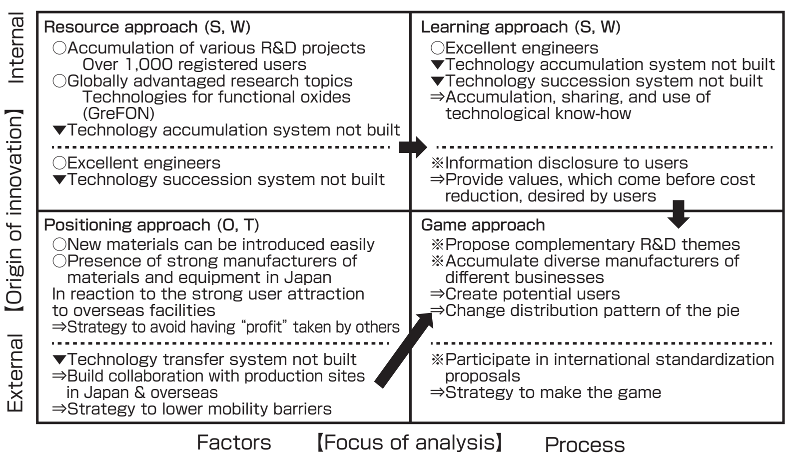

Fig. 4 Strategy analysis matrix for NPF based on the SWOT analysis (Fig. 3)
The process for establishing the game approach to differentiate NPF utilizing the STRENGTHS in the SWOT analysis are shown by black arrows. In the figure, the action items to overcome the WEAKNESSES (▼) that were not mentioned in the text are shown.

newly created users bring in new research potentials to NPF, and NPF incubates such potentials and hands them over to the partner companies and users, thereby further advancing the provided services. Through such positive feedback, the innovation platform with NPF at its core expands beyond the framework of NPF, and the continuously growing global innovation platform is built. In this scenario, the global innovation platform where NPF builds and advances the knowledge package and then hands it over to the user is expanded outward by new users, and grows hierarchically by taking in the partner companies and the business space of the foundries in Japan and overseas. Therefore, this growing global innovation platform is named the eco innovation R&D system from the viewpoint of seeing the foundry as a tool for promoting R&D. As mentioned earlier, the use of open foundries as R&D tools has become common in the last 10 years, and the manner of R&D has changed greatly as the foundries constructed a network. For example, the R&D system itself has changed as exemplified by the stakeholder comments: "The researchers and engineers are freed from the work of equipment maintenance, and therefore can utilize the limited time effectively," or "The technological potential necessary for R&D can be efficiently gained at the foundry." The author believes that by widening the global innovation platform through this eco innovation R&D system, an "open foundry that is a place to promote social acceptance (including the improvement of scientific literacy) of the R&D results"[2] can be realized.

Here, a detailed explanation for the eco innovation R&D system and its issues will be given from the perspectives of "advancement of provided services" and "user creation." First, the "advancement of provided services" cannot be promoted simply by technological advancement. For example, even technological know-how developed at a foundry for strengthening industrial competitiveness, such as product development using a new technology, will be caught up easily by others, if the know-how can be easily transferred so long as the same equipment is available at the institution that dispatched the user. Therefore, to develop a knowledge package that is the union of various technological know-how at the foundry, and then to transfer it to the production center as needed is far more efficient for the user, in terms of time investment from the perspective of avoiding excessive R&D competition. Moreover, if the packaging is done to maximize the profits at each level of design, manufacturing, and setting, after setting the business target at the open foundry, the "valley of death" that lies between product realization and commercialization can be overcome, and it will contribute to the establishment of business through which society can enjoy the innovation, and go further to establish new industry.[14] In packaging, the sifting and selection, and the linking of the research results or elemental technologies are done by people. The issues at the open foundries of the independent administrative bodies and universities are the training of process engineers that conduct the technological development, and the reduction of the barrier in moving personnel to the production center to which the technologies are transferred.

For the open foundry to create new users, it is important that diverse human resources gather at the foundry, and for the management to make it the center at which creative, young people will be trained. NPF holds a school for training and

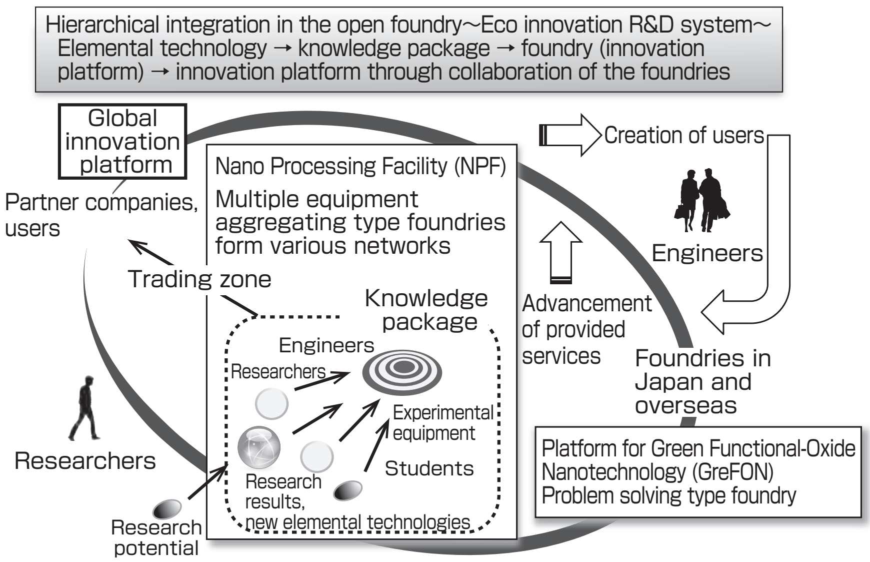

Fig. 5 Scenario to realize eco innovation

The open foundries that create knowledge packages by integrating the research results and new elemental technologies nurture their own innovation platforms. The open foundries advance the knowledge packages provided. The researchers, engineers, and users who have the advanced knowledge packages promote the collaboration of these foundries, and by integrating the innovation platforms, an even more advanced innovation platform can be built. This mechanism is the eco innovation R&D system.

provides a diverse curriculum. The school participants not only start using the foundry as new users, but also form spontaneous links with device developers that cooperate with the school and other students. There are several examples where new research topics and new users who pursue new topics were born from such linkages. This means that, by providing the users the value of practical skill improvement at the open foundry, the attractiveness of the foundry to the users increases. The increased user attraction is a profit for the foundry. Also, the increased skill is a profit for the user possibly amounting to more than the beneficiary pay. Therefore, the strengthening of the human resource training project has become an essential issue for the open foundry, as a way to resolve the dilemma described in subchapter 2.3. Recently, widening the human resource network overseas is being recognized as the issue of the open foundries in Japan. NPF has promoted information exchange with the foundries in various Asian countries since its inception,[15] and has started the energy element development support project in collaboration with CINT of the United States since FY 2010. Management for creating a global innovation platform transcending the country boundaries and the organization of the related rules are issues that need to be considered.

5 Summary – scenario for realizing eco innovation

Open foundry is a tool to construct a place where “people” and “knowledge” convene, by widely sharing the state-of-the-art “equipment.” The open foundry has the mechanism to efficiently distribute the “people” and “knowledge.” This is the open innovation function, and the meaning for AIST operating the open foundry. P.F. Drucker stated, “There is only one valid definition of business purpose: *to create a customer* (value). .... the business enterprise has two - and only two - basic functions: marketing and innovation.”[16] Following this statement, “marketing” for the foundry is the act of offering the equipment and technical know-how necessary to deliver the product desired by the user, whereas “innovation” is the creation of new users and new support requests using the powers of research promotion and development execution of the foundry and its ability to aggregate and transmit IP and information.

Figure 5 shows the scenario for promoting eco innovation in which there are global innovation platforms which are integrated hierarchically with the foundry at the core, and the platform space expands continuously. In this paper, this hierarchical integration is named the “eco innovation R&D system,” but the main players that promote this system are “people.” Professor S, whom the author respects, said, “It is important for Japan to nurture a culture where the users who conduct R&D and the engineers in charge of the process technology development acknowledge (respect) each other’s values. We must establish a true foundry for that purpose.” The big circle in the figure joins the researchers and the engineers by equal partnership. This circle strengthens the collaboration of the foundry, and generates the overlap of the respective innovation platforms. The construction of a sturdy and healthy circle is the continuous issue for the open foundries not only at the AIST but also throughout Japan.

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Note) Professor N, whom the Author respects, calls this the “proximity effect.”

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Discussions with Reviewers

1 Overall comment

Comment (Akira Ono, AIST)

This paper addresses the issues of open foundries to promote open innovation, and the author, who has plenty of experience in the actual management of such a facility, explains the scenario for its operation, the accomplishments, and the evaluation. The paper contains much information that should help the users and operators of foundries, and it is an excellent paper for *Synthesiology*.

2 Transmission of the knowledge package

Question & Comment (Hiroshi Akoh, Evaluation Department, AIST)

In the global innovation platform system, I think the transmission as well as the creation of the knowledge package is important. Please indicate the measures and methods for the transmission of the knowledge package.

Answer (Hiroyuki Akinaga)

The information transmission service is literally the first step in increasing the attraction for promoting open innovation. NPF categorizes the services it provides into the following eight: (1) technological consultation, (2) use of equipment, (3) technical support, (4) product creation support, (5) on-site training, (6) human resource training, (7) information transmission, and (8) networking.

The (7) information transmission service includes the publication of newsletters and textbooks and organization of various workshops, and recently we started using the ICT media such as Facebook. For example, results of a characteristic microfabrication process may be introduced in a newsletter, and we offer the knowledge package of the microfabrication process to the users who participate in NPF. On the other hand, the mechanisms for gathering the know-how for microfabrication or nano measurement/analysis, creating the archives, and sharing them among multiple users to further advance such knowledge have not been built, and we are currently working on it by trial-and-error. In reality, it is quite difficult to make clear-cut decisions, such as the research results should go to the users while the advanced technological know-how go to the foundry, or the process know-how described on the upper right of Fig. 2 should be used for supporting the research of a new set of users. I am aware these are future subjects to be studied.

3 Dilemma in operating the foundry

Question (Akira Ono)

In subchapter 2.3, you mention one of the dilemmas in operating the open foundry. Can you briefly describe any other operational dilemmas, other than the ones mentioned in this paper?

Answer (Hiroyuki Akinaga)

In subchapter 2.3, I described the dilemma of making use of idle time and the beneficiary pay, so here, I shall introduce the dilemma of fee setting and the beneficiary pay system.

When a sharing system of the state-of-the-art equipment is organized and made available, the equipment that is on the leading edge and has an easy-to-use sharing system will be used and reserved more, and as a result, many users can share the cost of operating that equipment. Here, when the actual cost necessary for the operation is allotted as the maximum cost of the equipment that can be paid by the beneficiaries, the following dilemma occurs. If the actual cost is set as the maximum, the charge for that particular equipment decreases through cost sharing. Because low charge is an attraction that brings in more users, as in the dilemma of idle time and beneficiary pay, the equipment aging is accelerated due to the cost reduction, and the "tragedy of the commons" will soon occur. From the perspective of managing the facility, I think it is better to set the charge higher for equipment that is used more frequently. For example, high charge setting has the effect of improving the congestion degree of machine use. Also, the excess charge collected over the actual cost can be allotted to additional installment of similar equipment or for the replacement of aged equipment, and as a result, this will further benefit the users.

On the other hand, someone with an excellent idea does not necessarily have sufficient R&D budget, and the open foundry must play the role of reducing the financial burden to such a person and support the startup of R&D. The organization of a system that promotes trial use by users is another future issue for the open foundry.

4 Updating the state-of-the-art equipment

Question (Hiroshi Akoh)

In subchapter 2.3 "Dilemma of managing an open foundry," I understand very well the importance of efficient use and the deceleration of the aging cycle. Can you tell us the policy for updating old equipment or introducing new state-of-the-art equipment?

Answer (Hiroyuki Akinaga)

When the NPF was first established, we prioritized the construction of integrated processes such as for material analysis, thin film growth, lithography, and device evaluation. Recently, since NPF is a network type foundry and is complementary to the collaborating foundry group, new equipment is introduced with the policy of advancing technology in the nanoelectronics or material science fields that are our strengths. For example, in the Nanotechnology Platform Project in which NPF is participating, other institutions have several devices for electron beam lithography and electron beam mask lithography, so NPF introduced a lithography device with excellent turnaround time. Moreover, priority is given on introducing state-of-the-art equipment for device fabrication process and evaluation.

5 Collaboration of foundries across the institutions

Question & Comment (Akira Ono)

In chapter 5 and Fig. 5, you indicate the scenario for hierarchically integrating foundries across different institutions to nurture global innovation platforms. I hope that the scenario is developed further in the future. Is such attempt taking place in the field of nanotechnology, and if so, how is it being done?

Answer (Hiroyuki Akinaga)

Other than the Nanotechnology Platform Project of Japan and NNIN of the United States described in subchapter 2.1, there are foundry networks in Taiwan, USA, the Netherlands, Australia, and others. With the United States, we have networks for microfabrication, measurement, and simulation, and there are hierarchical collaboration for microfabrication, microstructure analysis, and molecular/substance synthesis in the Nanotechnology Platform Project. In fact, while managerial issues remain in handling the intellectual property and the contracts for conducting research, the users who conduct R&D at these "network of networks" can utilize the foundries that belong to multiple organizations according to their objective and research phases, and have been successful in accelerating their R&D.

At NPF, increasing number of users are utilizing the foundries of multiple organizations that participate in the Nanotechnology Platform Project, such as the National Institute for Materials Science, the University of Tokyo, Tokyo Institute of Technology, and Kyoto University. Recently, NPF has started to utilize ICT technology to promote foundry collaboration with the Asian countries,[15] and we wish to become an open foundry with international attraction.

6 Comparison of the open foundry with a library

Question & Comment (Akira Ono)

I do not think it is easy to continuously and smoothly operate a research foundry at universities and public research institutions. In the past, analytical instrument centers were established as open foundries by universities, but it is generally thought they never took hold.

On the other hand, a library is an open facility for sharing books and resource materials, and its management at the universities and research institutions has been firmly established. Compared to an open foundry of equipment, what are the reasons that the library is so successful? Is it simply tradition and length of experience that make the difference?

Answer (Hiroyuki Akinaga)

The management of an open foundry is often compared to the management of a general hospital, but I think it is useful to compare it with a library.

In the operation of a library, the Five Laws of Library Science (Reference S1, S2) are widely known: "(1) books are for use, (2) every reader his/her book, (3) every book its reader, (4) save the time of the reader, and (5) the library is a growing organism." By replacing the "book" with "equipment or knowledge package including the know-how," "reader" with "user," and "library" with "foundry," for the Five Laws, I think we have the managerial policy of an open foundry as an innovation platform. The Five Laws were written in 1931, and for example, (2) indicates the social significance of the library and the issues of financing to achieve the objective, and (4) indicates a wide range of issues, from a library system to improve the readers' service to shelving and categorization of books. As you indicate, the library has tradition and accumulation of experiences for its management. Recently, there are reports of new attempts by the library to contribute to the creation of new knowledge by offering open access (Reference S3).

Studies of open foundry management is yet to be done systematically and academically. However, in the past 10 years, I think the importance of foundries at universities and research institutions is being strongly recognized. As shown in Fig. 5, a foundry promotes diverse R&D, and can be a place to return the results to society. Therefore, it must be able to play the due role as a bridge between research and society. The author believes that foundries will play a major part in the social acceptance of R&D results in the next 10 years,[2] and I hope this paper will be read as precursory advice by readers from wide-ranging fields.

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7 Scenario for foundry management and its time schedule

Comment (Akira Ono)

The construction of the nanotechnology open foundries at AIST was started in the beginning of the 2000s, and I think there was a vision (or scenario) of what kind of foundries they should be at the start. If you compare the scenarios of the 2000s and 2010s, I think the readers will better understand the development of the open foundry at AIST in these 10 years.

Question & Comment (Hiroshi Akoh)

In chapter 1, the organization and advancement of the foundry are positioned as the issues toward 2020. I think the scenario described here sets this timeframe as a goal. Therefore, I think the understanding will deepen, if you indicate the time schedule for the realization of the scenario. Also, by describing the positioning of the goal year 2020, I think the dynamics of the scenario for strategic management will become clearer.

Answer (Hiroyuki Akinaga)

The scenario that NPF wrote initially is described in subchapter 3.2, and the time schedule in subchapter 4.2. The author stated in Reference [2] that the evolution process of the foundry will be to become: a "user facility and network of user facilities" in 2005, "problem-solving user facilities, and networking" in 2010, and a "user facility as a center of science and technology formation" in 2015. I think the foundry in 2020 should be a "user facility in society, as a demonstrative test area and for outreach activities."

8 Aim of the corporate utilization of the open foundry

Question & Comment (Akira Ono)

As you describe in subchapter 4.2, I think it will be wonderful if the private companies engage in the whole process from target setting to packaging "at the open foundry." However, due to various reasons such as corporate secrets, isn't it normal that the private companies position the open foundry as one of the tools for the development and demonstration of elemental and core technologies? I imagine that although open innovation is important, "target setting" and "packaging" are done within the respective companies. Although I think the situations at SCR and NPF are different, even if the open foundry is merely one of the tools, isn't the use of the "open foundry" highly valuable for the companies?

Answer (Hiroyuki Akinaga)

This is an important discussion point concerning the role of the open foundry in industry. As you indicate, there are many cases where private company users conduct only part of the practical R&D process, particularly at the networking type or knowledge accumulating/integrating type foundry described in subchapter 2.1. This is the same at NPF. For example, they include elemental technology development when introducing new materials into a manufacturing process, or prototyping of a device and its property evaluation. In introducing new materials or technology, there are many cases where the results as planned cannot be obtained, and the use of the foundry can be seen as a risk avoidance activity, and is an example of "handling uncertainly" described in subchapter 2.2 and subchapter 3.2.

On the other hand, a bottleneck may become apparent in an R&D process, and if a new target must be set as a result, NPF may provide support from the phase of target setting, through the clarification of technological issues, the discovery of the cause of failure, and the swift provision of knowledge and technology needed to resolve them (Reference S4). In the process of new R&D, whether the responsibility for packaging the elemental technology falls on the private company or NPF depends on the case. However, it is not rare that NPF handles not only the process development, but also the obtainment of intellectual property (IP) rights through patent application, the development for field testing device, and the packaging of knowledge, in cases where NPF is closely involved in the R&D from the initial target setting. In such cases, as you have alluded, the issue will be the agreement on establishing a boundary between the background IP originally owned by the company and the foreground IP developed at NPF. Moreover, utilizing the foreground IP as the background IP in the innovative platform with NPF at the core is essential in realizing the eco innovation R&D system. We hope to build up successful cases one by one.

As a supplementary explanation, in the survey for NPF in Reference S4, there were many respondents who said, "NPF was useful for qualitative improvement or improvement of skills of the researchers." Not just for R&D promotion, but also from the perspective of employee training, the value of the "open foundry" for the private companies is increasing. In fact, there are companies that use the training sessions at NPF as part of their employee training program.

[S4] Monbu Kagaku Sho Sentan Kenkyu Shisetsu Kyoyo Innovation Soshutsu Jigyo "Nanotechnology Network" (MEXT Project on Common-Use Research Facilities for Innovation Creation "Nanotechnology Network"), Research Topic Follow-up Survey Report (2012) (in Japanese).

9 Merit of using the NPF for the companies and research groups

Question & Comment (Akira Ono)

Ten years have passed since the establishment of NPF at AIST. It has received continuous support of MEXT, and I am glad that our sponsor considers it a success. On the other hand, I think the degree of success is determined by the evaluation of the companies and research groups that participated in NPF.

Therefore, I would like to know the evaluation of the users about NPF, such as what merits were gained by the companies and research groups that were involved in NPF. However, I'm afraid the "quantitative and objective" evaluation like a statistical data may not necessarily be available. Can you, the author, who have interacted with the users on a daily basis and have actually managed NPF, introduce user evaluation for NPF even if it may be the "qualitative and subjective" version of the case studies?

Answer (Hiroyuki Akinaga)

NPF has promoted various human resource training projects such as the schools for microfabrication, nano measurement, and nano analysis. Questionnaire surveys were done after the schools to obtain responses from the students, to plan the curriculum for the school that would be held the following year. Recently, in the free response section of the questionnaire, I see more responses like "I participated in the school because my boss introduced me to it" or "I want to recommend it to my subordinates." As I answered in Discussion 8, I think there are many cases where the companies and research groups think, "It was useful for the qualitative improvement or improvement of skills of the researchers."

Also, NPF regularly conducts user satisfaction surveys. For example, in the questionnaire done in February 2007 (105 valid responses), to the question "Was your initial objective obtained through our support?" the percentage of answers "results surpassing expectations were obtained," "obtained," and "almost obtained" was 73 %. To the question "Were the results obtained through our support useful?" the percentage of answers "very useful" and "useful" was 92 %. We received an evaluation that "the user satisfaction is high even if a result different from what one expected was obtained," and from that perspective, the author highly praises the will and skill of the engineers (technical staff) who work at the sites of NPF.

Moreover, in the questionnaire survey of the NPF users conducted by an organization of the MEXT projects in June to July 2013, there were the following messages: "It was very encouraging that you gave me beneficial findings in addition to very detailed and careful explanation in the technological support" from a university user; and "You went as far as innovative technological development in the technological support…" from a corporate user. On the other hand, an independent administrative body institution user indicated, "Before actually using the facility, there are several steps of procedures on the web system and it is difficult to get through. However, the explanations of the respondent and personnel in charge were very easy to understand, and I am grateful." We are improving the NPF system* by revising the procedures for using the facilities from the user's viewpoint, to realize a readily accessible facility.

*NPF system: https://nanoworld.jp/npf/
NPF system is a support system to smoothly manage NPF. It was developed to realize "(4) save the time of the reader (user)" in the Five Laws of Library Science, described in the answer for Discussion 6. From the user side, the electronic application system enables requesting support, reserving equipment, confirming charges, and others. From the NPF side, the system enables the management of homepage display, various databases, progress of support, charge account, and others.

Development of an advanced sewage sludge incinerator, "turbocharged fluidized bed incinerator"

— The role of AIST in the development of a new system —

Yoshizo Suzuki *, Takahiro Murakami and Akio Kitajima

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Annual production of sewage sludge in Japan has increased, and most of the sewage sludge is incinerated. With conventional sewage sludge incinerators, a large amount of energy is needed for operation. Additionally, the emissions of greenhouse gas N_2O are expected to be high, because sludge contains a high concentration of nitrogen. In this R&D, an advanced sewage sludge incinerator "turbocharged fluidized bed incinerator," which can achieve not only energy savings but also a low environmental impact, was proposed in collaboration with Public Works Research Institute and companies. This new system consists of a pressurized fluidized bed combustor coupled with a turbocharger. The R&D to achieve practical use of the proposed system is primarily explained in this paper.

Keywords : Sewage sludge, incinerator, pressurized fluidized bed, turbocharger, energy recovery

1 Introduction

With the spread of the sewage treatment system, the amount of sewage sludge is increasing yearly in Japan, and most is incinerated. The sewage sludge after dewatering still contains about 80 % water. Currently, it is incinerated using large amount of supplementary fuel such as gas and fuel oil, and therefore, the sewage sludge incineration process is actually an energy consuming process. In addition, sewage sludge contains extremely high amount of nitrogen compared to other solid fuels such as coal or biomass, and large amounts of nitrogen oxide (NOx) and nitrous oxide (N_2O) are produced during incineration. In general, while the NOx concentration increases as the combustion temperature increases, the N_2O concentration decreases. Particularly, the global warming potential of N_2O, a greenhouse gas, is 310 times higher than CO_2, and the emissions of such gases are a matter of grave concern.

Currently, of the greenhouse gases (in CO_2 equivalent) emitted from the sewage plants, the emission of N_2O produced during sludge incineration dominates about one-fourth. Increasing the incineration temperature is attempted as a method to reduce the N_2O. The N_2O production is known to be inhibited at high temperature, and the N_2O emissions can be reduced to about 60 % by incineration at high temperature of 850 °C, which is 50 °C higher than the conventional operation temperature of 800 °C. Most of the sewage sludge incinerators in Japan were constructed during the 1980s to 1990s, and the incinerators have progressively aged. High temperature that may damage the incinerator cannot be used in many systems. Therefore, the Ministry of Land, Infrastructure Transport and Tourism (MLIT) has proposed measures for energy savings and greenhouse gas reduction in the sewage sludge incineration process,[1] and a system that essentially achieves both energy savings and low N_2O production is in demand. In the future, the need for updating a large number of the existing incinerators is expected, and the development of a sewage sludge incineration process using a new technology is an immediate issue.

A typical flow sheet of conventional sewage sludge incineration system is shown in Fig. 1. As shown in the figure, fluidized beds are often used in sludge incineration. Silica sand is usually used as a bed material. By supplying air from underneath the gas distributer plate, silica sand is fluidized with bubbles like when the water is boiling. The sand acts as the heat medium, and the dewatered sludge with high water content can be incinerated at stable temperature in the fluidized bed. The sewage sludge contains about 80 % water, and supplementary fuel (utility gas, fuel oil, etc.) is used to maintain the temperature within the incinerator. A fluidized bed incinerator is roughly divided into the sand bed (fluidized bed) and the freeboard that is mainly gaseous space on the upper part of the bed. Drying and pyrolysis of the sludge occur mainly in the sand bed. Next, combustible gas produced by pyrolysis in the bed burns in the freeboard. Flue gas is released into the atmosphere as clean gas after passing through the treatment system. In the conventional incineration system, two fans are needed for the operation. One is the fan to supply air for sludge incineration, and the other is the fan to induce flue gas from sludge incineration. The power

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to drive these two fans is said to dominate about 40 % of the energy needed for the entire system, and these fans are major causes of electricity-derived CO_2 emissions for which energy-saving measures must be taken.[2]

Through the joint development of AIST, the Public Works Research Institute (PWRI) of MLIT, and some private companies, a new incineration system as shown in Fig. 2 was proposed to raise the energy-saving capabilities and to decrease the N_2O emissions of the sewage sludge incinerator.[2][3] A unique characteristic of this system is that the fluidized bed incinerator is operated under pressurized conditions, and the generated high-temperature, high-pressure flue gas can be used to drive a turbocharger installed in the downstream of the incinerator to produce the combustion air. This system has the following advantages compared to the conventional system (Fig. 1).

1) Since combustion proceeds in the pressurized condition, the incinerator volume can be reduced for the same incineration capacity. This allows the reduction of heat loss from the incinerator, and the amount of necessary supplementary fuel can be reduced.

2) Since the combustion air can be produced by the turbocharger, the air supply fan is not needed. Also, since the flue gas can be released into the atmosphere by residual pressure from the pressurized operation, the induced draft fan is unnecessary. The two fans that are major power consumers can be eliminated, and power consumption can be reduced greatly compared to the conventional system. Moreover, the excess air can be used for aeration in the sewage works.

3) Since energy recovery is done within the turbocharger, the equipment is simpler compared to the one using a gas turbine. For matching with the turbocharger, operation pressure of only about 0.25 MPa is needed, and high-pressure operation and the expensive pressure vessel required to match with the gas turbine are not necessary.

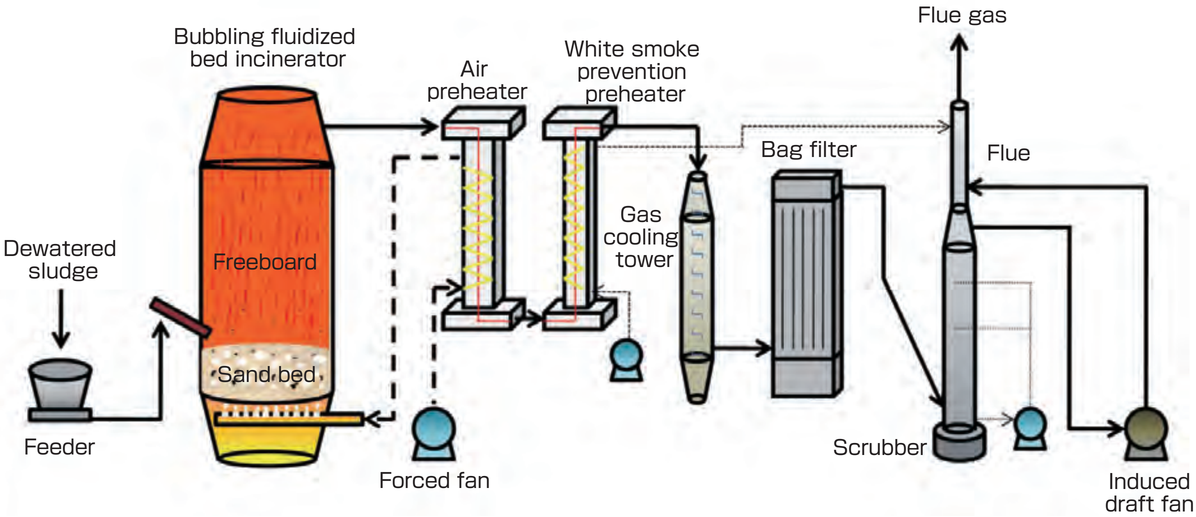

Fig. 1 Typical flow diagram of the conventional sewage sludge incineration system

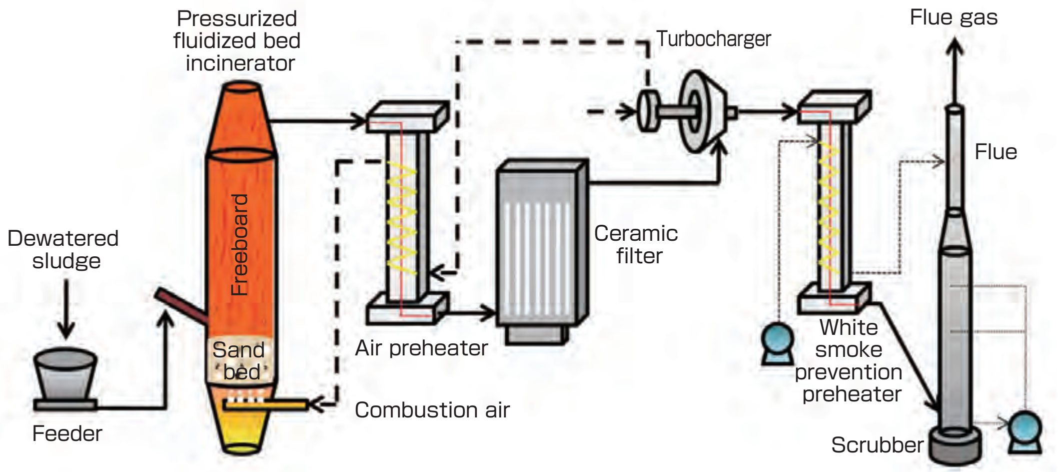

Fig.2 Flow diagram of the turbocharged fluidized bed incineration system

We named this next-generation sewage sludge incineration system the “turbocharged fluidized bed incineration system,” and conducted R&D with the goal of putting this system to practical use.

2 Scenario to realize the goal

The goal of this R&D is to realize a turbocharged fluidized bed incineration system as mentioned in the previous chapter. The average size of sewage sludge incinerators in Japan is that which can manage 100 t/d of sludge supplied to the incinerator. To commercialize such a large-scale plant with new technologies, it is necessary to conduct fundamental research using laboratory-scale experimental facilities, followed by demonstration research at a scaled-up demonstration plant based on the results of the fundamental research. Since several years are necessary to achieve each step, long-term R&D is necessary for practical application, just as in general process development. In this chapter, the road to commercialization will be explained.

In 2000, to plan the essential technological innovation for the sludge incinerator, PWRI established a research group jointly with private companies. In one of the research group sessions, a power generation technology combined with pressurized fluidized bed combustion was taken up as a new high-efficiency power generation method for coal and for which practical application was in progress. The sewage sludge could be easily transported to the pressurized system via a high-pressure pump, there was no problem in continuous supply, and the match with pressurized fluidized bed incineration was good. After studying the system, it was confirmed that there was a possibility for achieving dramatic energy savings by recovering the energy from the high-temperature, high-pressure combustion gas. However, in the field of sewage sludge or waste incineration, there was absolutely no experience with the pressurized fluidized bed incineration, and the development of a new system applying this type of incineration technology by PWRI and the incinerator manufacturer was difficult.

During this time, concern for greenhouse gas was increasing, and at the research institutes in Tsukuba, the research on estimating the greenhouse gas inventory was conducted across the ministries and agencies, with the leadership of the Ministry of Environment. In this project, AIST was in charge of the greenhouse gas emissions in the combustion process of fossil fuels, and we also assisted the measurement of N_2O gas emissions from the sewage sludge incinerator that was mainly been done by PWRI.[4] At the time, AIST’s main research topic was the pressurized fluidized bed combustion of coal, and through exchanges with the people of PWRI, we found that our initial research might satisfy their demands, and this led to the official request for joint research from the PWRI research group. This was the beginning of the research, and it was a technological development in which the characteristic of Tsukuba, where several research institutions are concentrated, was fully utilized.

There were two institutions that participated in the development, AIST and PWRI. The division of roles was clear from the beginning. AIST was in charge of the technical support in conducting the research, while PWRI was in charge of the technological evaluation and the PR activities to the local governments and companies. There were three private companies that initially participated in the joint research: Tsukishima Kikai Co., Ltd., Kubota Corporation, and IHI Corporation. In addition to the manufacturer of sewage sludge incineration plants, we collaborated with a gas turbine manufacturer that could sufficiently understand the basic concept of the research and also manufactured turbochargers. We started from independent research by these five parties. In conducting the independent research, we were about to obtain results for the basic research and the optimization of the system design using the new technologies. However, due to various reasons related to the economic situation in Japan, all the companies except Tsukishima Kikai withdrew from the joint research in 2005. Sanki Engineering Co., Ltd. that considered this technology highly joined, and a new start was kicked off with four parties including AIST and PWRI. A demonstration plant was constructed and operated after obtaining external funding, to confirm the durability performance by long-time operation of the demonstration plant. The process was thus completed.

Yet, the introduction of a new process without performance achievements was a cause of concern for users, and the completion of the process did not lead immediately to practical use. Therefore, the technical PR to the local governments, the main users of this system, was done by PWRI that had close relationships with the sewage administrators. As a result, the technology was highly acclaimed by the people concerned, but this did not lead to immediate employment.

As a result of considering the strategies for practical application within the development group, we reached the conclusion that it would be most effective to get the Tokyo Metropolitan Government, which leads Japan in the sewage public work, employ this process. At the time, the Bureau of Sewage, Tokyo Metropolitan Government was planning to reduce greenhouse gas emissions from sewage treatment (Earth Plan), and we conducted PR activities for this technology by concentrating on the energy saving and low N_2O characteristics. While we obtained understanding of the person in charge, a confirmation test would be done jointly with Tokyo for the long-time durability that was the greatest barrier in actually employing the new system. Ultimately, the goal was met, the system was registered as the main technology of Tokyo’s Earth Plan, and we received an order for the commercial unit.

3 Synthetic method to achieve the objective

3.1 Laboratory-scale pressurized fluidized bed incineration test

As mentioned in the previous chapter, this research started from independent research, and during that time, AIST was in charge mainly of the pressurized incineration experiment of the sewage sludge, while the private companies and PWRI were in charge of the optimal design for the turbocharged fluidized bed incineration system for sewage sludge. There was no combustion data under pressurized conditions for the sewage sludge. Therefore, the experiment was started by installing a bubbling fluidized bed incinerator for sewage sludge incineration and a high-pressure sludge pump for supplying sewage sludge to the testing equipment for pressurized combustion owned by AIST, as shown in Fig. 3.

The schematic diagram of the whole system is shown in Fig. 4.[5][6] The pressure vessel was originally designed and manufactured for the pressurized combustion experiment of coal. It was made of stainless steel, with an inside diameter of 1,200 mm, height of 3,200 mm, and designed pressure of 0.99 MPa. A bubbling fluidized bed incinerator (diameter of 80 mm, height of 1,300 mm) was installed inside the vessel, to maneuver the sludge supply, air supply, electric furnace, and others during the experiment, and the control device was installed outside the pressure vessel. The sludge was supplied continuously through a vertical tube on the uppermost part of the fluidized bed. One-touch connector was used for the joint that connected the sludge supply tube to the pressure vessel or the fluidized bed, considering the preparation before the experiment and cleanup after the experiment. To homogenize the sludge property during the experiment, 10-20 kg of sludge was mixed in the mixing tank of the high-pressure sludge pump for pre-experiment preparation. Water was added to improve fluidity of the sludge (Fig. 5).

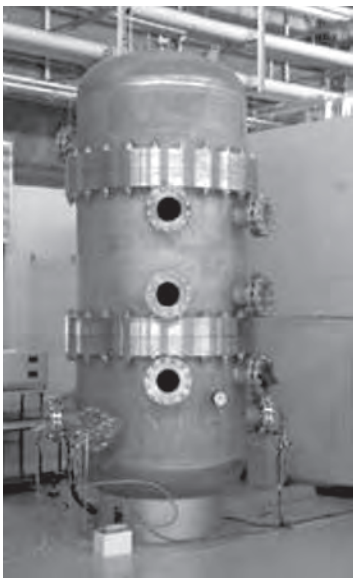

Fig. 3 Photograph of the pressure vessel

Table 1. Analytical values of the sewage sludge

Proximate analysis [wet, wt.%]	Water content	78.0
	Volatile content	13.9
	Fixed carbon	1.8
	Ash content	6.3
Ultimate analysis [dry, wt.%]	C	29.8
	H	4.0
	N	5.0
	S	1.1
	O	21.4
Higher heating value [MJ/kg (dry)]		17.10

Table 2. Example of the composition of sludge incineration ash

Ash composition [dry, wt.%]	SiO_2	39.97
	Al_2O_3	10.88
	CaO	6.33
	MgO	2.57
	Fe_2O_3	3.78
	Na_2O	0.63
	K_2O	1.63
	P_2O_5	20.51

For the sewage sludge used as the experimental sample, the actual dewatered sludge was supplied for each experiment by the Ibaraki Prefectural Kasumigaura Regional Sewage Office. The properties of the dewatered sludge are listed in Table 1. Compared to fossil fuel, it has higher ash and nitrogen contents. The odor specific to sewage sludge was a problem, but measures against odor were taken by storing the dewatered sludge in a sealed container and thoroughly cleaning the high-pressure sludge pump and feed pipe after the experiments.

In the basic research, it was necessary to check whether there is melting of ash and the emission of NO*x* and N_2O that are environmental pollutants. The former is a phenomenon related to the foundation in establishing the process. The ash of the sewage sludge contains a large amount of alkaline component with low melting point, as shown in Table 2,[2] and there were concerns that in the pressurized incineration conditions, stoppage of fluidization caused by ash melting might occur in the local high-temperature region. The combustion experiment under maximum 1 MPa pressure was conducted, and as shown in the photograph of fly ash captured by a ceramic filter attached at the exit of the fluidized bed incinerator in Fig. 6, majority of the ash was fly ash with reddish brown color and no melting was observed.[5] Iron flocculant added to increase the sedimentation property of the sludge in the thickener might inhibit the melting of the alkaline component.

After confirming that the process could basically be established since ash melting could be avoided, the combustion characteristics during pressurized operation such as the temperature distribution in the incinerator and the effect of temperature on NO*x* and N_2O emissions were clarified. The N_2O emission decreased with the increase in combustion temperature, and the result obtained was the same as the known general findings of N_2O temperature dependency. On the other hand, the NO*x* emissions decreased compared to the combustion of coal or dried sewage sludge at the same temperature.[5] This was thought to be the inhibition effect of NO*x* production by steam that comprises about 40 % of the gas produced after incineration.[7] From these results, it was clarified that there was no significant deterioration in the emission properties upon incinerating the dewatered sludge under pressurized conditions, but rather, there was potential of reducing the environmental load.

3.2 System design

For the optimal design for the turbocharged fluidized bed sludge incineration system conducted by the private companies and PWRI, it was expected that the plant with advanced technology would be employed when updating the existing sludge incineration system, and investigations were done from the perspective of energy savings. For energy savings, the elimination of the two fans, one to supply combustion air and the other to induce flue gas after combustion, was necessary since they were major power consumers, and this could be achieved by introducing a pressurized system. As mentioned previously, the sludge contains high amount of water, and the steam content within the high-temperature flue gas is high at about 40 %. Therefore, when recovering the energy from high-pressure flue gas, the high-content steam can be used. To be able to efficiently use the flue gas characteristic of sludge that contains high amount of water for energy recovery is a

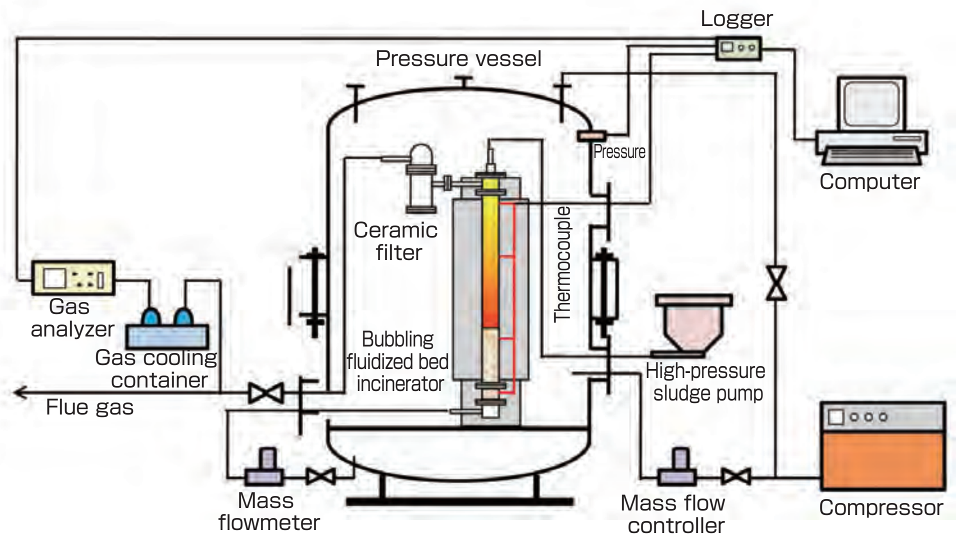

Fig. 4 Schematic diagram of the laboratory-scale pressurized fluidized bed incineration system

Fig. 5 Dewatered sludge supply by high-pressure sludge pump

Fig. 6 Photograph of the fly ash in the ceramic filter

major advantage. Moreover, in the pressurized system, the actual reactor volume becomes smaller than in atmospheric pressure when compared for the same capacity, as in general chemical plants. Therefore, the surface area of the incinerator is reduced, the amount of thermal radiation decreases, and the amount of supplementary fuel needed to maintain the combustion temperature can be reduced.

Normally, the method of manufacturing pressurized air using gas turbines is considered for the energy recovery from flue gas. However, the gas turbine that matched the flue gas volume of an incinerator having 100 t/d capacity that was our target must be specially ordered, since it was not of standard size, and it was found that the introductory cost and the maintenance cost would be extremely high. In addition, the optimal match with gas turbines required high pressure of over 1 MPa, and the incinerator must be installed in an expensive pressure vessel. From the above system analysis, we decided to abandon the pressurized combustion system using gas turbines.

As a solution, we decided to employ turbochargers that were more generally used compared to gas turbines. Combination with the turbocharger could be done at mild pressurized operation of maximum 0.25 MPa, and no pressure vessel was necessary. The pressure resisting structure of the incinerator would be simple, and the construction cost, necessary operators, and regular inspection were not so different from the conventional system. For the turbocharger that matched gas volume of 100 t/d capacity, a turbocharger for marine diesel engines already existed as a general-use product, and the introductory cost would be very reasonable.[2] From the above system considerations, the energy-saving “turbocharged fluidized bed incineration system” that could reduce both the CO_2 from power generation and the CO_2 from burning supplementary fuel was proposed, and a joint patent application was submitted.[8]

3.3 Demonstration test and practical use

Following the basic system design and the understanding of fundamental combustion property, it was necessary to build and demonstrate the proposed turbocharged fluidized bed incineration system. Therefore, we applied to the “Development of elemental technology for energy conversion to utilize the urban biomass collection system” of the New Energy and Industrial Technology Development Organization (NEDO), and fortunately, our proposal was selected. The construction site of the demonstration facility was the sewage plant site of Oshamanbe, Hokkaido where a demonstration circulating fluidized bed incinerator of Sanki Engineering was located. There, a plant of 5 t/d scale was constructed. The results of our basic research were applied to the design of this plant. The schematic diagram of the demonstration plant is shown in Fig. 7.[2][3] The pressurized incinerator with internal refractory structure was made of steel, with internal diameter of 700 mm and height of 9,200 mm. The turbocharger installed in the downstream of the fluidized bed incinerator was a general-use product installed in large diesel freight trucks, and the one of matching scale was installed in the demonstration plant. As a result, we succeeded in operation without the two fans that were used in the conventional system.[2][3]

From this phase, AIST was in charge of the setup of the gas analyzing system and the analysis of the operation results. As a result of conducting the continuous incineration test using actual sludge, it was found that the N_2O concentration in the flue gas was strongly dependent on the freeboard

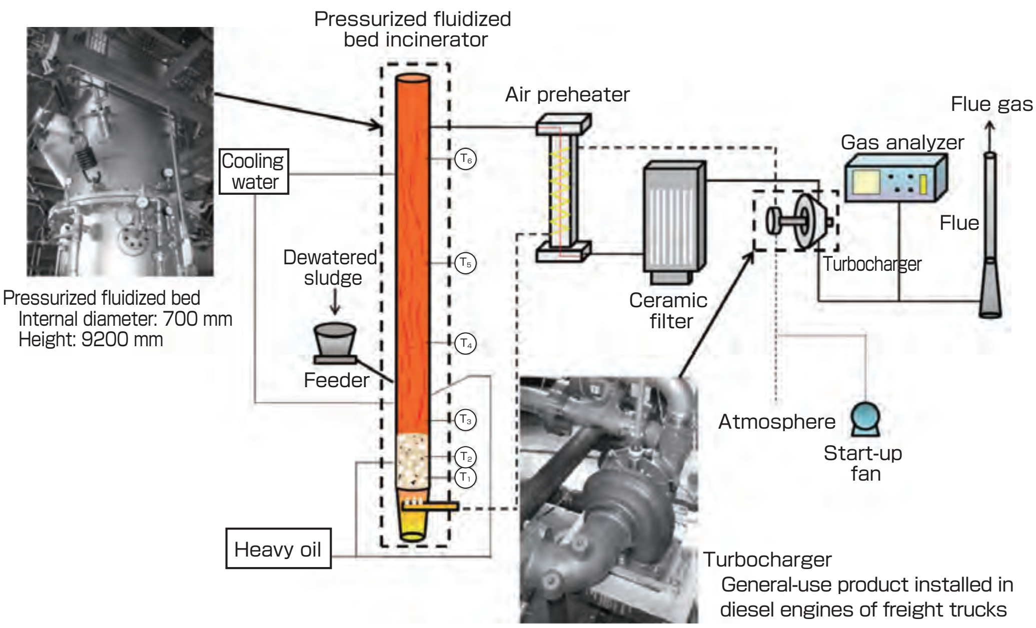

Fig. 7 Schematic diagram of demonstration plant

temperature, and the concentration decreased as the temperature increased, as shown in Fig. 8.[3] It was also found that the emission could be reduced to half compared to the high-temperature operation of the conventional system (Fig. 9).[3] AIST clarified the temperature dependency of N_2O emissions from the basic combustion experiment results, and from this experiment, focus was placed on the temperature distribution inside the incinerator of the demonstration plant. It was found from the analysis of the experimental results (Fig. 10)[6] that a local high-temperature region was formed in the lower part of the freeboard. The figure shows the results of comparing the temperatures of the atmospheric pressure operation and the exit temperature of the conventional system at about the same condition. In the pressurized operation, the combustion of the combustible gas generated by drying and pyrolysis of the dewatered sludge supplied to the fluidized bed occurs at the freeboard, similarly to the conventional type, but the combustion rates differ greatly. The local high-temperature region is formed at the lower part of the freeboard because of rapid burning of gases. In contrast, in the conventional atmospheric pressure operation, the combustible gas after pyrolysis burns evenly throughout the freeboard because the combustion rate of the gas is small, and the temperature increase is gradual. Therefore, the reduction in N_2O emissions at pressurized conditions in the turbocharged type should be because of the decomposition of N_2O in the local high-temperature region generated in the lower part of the freeboard.

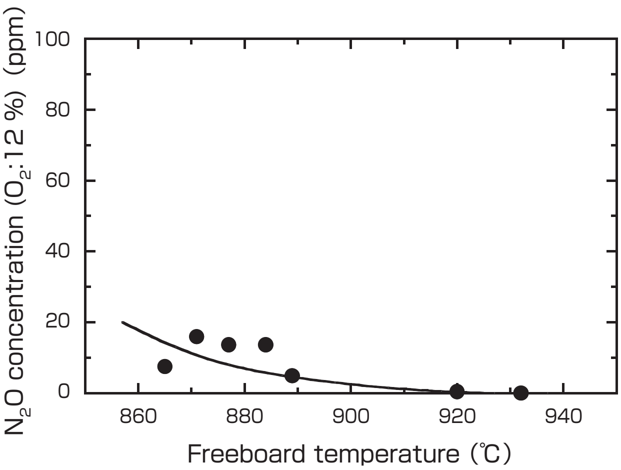

Fig. 8 Relationship between the N_2O concentration in flue gas and the freeboard temperature[9]

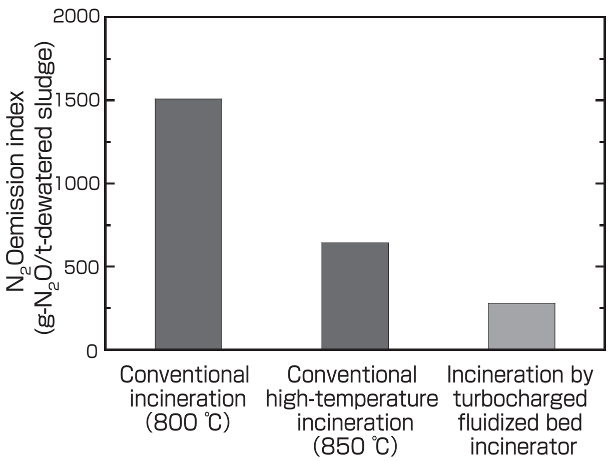

Fig. 9 Comparison of N_2O emissions[9]

The fundamental combustion experiments at AIST were carried out at over 0.6 MPa due to the limitation of the facility. Rearrangements were done to the facility for the demonstration experiment, combustion experiments were done at 0.2-0.3 MPa that was the same condition as the demonstration plant, and it was confirmed that the N_2O emission was dependent on temperature rather than operating pressure.[6] Also, to theoretically support the N_2O reduction effect, we calculated the freeboard temperature distribution using CHEMKIN, a software tool for solving complex chemical kinetics. As a result, as the pressure increased, the high-temperature region was produced in the lower part of the freeboard, and the same tendency as the demonstration plant was obtained.[9][10] The reason we were able to quickly clarify the cause of the N_2O reduction was because we were able to link the results of the basic research and the demonstration test.

Moreover, the emission of NO*x* was low similar to the basic research results at AIST, and we were able to half the amount compared to the conventional type. This was because, as mentioned earlier, the inhibition of NO*x* production by steam in the combustion gas and the NO reduction by char in the

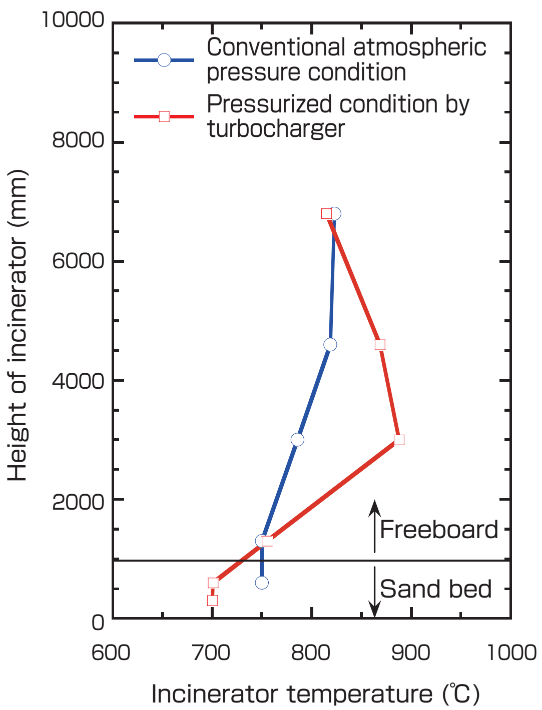

Fig. 10 Comparison of the temperature distribution in the fluidized bed incinerator[10]

fluidized bed were enhanced by pressurization.

In the completed system, the power consumption was reduced by about 40 %, use of supplementary fuel by about 10 %, NO_x emissions by about 50 %, and N_2O emissions by about 50 %, compared to the conventional system. For the greenhouse gas reduction effect (by CO_2 equivalent), about 4,000 ton per year could be expected for one 100 t/d capacity plant that is the average scale in Japan. There are about 240 sewage sludge incinerators in Japan, and estimating that about half of them introduce the new type, the reduction of about 480 thousand ton/year can be expected. This is about 7 % of the total greenhouse gas emissions by the sewage treatment plants in Japan. From the above, it was demonstrated that the turbocharged fluidized bed incineration system was an innovative system that can achieve energy savings as well as low environmental impact.[2]

As a result of the PR activities after the completion of the NEDO project, the Bureau of Sewage, Tokyo Metropolitan Government took notice of this technology. As a final technological evaluation, a joint research with two private companies was started in 2008 for the long-term durability test. Long-time operation was conducted and continuous operation of a total of 2,000 hours was successfully achieved. The reliability and durability of the turbocharger were confirmed, this technology was employed in the Earth Plan 2010 that set the greenhouse gas reduction as its goal, and an order was received for the commercial plant at the end of FY 2010. This first plant has the sludge incineration capacity of 300 t/d, and it is one of the largest plants in Japan. It is about 60 times larger in size than the demonstration plant, but the scale-up method of the fluidized bed incinerator has been already established. In common scale up methods, the combustion load or the sludge feed rate per cross-sectional surface area of the incinerator is matched, and basically the incinerator size is increased only in the radial direction, and the gas velocity and residence time of the gas in the incinerator are the same even if the plant scale is increased. The temperature distribution along the height of the incinerator remains the same, the low environmental impact operation will be possible after scaling up, and no major trouble is expected in its operation.

4 Technological ripple effect

In the FY 2010, the first order was received for the commercial plant with 300 t/d scale from the Kasai Water Reclamation Center, Tokyo. It was scheduled to start operation by the end of FY 2013. Including the first unit, orders for five units were received as of present.[11][12]

1 Kasai Water Reclamation Center, Tokyo; 300 t/d scale
2 Asakawa Water Reclamation Center, Tokyo; 60 t/d scale
3 Shingashi Water Reclamation Center, Tokyo; 250 t/d scale
4 Sagamigawa Ugan Treatment Plant, Kanagawa Prefecture; 100 t/d scale
5 Aigawa Region Sewage Central Mizu Mirai Center, Osaka; 100 t/d scale

The first to start operation among the five units was the unit for Asakawa Water Reclamation Center, and it commenced operation at the end of January 2013, went through a test run period, and the opening ceremony was held on April 26 at the site. The related patent applications were submitted (currently 11), and income from the patent fee would be expected for AIST after the start of operation. As a national research institution, we believe we were able to contribute to society through this technology. Also, as mentioned earlier, this technology was born from the advantage of Tsukuba at which various research institutes are concentrated, and it is a good example that indicates a direction for the technological development that should be done at the Academic City.

In receiving the order for the first plant, the press release was conducted at PWRI,[13] and there was great response from newspapers.[14] This practical application was recognized in the academic society, and the technology won several awards including the SCEJ (Society of Chemical Engineers, Japan) Award for Outstanding Technological Development in 2012, SCEJ Award for Technology for Fluidized Bed Working Group in 2011, Encouragement Award for Papers, Society of Environmental Instrumentation Control and Automation in 2008, and Encouragement Award, Japan Institute of Energy in 2008.

There are about 240 sewage sludge incinerators in Japan, and it is projected that the plants will be actively updated in the future, and the number of orders is expected to increase. There are several new technologies proposed for the sewage sludge treatment process instead of simple burning,[15][16] but the technology described in this paper was the first to be put to practical use. AIST is preparing a quick technological support plan for emergencies such as troubles during the operation of the commercial unit.

5 Future prospects

Until now, we have conducted research specifically for sewage sludge. As mentioned earlier, sewage sludge is fuel with high water content, and this technology is expected to be applied to similar high water content fuel such as livestock excrement or alcoholic beverage lees. Moreover, it can be applied to overseas use such as in China and Korea where waste is currently buried but where incineration is expected to become mainstream in the future.

Looking at each component technology, the turbocharged fluidized bed incineration system that was established in this research is not new, but is a combination of existing equipment. In this research, we showed that there is potential that a new thing may be born from new ideas, and we hope to continue our study.

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Completed the master’s course at the Department of Applied Chemistry, Faculty of Science and Engineering, Waseda University in March 1980. Joined the National Research Institute for Pollution and Resources, Agency of Industrial Science and Technology, Ministry of International Trade and Industry in April 1980. Was in charge of liquefaction of coal at the Sunshine Headquarter, Agency of Industrial Science and Technology in 1988. Senior Researcher, Research Institute of Energy Utilization, AIST in 2001; and Leader, Clean Gas Group, Energy Technology Research Institute, AIST from October 2005 to present. Since joining AIST, engaged mainly in the research of the combustion and gasification of coal, biomass and waste by fluidized bed. Obtained doctorate (Engineering) for the research of pressurized fluidized bed combustion in 2005. In this paper, was in charge of the laboratory-scale sewage sludge incineration experiment using the pressurized fluidized bed, and supported the development from the early stage of the project.

Takahiro MURAKAMI

Obtained the necessary credits but withdrew from the Department of Environment and Life Engineering, Graduate School of Engineering, Toyohashi University of Technology in March 2001. Became a faculty member of the Department of Ecology Engineering, Graduate School of Engineering, Toyohashi University of Technology in April 2001. Joined the Core Technology Research Department, Research Laboratory, Ishikawajima-Harima Heavy Industries Co., Ltd (current IHI Corporation) in October 2001; and appointed to the Thermal and Fluid Technology Department in April 2002. Joined as a Researcher, Clean Gas Group, Energy Technology Research Institute, AIST in April 2007; and Senior Researcher from October 2012 to present. Obtained doctorate (Engineering) in December 2001. Specialty is energy and environment field. In this paper, was in charge of the laboratory-scale sewage sludge incineration experiment using the pressurized fluidized bed, and the analyses of gas emission and operation results of the demonstration plant.

Akio KITAJIMA

Completed the doctor’s course at the Department of Mechanical Engineering, Graduate School of Science and Technology, Keio University in 2000. Doctor (Engineering). Joined the National Institute for Resources and Environment, Agency of Industrial Science and Technology, Ministry of International Trade and Industry in April 2000. Researcher, Research Institute of Energy Utilization, AIST in 2001; and Senior Researcher, Combustion Evaluation Group, Energy Technology Research Institute, AIST from October 2013 to present. Researcher of Public Invitation Proposal Project, New Energy and Industrial Technology Development Organization (NEDO) between 1998~2000. Industrial Science

and Technology Planner, Startup and Technology Affairs Division, Small and Medium Enterprise Agency, Ministry of Economy, Trade and Industry in 2011~2012. Engages in research for control of the combustion phenomenon in practical incinerators from the aspects of experimental and numerical analyses. In this paper, was in charge of the analysis of N_2O inhibition mechanism using detailed numerical calculation for chemical reaction in the gas combustion region inside the incinerator.

Discussions with Reviewers

1 Overall (Yasuo Hasegawa, AIST; Akira Kageyama, Research and Innovation Promotion Headquarters, AIST)

This is a comprehensive paper that explains the joint effort with other institutes and companies, for the design, development, evaluation, and demonstration testing of a new system to achieve energy savings and low N_2O emissions, looking at the sewage sludge incineration system that will soon need updating. We determined that the content is appropriate as a paper for *Synthesiology*.

I think it will be informative to the readers as the paper shows the way of conducting R&D where the technology generates value in society and is put to practical use.

Question and Comment 1 (Yasuo Hasegawa)

I think this is a good example where the private companies along with AIST and PWRI, which are research institutes located in Tsukuba but have different disciplines and are under different agencies/ministries, complemented each other’s potentials and succeeded in the practical application of a technology.

I think targeting the City of Tokyo, a representative of local governments, is effective in promoting the introduction of the new system. Can you clarify the difficulty in introducing the new system to the local governments, and what the role of PWRI was? I think the demonstration research played an important role in the practical application, is that so?

Answer 1 (Yoshizo Suzuki and Takahiro Murakami)

PWRI that belonged to MLIT which controls the sewage works played a central role in starting the project, as they first explained the excellence of this technology to the local governments in Japan. Although the local governments showed quite an interest, they said that they would make decisions after seeing the stable operation of the first unit. With such a background, Bureau of Sewage, Tokyo Metropolitan Government showed great interest in this technology, and started joint research with the two private companies. This technology was taken up in the Earth Plan 2010 that proposed reduction of greenhouse gas, and that was a major step up. Tokyo Metropolitan Government plays a central role in the sewage treatment business, and the other local governments were closely watching what Tokyo would do. For the introduction of the actual unit, the performance evaluation by long-time continuous operation of the demonstration system was important. We were able to demonstrate that there was no problem in the performance or operation through the demonstration research, and that ultimately led to their decision.

Question and Comment 2 (Akira Kageyama)

This paper takes the core issues that the sewage sludge incineration facilities that were installed in the 1980s to 1990s are facing the need for updating, and that the current incinerator consumes a large amount of energy and produce relatively high concentration of nitrous oxide. Therefore, the development of a new sewage sludge incineration system with low energy consumption and low N_2O concentration was started.

AIST with the accumulation of elemental technologies for pressurized combustion, PWRI with the knowledge of evaluation/design technologies of sludge incinerator, and the related companies gathered. The point to note is that the parties worked to develop a new sludge incineration system while complementing each other, and obtained innovative results.

Answer 2 (Takahiro Murakami)

At the beginning of development of this system, we created a concept that placed importance on a system that can save energy. Therefore, we came up with the idea that we can eliminate the two fans with high power consumption by burning the sludge under pressurized conditions and by making combustion air by processing the high-temperature and high-pressure flue gas with a turbocharger. The N_2O reduction was positioned as secondary, or something to be looked at after the results of the combustion tests, but we were able to obtain good results where the emissions could be halved compared to the conventional high-temperature incineration.

Question and Comment 3 (Akira Kageyama)

In the development of the system using the turbocharger, was there any technological issues in the turbocharger itself? In this research, it is a victory of the creative use of information that enabled you to obtain the participation of companies that were manufacturers of both gas turbines and turbochargers. In conducting a true synthesiological research, I think the efforts of bringing out the creative use of information and the integration effect of multiple companies and institutions are important, not just the technological development in a narrow sense.

Answer 3 (Takahiro Murakami)

In introducing the turbocharger system, the technological hurdle was the durability of the turbocharger. The joint research for long-term durability tests was started with two private companies from FY 2008. Long-time operation was conducted, and we succeeded in continuous operation of over a total of 2,000 hours. We were able to clarify that there were no problems in the reliability and durability of the turbocharger, and this led to practical application.

The point of success was that among the gas turbine manufacturers that had strong linkage with AIST through various R&Ds, we were able to link up with those who sufficiently understood the basic concept of this R&D. We were able to quickly build collaborative relationship with the companies that had experience in manufacturing not only gas turbines but also turbochargers, in addition to the sewage sludge incineration plant manufacturers.

A novel material design system method for on-demand material development

— A method born from a development field —

Teiichi INADA[1]* and Tokuro MATSUO[2]

[Translation from *Synthesiology*, Vol.7, No.1, p.36-42 (2014)]

Advanced materials for the semiconductor industry are being developed every month. To reduce the development period, we constructed a novel material design system method based on linear programming, combinatorial optimization, and graph theory. This method (called weak conditioned combinatorial linear programming) enabled us to find formulation composition candidates that satisfy a number of properties at the same time. By defining the solution area as a function of the combination index, the optimum formulations were acquired. This optimization could be done by newly developed user-friendly software. This system is applicable to optimization of materials with complex properties and time-series properties such as creep. The method enabled us to develop materials satisfying target values efficiently.

Keywords : Linear programming, combinatorial optimization, on demand development, material design

1 Introduction

The most important points in material development are long-term steady research and eyes that do not miss any accidental finds (serendipity). While we do not wish to raise objection to this mainstream thinking, it is a fact that new materials must be developed almost every month at the development sites of the state-of-the-art semiconductor materials. There is no time to wait around for the arrival of some novel materials or serendipitous finds, and in reality, there is much struggle and battle to fulfill the target values within a set deadline. With this background, what style of development can the researchers use?

Since such material development is done by combining the materials at hand with the skill of a craftsman, it may fall in the realm of *bricolage* (or tinkering) as described by Lévi-Strauss.[1][2]

However, the authors have engaged in ultra short-term developments for over 10 years, and we started to feel that we wished to develop materials that satisfy the target values through rational design, rather than by mere *bricolage*. This thinking is close to engineering (the way of manufacturing by preparing the necessary tools and making it according to a design plan) that is the counter-concept of *bricolage*. We wished to construct a development method that has both the merits of the creative aspect of *bricolage* and the rational aspect of engineering design.

The style of material development that was generally done and the style devised by the authors are compared in Fig. 1. The normal material research is carried out to find an innovative material with outstanding property. The research style proposed in this paper is a material design in which the already existing materials are combined and outstanding performance is not sought. For example, in the semiconductor package manufacturing process, while there are diverse target properties such as fluidity and viscosity, it is important for the individual properties to fall in a certain range, as outstanding excellent properties are not sought.

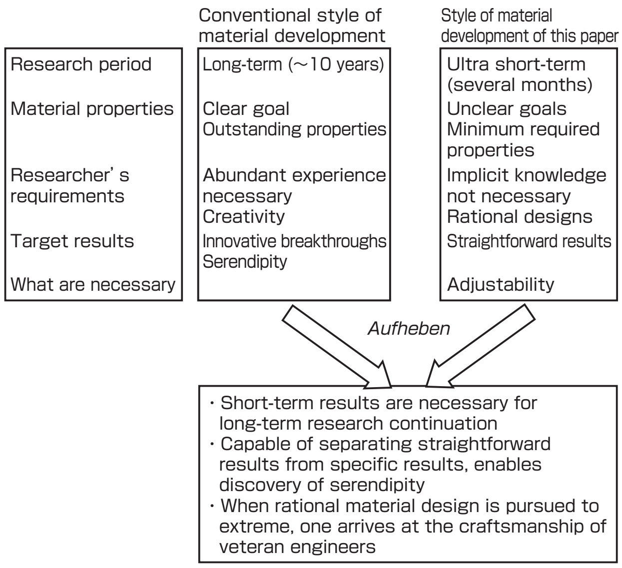

Fig. 1 Comparison of the conventional style of material development and the style described in this paper

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The greatest characteristic of this style of material development is to accomplish the project in an extremely short time, and therefore, it will be called on-demand material development in this paper. The concept of the on-demand material development method that the authors established and the actual applications will be explained.

2 Background of research

The state-of-the-art electronic devices such as smart phones, tablets, ultra thin laptop PCs, and servers that support the cloud are evolving continuously, and the semiconductor elements and semiconductor packages that are the heart of such devices are also evolving.[3]

Various materials are used in the semiconductor package as shown in Fig. 2. Since the semiconductor package changes in structure in response to the preference and trend of the consumers, mainly young people (for example, downsizing and increased memory of smart phones), the trend of technological evolution is characteristically difficult to predict. For example, the requirements of the die-bonding film, or the adhesive material for semiconductors used to attach the semiconductor chip to its supporting substrate, change every month.[4][5]

As shown in Fig. 3, the assembly process of the semiconductor package is diverse, and various properties are required for each process. The commonly required properties include:

(1) It must be fluid at temperature 80 °C or lower, and be able to bond to the wafer.
(2) Since it is used to bond the chip and the substrate, it must be able to absorb the difference of coefficient of thermal expansion and relieve stress.
(3) It must not flow or detach during the soldering process (about 260 °C) to attach the semiconductor package to the wiring substrate.

Even a semiconductor manufacturer may not know the required properties of materials at the beginning of the development for a new structure. Rather, several materials are evaluated to clarify a target value.

The development period of a material is as short as a few months, but it is extremely difficult to synthesize any new material such as polymers in a few months in a specific form such as films.

On the other hand, it is well known that the state-of-the-art semiconductor industry cannot survive without extremely high facility investments that must be recovered in a short period and then invested for the next generation. In the state-of-the-art semiconductor industry, there is an increased demand for rational design and optimization methods for quick development of materials to strengthen the competitiveness and to reduce the investment risk.

The mathematical optimization methods that have been considered so far include linear programming, nonlinear programming, and combinatorial optimization.[6]-[9] Although these methods are expected to be applied to material design, there are several issues in utilizing them:

(1) It is necessary to select the optimal combination among several chemical materials, but in practice, the number of materials that can be actually used is limited due to the limitations of the number of tanks for storing and mixing the materials, the number of waste fluid pipes, or the risk of supply cutoff due to natural disasters or plant accidents.
(2) There are cases where the candidate set of solutions is not a convex set because the constrained function becomes complex due to the limitation of patents held by other companies.
(3) In designing the adhesive agent, the optimization of the complex physical properties such as the complex elastic modulus is essential. However, the conventional mathematical design targets the real vector space, and the handling of complex numbers has been difficult.
(4) It is not necessary to find the optimal value for one point

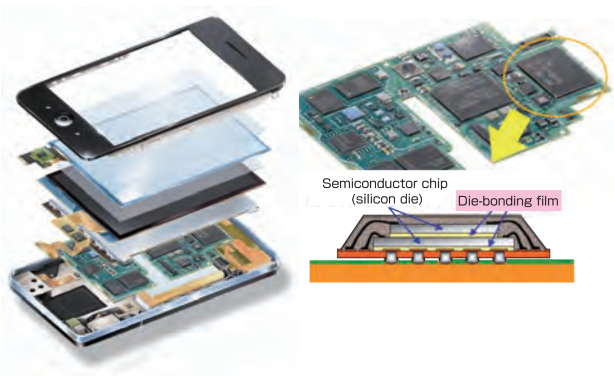


Fig. 2 Examples of an electronic device and a semiconductor package

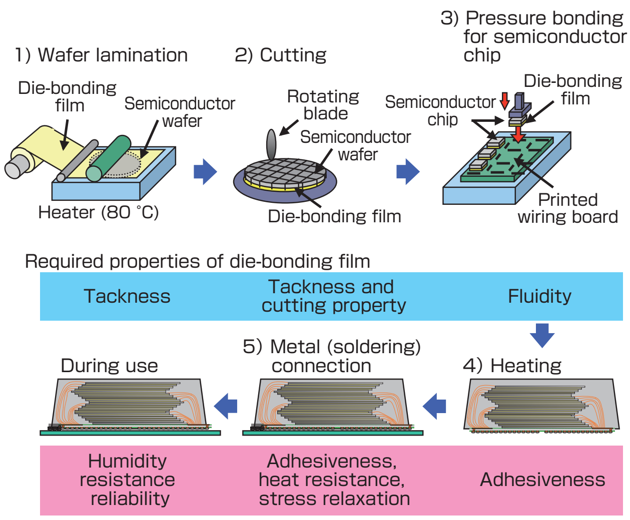


Fig. 3 Assembly process of the semiconductor package

only, but rather, the breadth of solution range that satisfies the target value to prepare for the variations and design change is important.

Therefore, it is necessary to build a mathematical design method to solve these issues and to utilize them in the actual development.

The authors have investigated the design system methods that were appropriate for material design and were readily usable on site. After carefully surveying the correlation between the composition of the materials and their properties, we thought the shortcut was to build a method based on linear programming, because in many cases, a quasi-linear relationship existed between the composition and the material property. However, when this was applied to material development, even if the target function was expressed as the only line, the solution did not necessarily exist. Also, the robustness against the variation of the film property was necessary. This meant that it was important to consider the breadth and form of range that satisfied the target value by weakening the condition of the solution, rather than strengthening the limiting condition of the solution (or consider only the optimal value). Therefore, we developed weak conditioned combinatorial linear programming and software, by applying linear programming, combining multiple materials, and calculating the combination to satisfy the multiple target values.[10]-[12]

3 Basics of the weak conditioned combinatorial linear programming

Die-bonding film is a composite material made by combining various materials including epoxy resin, fillers such as inorganic particles, as well as acryl rubber, and catalysts. By changing the composition ratio, a wide range of changes is possible if focus is placed only on elastic modulus, as shown in Fig. 4a. We are often asked by the semiconductor manufacturers, “The goal is mostly satisfied, so can you just lower the elastic modulus?” However, this is the most difficult request, because when the amount of ingredients is changed, all the property values change, not just the elasticity, as shown in Fig. 4b. By lowering the elasticity, all the properties that had previously satisfied the target values may shift from the acceptable target range.

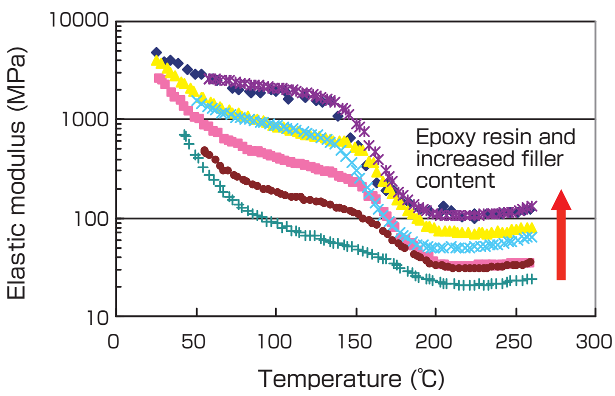
To solve this issue, the authors constructed a design method based on linear programming as shown in the equation below. The value that is linear mapped by the composition/property matrix from the composition is the property. For example, a_{mn} shows the relationship between the composition content and the adhesiveness of an epoxy resin. The matrix consisting of a_{mn} is the property/composition matrix, one for $(c_1 \ldots c_n)$ is the content vector, $(p_1 \ldots p_n)$ is the property vector, $(k_1 \ldots k_n)$ is the combination vector, and $\otimes$ is the Hadamard product.

$$\begin{pmatrix} p_1 \\ p_2 \\ \vdots \\ \vdots \\ p_m \end{pmatrix} = \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ a_{12} & & a_{2n} \\ \vdots & \ddots & \vdots \\ \vdots & & \vdots \\ a_{m1} & \cdots & a_{mn} \end{pmatrix} \left(\begin{pmatrix} k_1 \\ k_2 \\ \vdots \\ \vdots \\ k_n \end{pmatrix} \otimes \begin{pmatrix} c_1 \\ c_2 \\ \vdots \\ \vdots \\ c_n \end{pmatrix} \right)$$

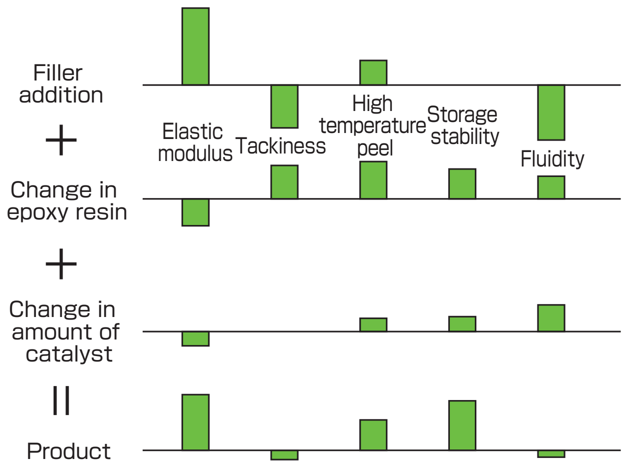
The Hadamard product of the matrix is defined as follows.

$$A \otimes B = \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ \vdots & & \vdots \\ a_{m1} & \cdots & a_{mn} \end{pmatrix} \otimes \begin{pmatrix} b_{11} & \cdots & b_{1n} \\ \vdots & \ddots & \vdots \\ \vdots & & \vdots \\ b_{m1} & \cdots & b_{mn} \end{pmatrix}$$

$$= \begin{pmatrix} a_{11} \cdot b_{11} & \cdots & a_{1n} \cdot b_{1n} \\ \vdots & \ddots & \vdots \\ \vdots & & \vdots \\ a_{m1} \cdot b_{m1} & \cdots & a_{mn} \cdot b_{mn} \end{pmatrix}$$



a) Elastic modulus at various composition

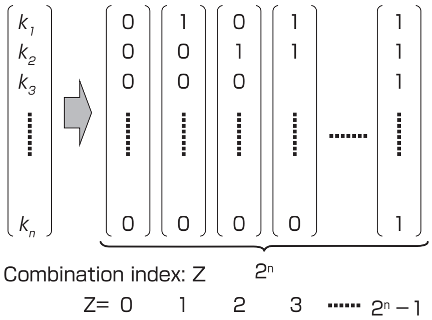


b) Conceptual diagram of contribution of various elements to the properties

Fig. 4 Correlations among various properties

If the quantities of the materials are changed as shown in Fig. 4b, all properties fluctuate. They can be matched to the target value by offsetting and adding the fluctuations.

The material combination k_n parameter is set as 1 when material n is used, and 0 when it is not used. The material combination vector will be in one-to-one correspondence with the combination index (will be described Z). For example, when considering the composition by selecting 0~n types of material from n number of materials, there will be 2^n combinations. If the expression of combination is expressed as 010101…, the expression becomes complicated when there are many types of materials. Therefore, the number sequence is set as binary, and one-to-one correspondence is given to decimal Z. The corresponding composition parameter c_n is changed to see whether the property values lie in the target range, and this will enable the check of the composition range that satisfies the target value.



While the conventional linear programming sought the maximum or minimum values of the evaluation function, here, all the solutions that satisfy the target values are considered as the solution set, and therefore, it is called "weak condition." Weakening the condition of the solution contributes to shortening the computation time.

Mathematically, the weak conditioned combinatorial linear programming creates the space P of the realizable properties, as the space C created by the composition parameter c_n that possesses limitations is linear mapped to the property space by the matrix consisting of the composition/property parameter, as shown in Fig. 5. The product set $S(=P \cap T)$ of space P and space T of target value comprise the space that satisfies the target value. Also, space C_S created by compositional parameter c_n that satisfies S is defined, and this is the composition that satisfies the target property. Wider the range of S or C_S, more capable it will be to deal with the changes in the required property in the future, and such breadth is preferable. In practice, the cost and tolerance are also considered within this composition to determine the final composition.

4 Weak conditioned combinatorial linear programming system

The aforementioned mathematical process is too complicated for a material engineer to conduct as a daily routine, and the volume of computation becomes extremely large when n increases because it is necessary to calculate the solution space for each two combinations. It is nearly impossible to calculate the solution space by Excel or by hand. Therefore, we developed the solution search software M-Designer that can be used practically at the site of material development.[10]-[12] The M-Designer is a weak conditioned combinatorial linear programming software with interface shown in Fig. 6. Using the M-Designer, it is possible to compute whether there is a composition (solution set) that satisfies the target value for each combinatorial index. Specifically, the maximum and minimum values of the property/composition matrix, range of target property, number of compositions, and content that were obtained experimentally or theoretically are entered. The contents of the material are automatically changed at appropriate intervals, decision is made whether it satisfies the target, and the compositions that satisfy the target value are provided.

The composition candidates must simply satisfy the target value, and it is not necessary to seek the optimal value. If the range is wide, the possibilities of various usages increase. Since it is a simple system without the implementation of the algorithm to calculate the optimal value, we found that it could be used widely for nonlinear programming including complex physical property values as explained later, as well as for compositional design including the time-series data.

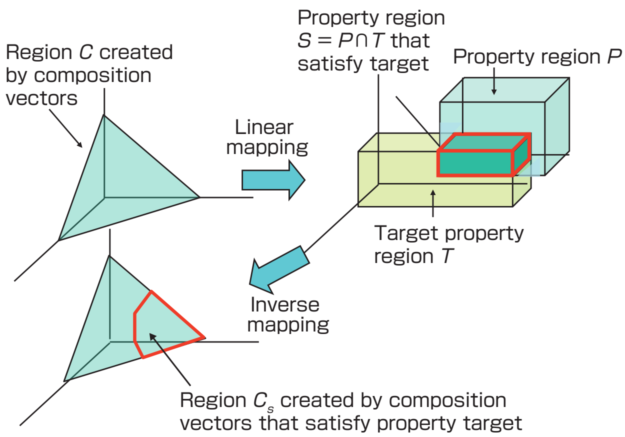


Fig. 5 Outline of the weak conditioned linear programming

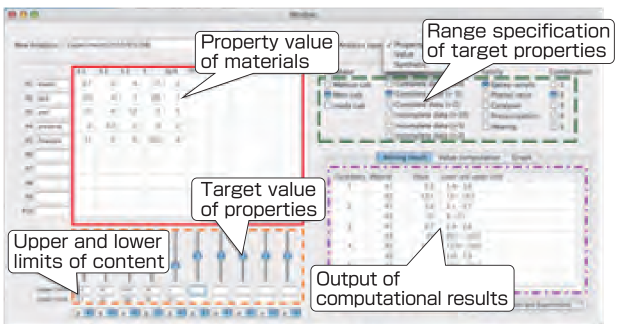


Fig. 6 System interface

Figure 7 shows an example of a simulation. The comparison of the actual results had been reported,[13] but the property can be roughly predicted, although it may lack precision. To increase the precision, the relational equation between the composition content and property should be preferably expressed by nonlinear simultaneous equation. However, in the case where several combinations of materials must be investigated, extremely large amount of experimental data becomes necessary to calculate the function of n variables for each combination. In practice, according to the procedure shown in Fig. 8, the candidate materials are narrowed down by linear approximation, and the nonlinear approximation is conducted only when precision is required.

This system was used for investigating the adhesive agent composition where several materials were combined. As shown in Fig. 9, it was found that wide ranges of functional extensions and applications were possible such as extension to nonlinear programming,[14] calculation of material supply risk,[13] and database building.[15]

With adhesive tapes and adhesive agents, if there is gap θ in phase between the stimulus and response of the material, for the strain expressed by the sinusoidal function $x = Ae^{-i\omega t}$, the property value (elastic modulus) defined between the two becomes $y/x = (B/A) \times e^{i\theta}$, when the stress is $y = Be^{-i(\omega t-\theta)}$. Then, the property value becomes a complex number and its control is extremely important. In this case, the relationship between the composition and property becomes a complex nonlinear function. Such complex property value can also be processed by the aforementioned system by handling the complex number as the vector of the Gaussian plane.[10][16]

One of the points that became apparent in the Great East Japan Earthquake in 2011 was the risk of material supply cutoff. In the highly efficient and aggregated semiconductor and automobile industries, the cutoff of a single material or part can have major effects. Using this system, it is possible not only to calculate the candidate compositions, but also calculate the supply risks, considering whether the multiple candidates use a common material. Although there is the issue that the material supply risk cannot be accurately grasped, if it is assumed that there is a certain risk for each material such as 0.01 %, the index that expresses the supply robustness of the composite product can be calculated. It is then possible to consider the risk countermeasures in the design phase.

Such risk calculation was not possible in the conventional linear programming, and it became only possible with the weak conditioned combinatorial linear programming and the construction of its computation system. This result demonstrated the effectiveness of this method.

The database that can organize and store the data for property/composition matrix is useful in utilizing the past failure data in the new development. If only the past experimental data were stored, it would not be very useful

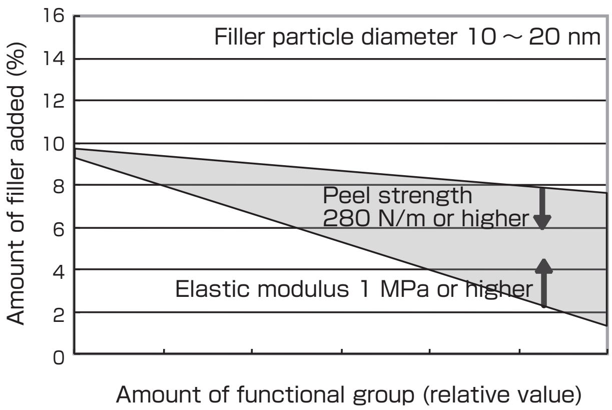


Fig. 7 Example of simulation

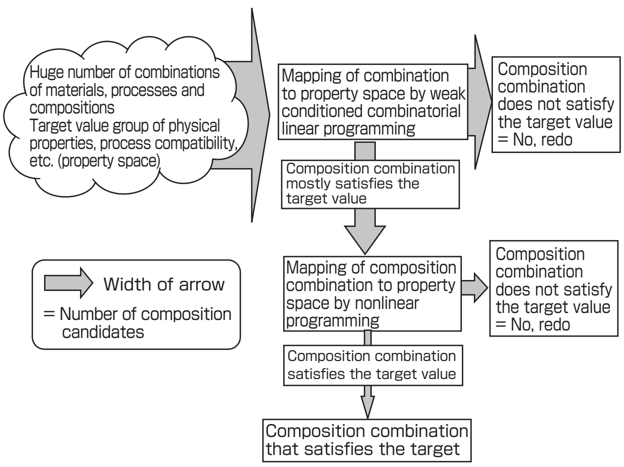


Fig. 8 Distinction of linear and nonlinear approximations

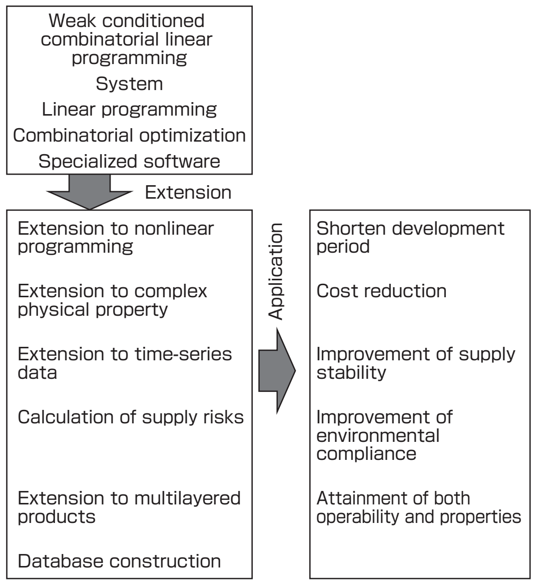


Fig. 9 Extension of weak conditioned linear programming and its application range

since the correlation between the property and composition is unknown, but the property/composition matrix data can be stored, entered into the M-Designer, and calculation can be conducted for reuse. For example, although something was a failure in the past, with major changes in structure and target values, the composition could satisfy the target value with some corrections. Such database can prevent repeating the same mistakes because one did not know the past results.

5 Application of the weak conditioned combinatorial linear programming

Since this method is particularly useful for short-term development, it is not only useful for the development of semiconductor materials, but can also be applied to various fields such as foods and environment in the future.

In this paper, focus was placed on the optimization of composition, but the design method is not limited to composition. Instead of the composition content, various manufacturing conditions other than substances, such as temperature, humidity, or speed, can be considered.

The optimization method of this paper can be applied to various fields in the future. For example, there is an endless list of fields where combinatorial optimization is important, such as cooking and blending perfume, alcoholic beverages, or spices, as well as drugs such as herbal preparation and synthesized drugs. Particularly in the food industry, the design of taste by the combination of flavors or ingredients is an extremely important theme. In practice, the cook determines the taste according to his/her expert perception and experience, such as changing the flavoring to utilize the seasonal ingredients, and mathematical design has almost never been done. With the development of the taste sensor and the quantitative evaluation of taste, we predict that the mathematical design will greatly advance in this field in the future.

6 Conclusion

In this paper, we described the material design method constructed to increase the design efficiency of the semiconductor-implemented materials. By utilizing this method, it became possible to conduct on-demand product development with adjustability, or the ability to match the target value by flexibly changing the material properties.

Because breakthrough is not the objective, our method may be criticized as merely being a partial optimization that is a diversion from larger work. Yet, breakthrough can be sought by someone else. If there is no compromise, short-term development will not be possible.

The site of short-term material development was considered alien to serendipity. However, when we conduct experiments after predicting the properties from the material combination using this method and clarifying the baseline, we unexpectedly became capable of detecting the deviations from the prediction. While most cases are errors in prediction, in rare instances, some were synergetic effects of unforeseen, new structures. We are now able to detect the hints of serendipity.

We believe that with more feedback, the new material design method and the system proposed in this paper will become an essential tool for the timely development of necessary materials. The ultimate goal is to create an on-demand material development system that is fused with craftsmanship.

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Discussions with Reviewers

1 Overall

Comment (Hideto Taya, Public Relation Department, AIST)

This paper discusses the effort for building a tool to support material design for developing materials with target performance within a limited time, by combining the existing materials at the manufacturing sites of state-of-the-art products. It is very interesting, and the content matches the objectives of *Synthesiology*.

2 Style of material development

Question (Hideto Taya)

At the manufacturing sites of the state-of-the-art semiconductor materials, in the constraint of an extremely short time limit, the on-demand material development method has been devised "to develop materials that achieve the target value in a practical and certain manner rather than by simple *bricolage*."

Is the on-demand material development method an add-things-together development that is merely practical but not creative, or is it a "method that combines the merits of *bricolage* and engineering (*aufheben* in Fig. 1)"? How will the relationship between the two develop in the future?

Answer (Teiichi Inada)

The style of material development in this paper is, first, an add-things-together development that is merely practical but not really creative. However, when this is taken to the extreme, unexpectedly, we were able to discern unforeseen synergetic effects. This is explained by the diagram for *aufheben* of practicality and creativity, as shown in Fig. 1.

For example, when properties were predicted from the material combinations using our method and experiments were done after clarifying the baseline, we realized we could detect deviations from the predictions. That meant, by predicting the experimental results without synergetic effect, we became capable of detecting small synergies. There were examples in which after discovering small synergetic effects, we succeeded in increasing the synergies and created a differentiating technology. Although the material development style in this paper seem to be cut-and-dry development conducted under time constraints, it can also play the role of a microscope to discover unforeseen effects.

3 Structure of the paper

Question (Hideto Taya)

For chapter 3 "Basics of the weak conditioned combinatorial linear programming," how about setting up new subchapters, and add more detailed explanations for simulation results, different uses of linear and nonlinear, and expandability?

Answer (Teiichi Inada)

I revised the chapters and increased the explanations. The content is included in the paper, and here, I shall explain the main points only.

1) Expandability to complex numbers

With adhesive tapes and adhesive agents, the property values often become complex numbers. It was clarified that such complex physical properties could be processed using the aforementioned system by handling the complex numbers as vectors of the Gaussian plane.

2) Calculation of the supply risk

It is important that the materials can be supplied stably, and not just satisfy the target properties. In cases where there were risks of material supply cutoff, we considered whether the composition candidates used common materials, and calculated the supply risk. As a result, we were able to estimate the supply risk along with the material that satisfied the targets. Such risk calculations could not be done with conventional linear programming, and it became possible for the first time with the construction of the weak conditioned combinatorial linear programming and the computation system.

3) Database construction

By storing the past experimental results and data in the form of property/composition matrix, such data can be utilized effectively by entering them in the M-Designer and then reusing them for calculation. For example, although they were failures in the past, there were cases where because there were major changes in the structure and target values, the target value could be satisfied with only slight revisions. The development efficiency can be improved by using the past results.

4 What are the problems of this development method?

Question (Hideto Taya)

What were the evaluations and comments when applying the on-demand material development method at the actual production sites? Were there any points that you particularly considered in the implementation?

Answer (Teiichi Inada)

When we explained this method at the company, a senior engineer remarked, “If you write out all that goes on in the head of a veteran engineer, you will have something like this.” Certainly, a veteran engineer, who is thoroughly versed in the good and bad of a material, designs things so the bad part stays in the background and the good part floats to the foreground. When we pursued material development in a rational manner, we ended up at craftsmanship. This is not surprising, and it shows how craftsmanship is systematic and excellent. In the future, I think we can construct a system that goes one step further, by sublating and integrating the rationalization and craftsmanship.

5 Shortening of the development time by using this method

Question (Hideto Taya)

You say, “This method is particularly effective for short-term development.” Based on your experience, how much was the development time shortened?

Answer (Teiichi Inada)

Since target values and conditions differ each time in the actual development, it is difficult to accurately compare the cases where this method was used or not used. However, based on experience, there are the following merits:

1) There are myriad composition candidates, but by using this method, first, the compositions that are totally off-target could be eliminated, and the choices can be narrowed down to highly potential candidates only. Since this method is a linear approximation, there is certainly a deviation from the experimental data, but it is sufficient for narrowing down the candidate materials, and the development time can be shortened greatly.

2) The product improvements are modified based on the past results. For example, when developing a new product by revising a product made by our predecessors 10 years ago, there are cases where we have good performance although we do not know why some materials were included. In such cases, we do not know why we get a certain function or why this certain chemical is needed, and time must be taken even for slight modifications. In such cases, the analysis system and database are extremely useful to shorten the development time.

Towards large-capacity, energy-efficient, and sustainable communication networks

— Network topology research for dynamic optical paths —

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Internet traffic continues to increase due to the growth of video-related communication services. Such video-related services are expected to support future advanced communication services such as tele-presence based on real-time high resolution bidirectional video communication, tele-diagnosis, and remote education. However, the risk of an energy crunch in communication networks is increasing with the increase in traffic since energy consumption of current IP router based networks depends on traffic volume. In this paper, we present a network architecture, called "dynamic optical path network (DOPN)," whose energy scaling is much less dependent on traffic volume than that of the current networks. This paper demonstrates the validity of DOPN to realize greater bandwidth, national-scale, and energy-efficient network, by defining detailed network topologies and node architectures of DOPN.

Keywords : Large-capacity and low-energy-consumption communication network, optical path network, optical switch, super high vision video communication

1 Introduction

Communication infrastructure such as the telephone network or the Internet has become important lifeline equivalent to electricity, water, and gas. With the development of broadband communication infrastructure and advancements in video applications, the traffic volume accommodated in the network is increasing globally.[1] Taking a look at the case of Japan, the total traffic volume increases every year. As the subscribers to the broadband service increase, the subscribers to the digital subscriber line (DSL) have decreased while those for "fiber to the home" (FTTH) service are increasing. The traffic per subscriber also increases yearly due to the progress of the shift to higher broadband services. With such a trend, the Japanese network experiences a yearly growth of about 20~40 % in communication traffic.[2][3] The traffic increase is expected to continue in future due to the expansion of high capacity contents such as high definition videos. If the traffic increase of 20~40 % per year continues for the next 20~30 years, the future network must accommodate 1000 times larger traffic volume than the current demand.

As the traffic increases, the importance of the communication network increases, and once a disconnection occurs, it will have a major impact. Currently, in cases of failure such as disconnection, the continuity of the network service is maintained by having multiple routes between the communication points (such as west-bound and or east-bound routes), and switching to one route if the other is disrupted. However, in a major disaster such as the 2011 Off the Pacific Coast of Tohoku Earthquake (Great East Japan Earthquake), failure recovery doesn't work well since failures may occur in a wide region at many locations, and both routes can be disrupted. In that disaster, agile and wide-scale reconfiguration of the network was necessary. Moreover, to continue the network service without being affected by the instability of power supply due to the disaster, the importance of low power-consuming network operation in ordinary times has been recognized.

Communication networks consist of links that transmit the signals and communication nodes that process the signals. Signal transmission is mainly done in optical domain using optical fiber links. It is possible to transmit multiple optical signals through single optical fiber, as in wavelength division multiplexing (WDM), and the transmission experiment of capacity more than 100 Tbps in a fiber has been reported.[4] On the other hand, the signal processing in a communication node is mainly done in the electrical domain using optical-to-electrical converters and electric switches or IP routers. The power consumption of the converter, the electric switch, and the IP router increases in proportion to the signal transmission rate or the signal throughput. To realize a large-capacity future network, the increasing power consumption may become a bottleneck.[5] Reducing the power consumption in communication networks is an important issue not only to achieve disaster resistant networks but also to realize future

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large capacity networks.

Currently, to achieve a large-capacity communication network with low power consumption, there are studies on conducting traffic processing at nodes at lower layers that have low power consumption (IP traffic offloading).[6][7] One of the traffic offloading technologies includes the optical cut-through technology in which the destination of the optical signals are switched by the optical switches without using optical to electrical conversion at the node. This is being implemented along with the reconfigurable optical add drop multiplexer (ROADM) technology. However, these traffic offloading technologies are based on the current IP router network, and the signal processing at the network edge cannot be avoided. Therefore, the effect of reducing the power consumption is limited to about 20~30 %.[8][9] In the long-term prospect of triple digit increase in traffic volume, fundamental considerations are required.

To achieve a sustainable large-capacity communication network for the future, we are working on a network architecture called "dynamic optical path network (DOPN)."[10][11] The main cause of the future traffic increase will be video-related applications with high or ultra-high definition quality images. To support such large capacity applications, DOPN provides end-to-end path connectivity with Gbps or more capacity according to their requests. By focusing on such large-granular communication requests, DOPN can be constructed only from low power consuming optical switches and low-layer electric switches, to achieve power consumption property with low dependency on traffic volume. On the other hand, current communication services such as web and mail generate small-capacity and frequent communication requests. For such services, the current IP router network is suitable since it can handle packet switching and the capacity of the packets is several tens to several hundred kbit. Consequently, DOPN does not replace the current IP router network, but coexists in a complementary relationship. For the operation and management of DOPN, a new integrated resource management technology is necessary where not only the network resources (bandwidth) but also the storage resources (content) are comprehensively controlled.[12] The resource management system automatically selects the network to use according to the application. For example, the conventional IP router network can be used for the conventional service such as web or mail, while the DOPN can be used for a large-capacity service such as high definition video on demand (VOD) or teleconferencing(Fig. 1). The resource management system allows the user to use the IP network and DOPN seamlessly, without thinking about their differences. We are investigating the network resource management system in collaboration with the Information Technology Research Institute in AIST. In addition, the technologies for developing DOPN can also contribute to agile and large-scale network reconfiguration in an emergency such as disasters, as DOPN involves the dynamic switching of the physical layer defined in OSI 7 layer.[Term 1]

If large-capacity paths can be provided smoothly among users through the DOPN, it will become a platform for achieving numerous large-capacity communication services. One of the target applications of DOPN is video related service with ultra-high definition (UHD) images that is currently under development. UHD has 16 times higher definition than high-definition television (HDTV) requiring bandwidth of 72 Gbps or more for uncompressed data transmission. Compared to 40.5 Mbps, which is the peak connection speed of the current Japanese Internet,[13] there is a gap of over three digits. The necessary bandwidth for uncompressed transmission for UHD can be stably provided using the DOPN. Of course, the video compression technology is also being developed, but to achieve the highly realistic sensation that is almost equivalent to experiencing the real event, there is a limit in using the video compression technology. If a high-presence

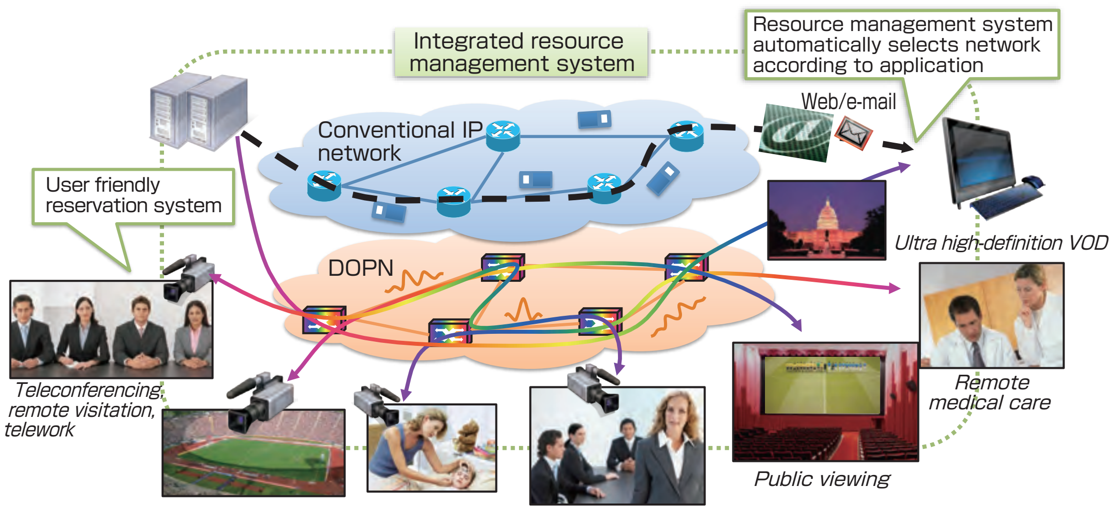


Fig. 1 Image of the future information communication network and service composed of the IP network and DOPN

communication can be achieved by using UHD technologies, the remote teleconferencing for important scenes such as meetings that involve decision-making or interviews for job qualification can be done. If the applications using UHD images such as teleconferencing, remote medical care, or remote education diffuse throughout society, collaborations that are not limited to geographical distance will become possible. It is expected to lead to major social values such as eliminating the regional gaps in education or medical care.

The goal of this paper is to present the validity of DOPN to realize a future communication network infrastructure. There are three requirements for the communication infrastructure that supports the future video services: 1) resolution of bottleneck of power consumption for increased communication demands, 2) scalability to accommodate tens of millions of users, and 3) ability to handle various large-capacity services from remote presence (~100 Gbps) to high definition VOD (several Gbps). This paper investigates the network topology and node structure of DOPN in detail, and shows that the DOPN is capable of accommodating over 50 million consumer users using the 1~2.5 Gbps path and over 600 thousand enterprise (business) users using the 40~100 Gbps path, as well as possessing the potential to improve the power consumption efficiency by two to three digits compared to the current network.

2 Dynamic optical path network (DOPN): its goals, issues, and elemental technologies

The dynamic optical path network (DOPN) tries to achieve a sustainable large-capacity and low power-consuming network for the future, by using the low-power-consumption optical and electric switches as its main components. Figure 2 shows the goals that are expected to be achieved by DOPN explained in this paper, and the correlations of the elemental technologies used to achieve the goals. The details are explained below.

Elemental Technology 1: Optical switch

One of the most important features of the optical switch is that the power consumption scales with the number of switch ports regardless of the total throughput. By using such optical switches as main components, the power consumption of DOPN will be less dependent on the traffic volume than the current router based networks. However, there is a technological problem that the optical switch is incapable of having large number of input/output ports. The current optical switch products have about only 8~200 ports while the switching equipment used in telephone networks have tens of thousands of ports. The number of subscribers would be limited by the number of switch ports in path switching-based networks. Moreover, there are two types of optical switches: optical matrix switch that switches optical signals in a fiber granularity; and wavelength selective switch (WSS)[Term 2] that switches optical signals in a wavelength granularity. One optical fiber can accommodate several Tbps and one wavelength channel can accommodate several tens to several hundreds of Gbps. There is an issue that the optical switch alone is inefficient for small-granular (of about several Gbps) communication demands.

Elemental Technology 2: Sub-wavelength switch

The sub-wavelength path is introduced to solve the issues in using the optical switches as the main components discussed above. The sub-wavelength path is assumed to address

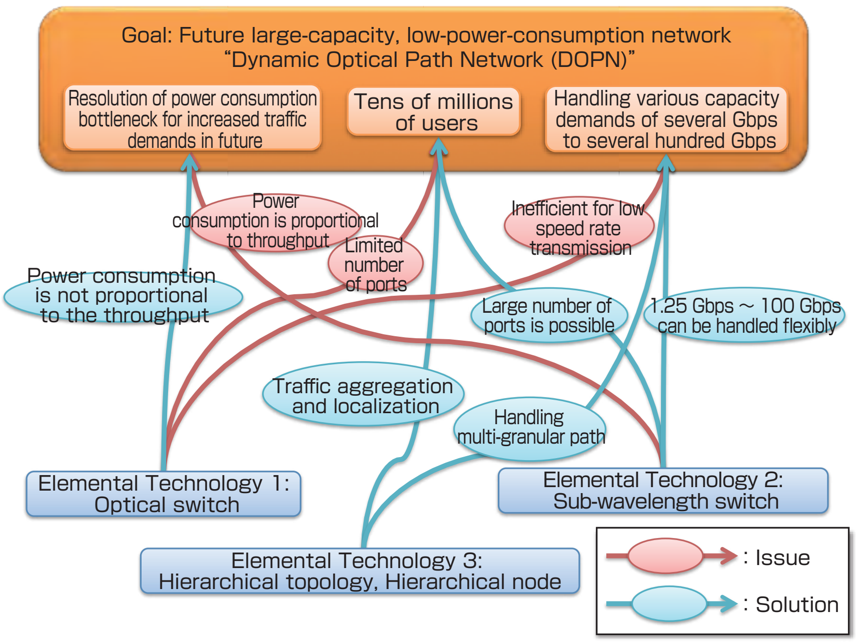


Fig. 2 Correlation among the goals, elemental technologies, and issues

electrical time-division multiple access and provides finer granularity than wavelength or optical fiber paths. In this paper, the use of the optical data unit (ODU) is expected as the sub-wavelength path.[14] Although the power consumption of the ODU switches scales with the throughput, the power consumption is one-sixth compared to the packet router since the granularity of data handled is large at 1.25 Gbps or more.[15] The ODU path can handle 1.25 Gbps ~ 100 Gbps with 1.25 Gbps tributary slot granularity (ODUflex), and the ODU switch with Tbps class throughput and several thousand ports is being developed. Figure 3 shows the path granularity handled by the DOPN in this paper.

Elemental Technology 3: Hierarchical topology, hierarchical node

The hierarchical topology/node is introduced to effectively use the elemental technologies 1 and 2. The hierarchical node architecture is to efficiently handle the multi-granular paths. The hierarchical node consists of multiple switches for different granularities such as the optical switches and sub-wavelength switches and they are hierarchically connected. By processing the demands in a large-granular path as much as possible, the size of the hardware needed in the whole network is reduced.[16][17] The hierarchical topology is a network topology where the access network on the user side, the aggregation network that bundles the traffic, and the core network for long-hole transmission are hierarchically connected. Since a number of demands is aggregated into the core network, a huge capacity is required for the core network. To mitigate the necessary capacity in the core network and support the network scalability to tens of millions of subscribers, the aggregation network loops back the local connection requests without connecting to the core network (localization of traffic). Such hierarchical network topology is highly compatible with the current network topology, and is effective from the perspective of facility sharing in the migration to DOPN.

3 Network topology and node architecture

The topology and the node architecture for the DOPN are investigated in this chapter. First, based on the number of broadband subscribers in Japan and the expected applications, the target numbers of DOPN subscribers and their bandwidth are considered. Based on the current optical switch technologies, the requirements for the optical devices and the topology are also considered. Specific topology and detailed node architectures are presented, and we shall demonstrate that the requirements can be satisfied.

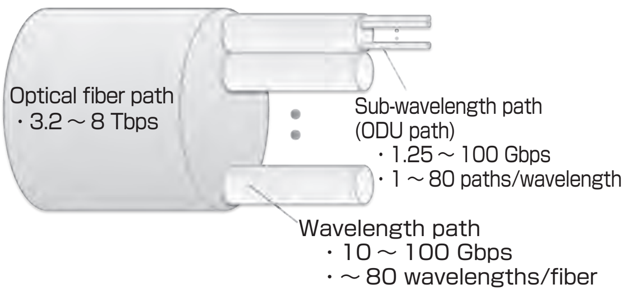


Fig. 3 Schematic diagram of the multi-granular hierarchical path addressed in this paper

For the optical fiber path capacity, maximum 100 Gbps per wavelength and maximum 80 wavelengths multiplexed in a fiber were assumed, based on the currently commercialized technology. In the future, this can be enhanced to 100 Tbps per fiber as described.

3.1 Goals and requirements

One of the main users of the future video application in the DOPN is consumer users that mainly use few Gbps for high definition VOD and TV phones. The other will be enterprise (business) users that mainly use several tens to 100 Gbps for ultra high-definition public viewing and large-capacity file exchange. Considering the current Japanese situation, there are about 50 million households and about 600 thousand businesses with dozens or more employees.[18][19] Hence accommodating 50 million or more consumer users with1 Gbps or more and 600 thousand or more enterprise users with 40~100 Gbps are set as target values for the DOPN.

The following four requirements were assumed for the optical devices and topology of the DOPN.

1) The number of optical matrix switch ports is equal to or less than 500: Although the technology for increasing the number of optical switch ports is being developed, the number of ports of the optical matrix switches that are currently released as products are: about 200 ports using the micro-electro mechanical system (MEMS) technology; and about 16 using the planar lightwave circuit (PLC) technology. A 32-port Si photonics switch is under development. The Si photonics technology has high expectations from the perspectives of switch speed and manufacturability. The 500-port switch can be constructed by combining multiple 32-port switches with 3-stage Clos-network structure.[20] From the above technological trends, the maximum number of ports for the optical matrix switch used in this paper was assumed to be 500.

2) Number of WSS ports is equal to or less than 1×35: Currently, the WSS with 1×9 or 1×4 ports using the liquid crystal on silicon (LCOS) or the MEMS technology are released by several manufacturers. Higher port count WSSs are being developed, and a product with 1×20 ports was announced in 2011.[21] Considering the technological advancement in the future, the maximum number of ports for the WSS used in this paper was assumed to be 1×35.

3) The basic fiber topology shall be tree, ring, and mesh topologies: Since the fiber ducts and the base station facilities that are used in the current network will be used, the geographic fiber location for DOPN will be common to the current network. That is, the tree topology that is highly

compatible with the passive optical network (PON) will be used as the geographic fiber location in the access region of the DOPN, ring in the metro region, and mesh in the core region.

4) Flexible grid accessibility shall be employed: In the current network, fixed bandwidth (ITU-T grid with 100 GHz or 50 GHz intervals[22]) is used regardless of the transmission data rate of the wavelength channel. To increase the spectral efficiency, the flexible grid technology that enables the flexible use of the channel bandwidths according to the signal data rate has been proposed and investigated, and about 25~50 % increase in efficiency is estimated.[23] To achieve an efficient large-capacity communication network, it shall be connectable to flexible grid from end to end, including the access network.

3.2 Topology

The DOPN topology that satisfies the requirements presented in subchapter 3.1 is investigated. The major issue is the limited optical switch port counts to provide path connectivity among tens of millions of users. As mentioned in Elemental Technology 2 of chapter 2, from the points of limited number of ports of the optical switch and traffic aggregation, a flat network structure cannot be used, and therefore, hierarchical topology where the user terminals are grouped and connected in a hierarchical manner is essential. In a hierarchical network topology, a simple structure with a small number of layers is preferable. There must be two layers: a lowermost layer for traffic aggregation, uppermost layer for long haul path establishment. The point is how many other layers are required for what purposes. In the DOPN, the sub-wavelength path is aggregated consecutively to the wavelength path and wavelength path to the fiber, according to the user's path granularity. The reasons for having two layers for traffic aggregation are to improve the efficiency of use of transmission line by aggregating from sub-wavelength path to wavelength path at a location close to the user, and to reduce the number of ports of the sub-wavelength path switch that will become necessary when aggregated to the fiber capacity. Considering the target number of users and the bandwidth per user, the traffic volume aggregated in the uppermost network will become enormous. To accommodate such enormous traffic volume, utilizing optical fiber switches in the uppermost network is essential; the number of optical fiber switch ports is currently much larger than that of wavelength switches and thus the optical fiber switch can handle larger capacity than the wavelength switches. At the same time, it is necessary to connect to the uppermost network under the condition where the wavelength and sub-wavelength paths are organized so that they can be switched with the fiber granularity (grooming[Term 3]). As a result of quantitative investigation of the node architecture used in the aggregation network, it was found that it is difficult to aggregate enough traffic due to the loss and number of the optical coupler branches for multiplexing the wavelength paths to the fiber paths. Before connecting to the uppermost network, there must be an additional network layer for the grooming operation. Through such investigation processes, we figured out a four-layered network as shown in Fig. 4. With a detailed numerical investigation, it was found that this network structure would satisfy the requirements discussed in subchapter 3.1. The details of the topology and the specific numerical investigation will be explained in the next section.

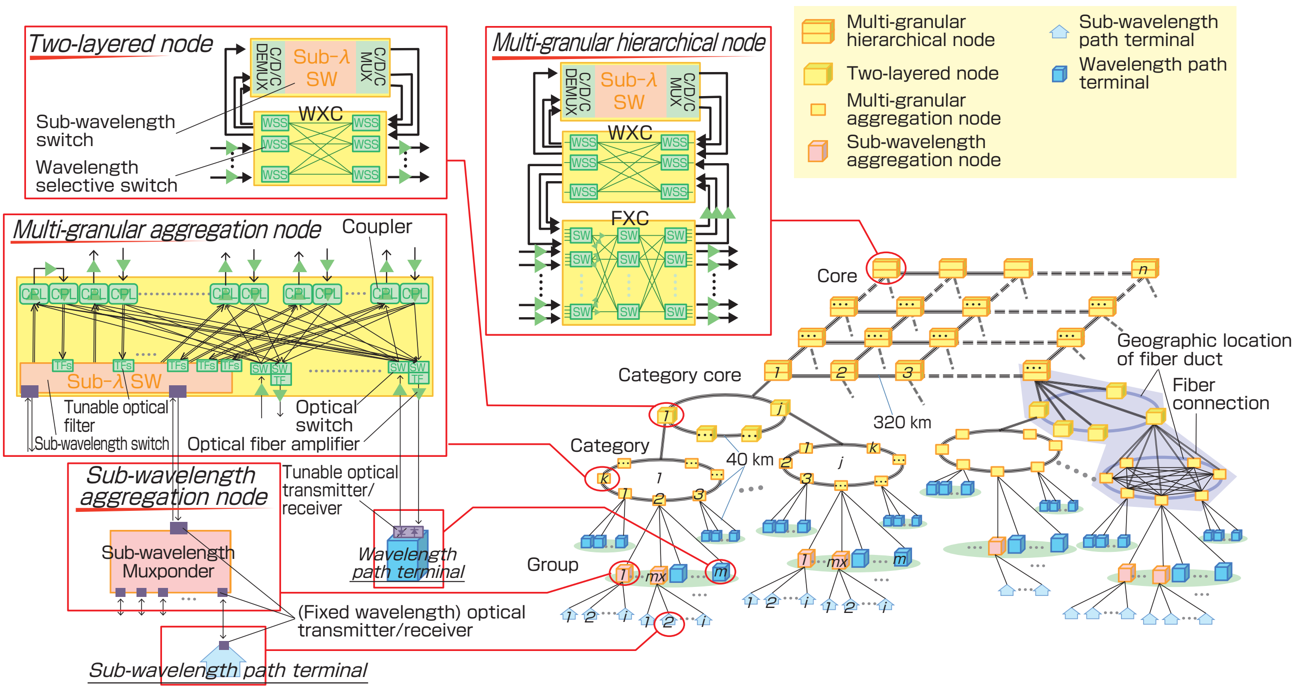


Fig. 4 Topology and node architecture of the DOPN

3.2.1 Role of each network

The network topology investigated here consists of four layers. They are the following: group networks (NWs) that consist of multiple user terminals, category NWs that aggregate multiple group NWs, the category core NWs that aggregate the multiple category NWs, and the core NWs that connect the multiple category core NWs. The group NW aggregates the traffic for the first phase, the category NW aggregates the traffic for the second phase, the category NW grooms the aggregated traffic, and then the core NW establishes the long-hole paths.

The group NWs consist of the sub-wavelength path terminals for consumer users, the wavelength path terminals for enterprise users, and the sub-wavelength path aggregation nodes that multiplexes the sub-wavelength paths to the wavelength paths. These terminals, nodes, and upper layer category NW nodes are connected with tree topology. This topology is compatible with the current PON. To achieve a flexible wavelength assignment with minimum blocking for the whole network, the tunable optical transmitter/receiver is assumed to be installed on the uplink side of the wavelength path terminal.

At the category NW, the multiple wavelength paths from the multiple group NW are multiplexed to the fiber paths, and are connected to the upper layer (category core NW) or another group NW within the same category NW according to the path destination. While the geographic fiber topology of the category NW is the ring, the logical fiber connectivity is assumed to be full mesh within a category NW. Consequently, the nodes that are not adjacent to each other on the ring topology will be connected directly by fibers at the nodes along the way as shown in the schematic diagram of Fig. 5. The logical fiber connectivity between the category and category-core NW is assumed to be star network. By using the full mesh and star connections, the category NW node can handle only the traffic transmitted/received from the group NW to which it connects. Since it does not have to handle the transit traffic that is generated/terminated from/at other group NWs, the node architecture can be simplified and the number of necessary optical switch ports can be reduced.

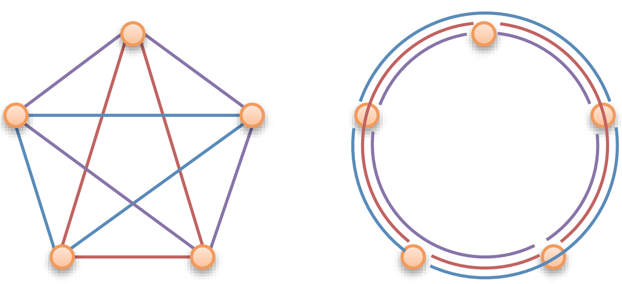


Fig. 5 Example of the intra-node fiber connection (left) and the geographic fiber location (right) at the category NW section

At the category core NW, the paths connected from the category NW is connected to the core NW. Here the paths are sorted to enable switching for each fiber as much as possible at the core NW. That is, the wavelength paths with the same destination node at the core NW are aggregated to the same fiber (wavelength path grooming), and the sub-wavelength paths with the same destination are aggregated to the same wavelength path (sub-wavelength grooming). While the geographic fiber topology of the category core NW is the ring, the fiber connectivity between the category-core and core NW is assumed to be star topology. Also, to simplify the node architecture and to reduce the number of necessary optical switch ports, the loopback at category NW is not considered.

At the core NW, long-distance paths will be established for the aggregated traffic.

3.2.2 Bottleneck of the network

In the network capacity design, it is not realistic to assume that all users continue to request connection at all times. To increase the network utilization, the network capacity of the core NW and the category core NW which share many users are limited compared to the category NW and the group NW. This is called oversubscription. An example of the capacity design is shown in Fig. 6. Here, the oversubscription is set as 10, and 10 % of the traffic from each group NW is allowed to connect to the category core NW through the category NW. For the remaining 90 %, the loopback connection is allowed within each category NW. This loopback connection enables connection with low blocking rate for the connection request within the same category NW. On the other hand, since the long-haul connection request must go through the core NW, this will be affected by oversubscription.

The optimal value of oversubscription is strongly dependent on the traffic pattern and application service model, and therefore detailed investigation is impossible at this point.

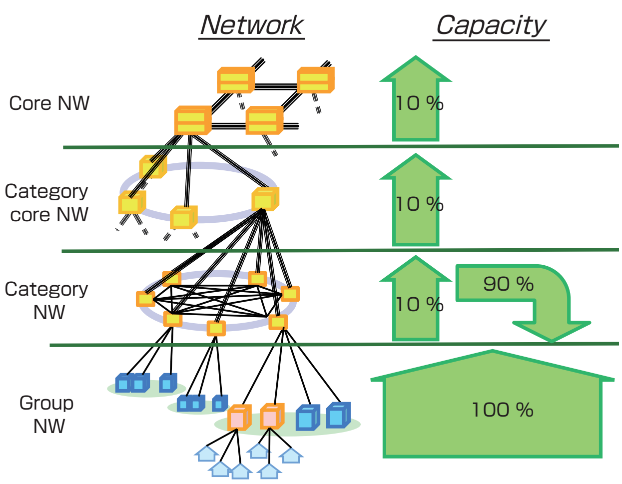


Fig. 6 Example of the network capacity design

As a typical example, considering the high definition teleconferencing application, a reservation service is expected. It can be expected that even with relatively high blocking rate of a few tens of percent or large oversubscription, meaningful service operation can be provided through efficient reservation algorithms and clear fee schedule according to the time zone of use.

For download services, the blocking rate can be reduced by allocating content servers appropriately. For example, allocating content servers for each category NW may substantially reduce the blocking probability since the blocking probability within the same category NW is very low. In addition, the DOPN can efficiently accommodate the connections between the servers since the requests from multiple users are aggregated at the servers and large-capacity demand occurs between the servers; the DOPN is capable of handling such large-capacity paths. On the other hand, there is a tradeoff relationship between the reduced blocking probability by contents server array and increased power consumption and cost. The optimal allocations of content servers with low blocking probability and low power consumption for download services depends on the server performance and the service format, and detailed study is necessary in the future. For the investigation of the efficiency of the download service, the file transfer time (path/service holding time) and path switching time are also important factors. That is, the path switching time must be much shorter than the path holding time. The switching time of the optical switch depends on the technologies: MEMS switches take several tens of millisecond order; Si photonics switches take microseconds to sub-milliseconds; WSSs of LCOS takes several tens of millisecond order. Assuming that the path switching time is several hundred milliseconds, the service with holding time of several minutes or more (file size about 40 GByte or more) is suitable as the target service of DOPN. If the path switching time is reduced to the order of sub-milliseconds, the file transfer of about 100 MByte (path holding time is several seconds) can be a target application of DOPN.

3.2.3 Network size

The number of users that can be accommodated by the whole network depends on how many nodes or terminals compose each network. Table 1 shows the list of parameters necessary for setting the network topology and the example of numerical values to achieve the requirements. In the given example, about 20 thousand user terminals can be accommodated per one group NW, and about 200 thousand user terminals per one category NW.

3.2.4 Details of each network node

As mentioned before, since each network has different roles and different aggregated traffic volumes, it is necessary to employ appropriate path granularities and node structures for each network. The details of the nodes used in each network are explained below.

Table 1. List of the network topology parameter and the numerical value example for 5,1840,000 accommodated users

	Expression	Numerical example
Number of nodes in core NW	n	25
Number of nodes in category core NW	j	10
Number of nodes in category NW	k	10
Number of fibers that connect from each category NW to upper layer category core NW	k_c	1
Number of wavelength path terminals within the group	$m(1-x)$	256 (m=768, x=2/3)
Number of sub-wavelength path aggregation nodes within the group	mx	512 (m=768, x=2/3)
Number of sub-wavelength path terminals per sub-wavelength path aggregation node	i	40
Number of wavelengths per fiber	w	80
Transmission rate of wavelength path user	B_w	40 Gbps
Transmission rate of sub-wavelength path user	B_s	1 Gbps
Total number of sub-wavelength path terminals	$ijkmnx$	
Total number of wavelength path terminals	$jkmn(1-x)$	

The sub-wavelength path aggregation node in group NW provides the function of aggregating/multiplexing i sub-wavelength paths to one wavelength path. Here, the use of ODU signal multiplexing function (muxponder) is expected. The oversubscription at group NW is avoided by setting $B_w \geqq iB_s$.

The category NW node is a multi-granular aggregation node shown in Fig. 4. The downlink side of this node has m ports for wavelength paths, and accommodates one group NW. The uplink side has $k+k_c$ fiber ports. Of these, k port is the loopback port within its own category NW, and the number of connecting fiber to the upper network is k_c. That is, the oversubscription is expressed as m/wk_c, and in the example shown in Table 1, it will be 9.6. This node is composed of m×1 optical couplers, $(k+k_c)$×1 optical switches, sub-wavelength path switch with throughput $imxB_s$, and tunable optical filters (TF).[Term 4] The flexible grid connectivity is achieved by using optical couplers with port/wavelength/bandwidth independent multiplexing capability for multiplexing wavelength paths to fiber paths.

The node used in the category core NW is a two-layered node consisting of the wavelength cross connect and sub-wavelength cross connect (Fig. 4). Each node has average $(1-x)wkk_c$ of wavelength paths and $iwxkk_c$ sub-wavelength paths connected from the category NW. To conduct wavelength path and sub-wavelength path grooming for all of these, the number of ports required for the wavelength path switch will be $kk_c+\lceil xkk_c \rceil$ and throughput $iwxkk_cB_s$ at the sub-wavelength path switch.

The node at the core NW is the multi-granular hierarchical node composed of the fiber switch, wavelength switch, and sub-wavelength switch (Fig. 4). At the core NW, the traffic is considered to be sufficiently aggregated and sorted by the grooming process in the category core NWs. Thus the switching operation in the core NW can be mainly done with the fiber path granularity. In cases where the grooming is insufficient, the grooming using the wavelength and sub-wavelength path switches are done in the core NW. The number of switch ports necessary for each multi-granular, hierarchical node is investigated in subchapter 3.3.

3.2.5 Variations of network topology

For the core NW structure, according to the geographic conditions, using the $N\times M$ ladder type or other asymmetrical topology instead of the $N\times N$ grid types can be considered as variations of network topology shown in Fig. 4. There is also a variation in correspondence with the content server allocation as mentioned in section 3.2.2. According to the allocation of content servers, partial changes in category NW or category core NW or slight modifications of the node architectures may be required. However, major changes involving the increase or decrease in the number of network layers is difficult. That is, decreasing the number of layers is difficult from the perspective of switch port numbers. Increasing the number of layers is not advisable since it leads to an increase of the necessary number of nodes and hence of cost and of network power consumption. To achieve the DOPN using a completely different structure from the network topology shown in Fig. 4, changes in goals for target numbers of subscribers and traffic volume, or changes in the device requirements involving the dramatic improvement in device technology such as increased number of optical switch ports are necessary. For example, if a WSS with several hundred ports can be realized, it may become possible to simplify the category core NW structure or to even eliminate the category core NW layer by introducing a large scale wavelength grooming operation in to the core NW instead of the grooming operation in the category core NW.

3.3 Number of optical switch ports and subscribers at core NW

For category NWs and category core NWs, the path route is uniquely determined because the fiber connection is a simple tree and star structure. Therefore, the number of switch ports needed at each node can be defined according to the number of subscribers and oversubscription rate accommodated or aggregated at each node independently of the traffic distribution. On the other hand, core NW has a mesh topology, and there are several path route candidates. Moreover, since each node has to handle the traffic from the terminals that do not belong to its own node (transit traffic), the number of switch ports depends on the traffic pattern and cannot be determined definitely.

The number of switch ports needed at the core NW is calculated as follows. A uniform distributed traffic pattern is assumed. As an ideal condition, all demands are assumed to be switched with fiber granularity. In this condition, the result of the optimal route assignment that minimizes the necessary number of switch ports is shown in Fig. 7. The horizontal axis at the top of the graph is the number of accommodated users in the case where the numerical example from Table 1 is used as the parameter except n. For parameter n, the values for 9 (3×3 topology) to 64 (8×8 topology) are considered.

The number of necessary accommodating fiber paths at core NW of DOPN topology investigated in this paper is $jnkk_c$, and $jnkk_c$=2,500 according to the numerical example of Table 3. The graph shows that to accommodate 2,500 fiber paths, optical matrix switch with 450 ports is necessary for 5×5 topology. If 500-port switches are used, the remaining 50 ports can be used for the grooming operation, connecting with the wavelength switches. In a case where more grooming operations are necessary, it is necessary to increase the number of optical matrix switch ports. For example, it is necessary to expand the number of stages of the optical switch structure if the multi-stage Clos network structure is used. The number of ports necessary for the grooming operation depends on the traffic patterns and the path accommodation algorithms, and these are future topics of investigation. However, from the perspective of power consumption, the percentage of power consumed by the core NW is small, as will be explained later, and the total power consumption is not greatly affected even if the number of optical fiber switches used in the core NW is increased.

4 Investigation of the optical signal transmission distance

The optical signal power is attenuated as it passes through optical devices such as the optical fiber or the optical switch. To compensate the loss, it is necessary to place the optical amplifier at a certain transmission distance or at a

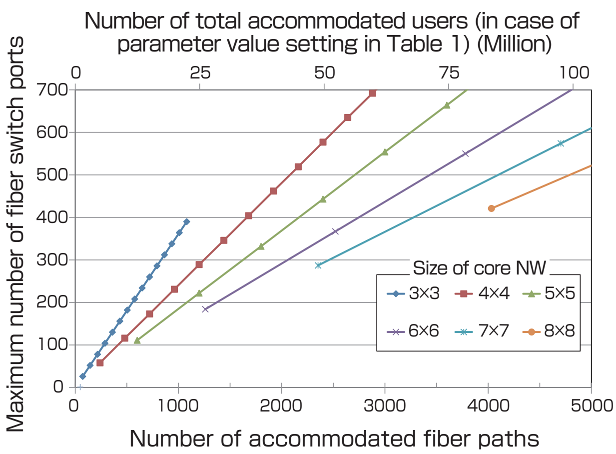


Fig. 7 Result of the calculation for number of optical switch ports needed at core NW in the optimal route assignment

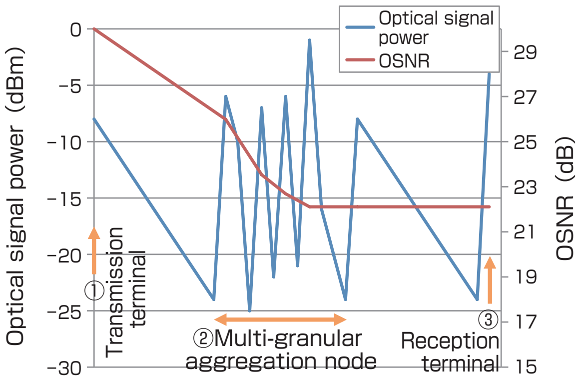
certain loss of optical signal power. For the amplification of optical signals at 1.55 μm-band used for long-distance communication, the erbium doped fiber amplifier (EDFA) is generally used. The optical signal that passes the EDFA has its power amplified, and also gains the spontaneously emitted light generated by EDFA, and this becomes the noise for the signal. If several EDFAs are cascaded, the noise is accumulated, and the signal-to-noise ratio is decreased. For receiving the signal properly, the signal must be regenerated and repeated while the signal-to-noise ratio is within a certain range. The necessary frequency of signal regeneration or the level of accumulated noise by EDFAs depends on the noise/gain profiles of the EDFA and the input signal power. Generally, when the EDFA with large gain is used at low frequency, the accumulated noise becomes great, and when the EDFA with small gain is used at high frequency, the accumulated noise can be kept low.

The number and the location of necessary signal regenerative repeaters and optical fiber amplifiers for the DOPN were investigated by calculating the optical signal-to-noise ratio (OSNR). The typical loss value of the optical device used in the calculation is shown in Table 2. The noise figure of the EDFA is assumed to 6 dB and the noise bandwidth is set to 12.5 GHz. The assumed fiber length at each network section is shown in Fig. 4.

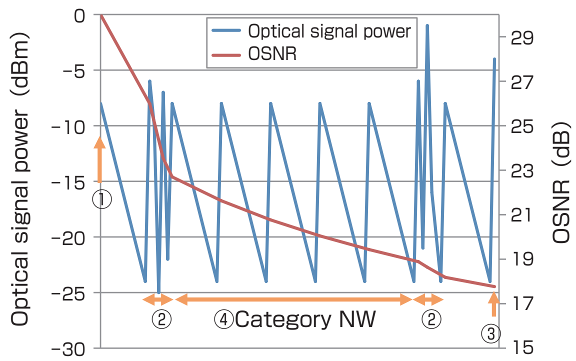
Table 2. Insertion loss value of each optical device used in estimation

Item		Loss
Optical fiber		0.4 dB/km
Multi-granular aggregation node	1×10 switch	4 dB
	1×768 optical coupler	30 dB (amplify at every 15 dB loss)
	Tunable optical filter	4 dB
Two-layered node	1×17 WSS	6.5 dB
Multi-granular hierarchical node	3-stage 500×500 matrix switch	24 dB (amplify between stage)
	1×35 WSS	6.5 dB

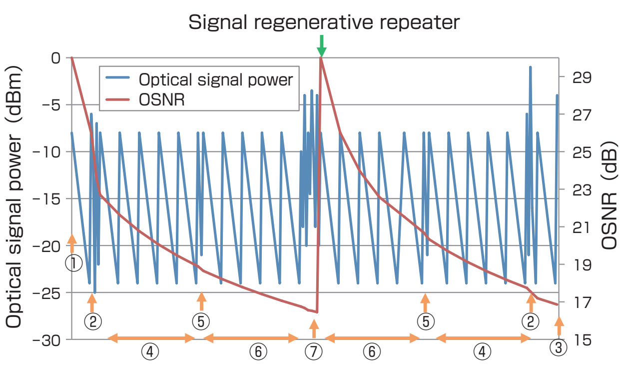
The result of the calculation is shown in Fig. 8. The level diagram shows the input optical signal power and gain of the EDFAs. In the multi-granular aggregation node, large loss occurs because couplers (CPL) with large numbers of branches are used. To reduce the OSNR degradation there, the EDFAs are placed at an intermediate stage of the branch.



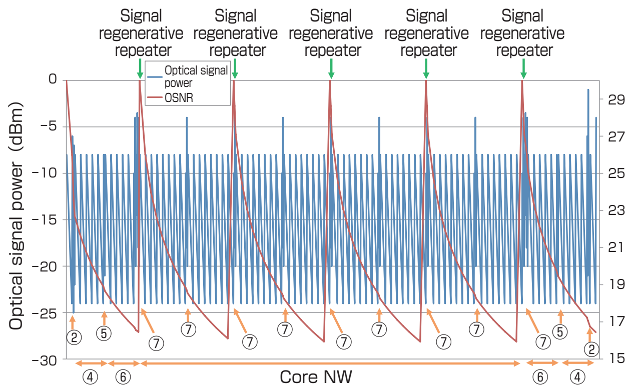
(a) Path within the same group



(b) Path between other groups within the same category



(c) Path within the same core node between other categories



(d) Path between other core nodes

Fig. 8 Level diagram of the typical path route and result of the OSNR calculation

The numbers inside the graph correspond as follows: ① transmission terminal, ② multi-granular aggregation node, ③ reception terminal, ④ category NW, ⑤ two-layered node, ⑥ category core NW, and ⑦ multi-granular hierarchical node.

Also, the EDFAs are placed at an intermediate stage of the 3-stage Clos network switch structure to prevent the OSNR degradation in the fiber path switch of the multi-granular, hierarchical node. The calculation results show the signal regenerative repeater had to be placed in the core NW node, and the signal regeneration must be done when the signal enters the core NW, when it leaves the core NW, and once every two nodes during the core NW transmission. The OSNR threshold was set at 15 dB assuming the use of 100 Gbps dual polarization quadrature phase shift keying (DP-QPSK),[Term 5] which employs the digital coherent transmission/reception technology that is recently being put to practical use.[24][25]

Table 3. Power consumption values for each device used in the estimation of the DOPN power consumption

Network equipment	Power consumption	Remarks
Single wavelength optical fiber amplifier	2 [W/span/fiber]	40 km/span
WDM optical fiber amplifier	20 [W/span/fiber]	40 km/span
Sub-wavelength cross connect	1 [W/Gbps]	
Wavelength path terminal	1 [W/Gbps]	40 Gbps or more
Sub-wavelength path terminal	5 [W/device]	Less than 5 Gbps
Optical matrix switch	0.05 [W/port]	The use of Si photonics switch is expected
Wavelength selective switch	20 [W/device]	
Tunable optical filter	5 [W/device]	

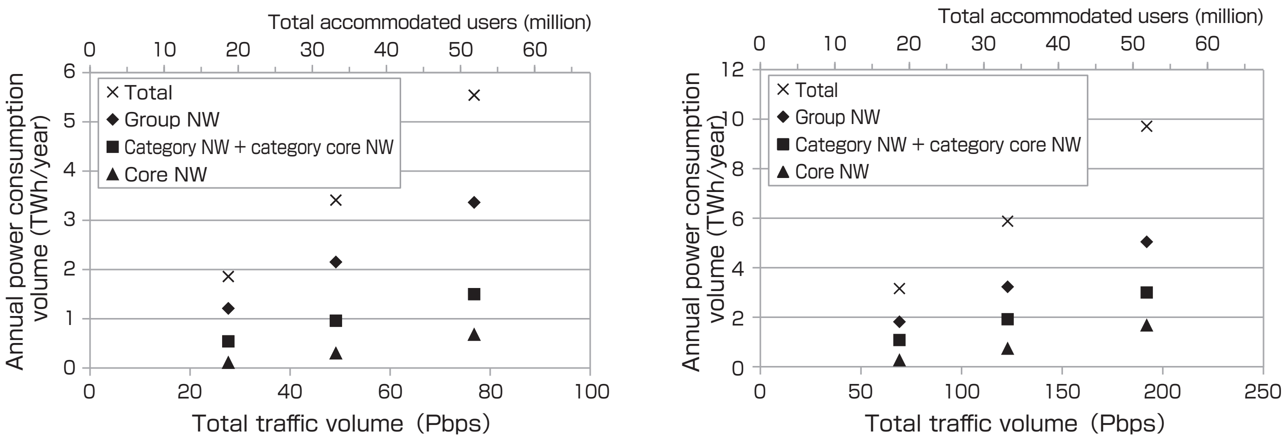
5 Estimate of power consumption

Through the investigations in chapters 3 and 4, the location and the necessary numbers of the main component devices for the DOPN topology including from the path switching devices to the signal regenerative repeater were clarified. By summing up the power consumptions of each device, the total power consumption of the DOPN can be estimated. Table 3 shows the power consumption of each device; the values are determined based on product catalogs and specification sheets. Figure 9 shows the result of the calculation of the power consumption of the whole network.

The estimation result shows the group NW or the communication terminals dominate the power consumption of DOPN. In the case where the terminal speed is constant, the total power consumption increases in proportion to the number of subscribers. If the terminal speed increases while maintaining the number of subscribers, the total power consumption increases in correlation to the increase in overall traffic volume. This is because the DOPN uses not only the optical switch of which power consumption is not dependent on the throughput, but also the sub-wavelength path switch, wavelength path terminal device, and signal regenerative repeater that are devices whose power consumption scales with the throughput.

In the current Japanese network, the total traffic volume is said to be 1.9 Tbps and total power consumption is ~10 TWh/year.[3][26] The DOPN can accommodate four to five digits more of traffic with about the same power consumption. Although the power consumption needed for control systems and the network utilization ratio are not considered in the estimation. However, even if the power consumption is multiplied ten-fold due to the overhead, the DOPN can offer an energy efficiency benefit of three orders of magnitude.

For further reduction of power consumption in the DOPN, the introduction of sleep function to the transceivers of the user terminal can be considered. Assuming that the average usage time of DOPN for each user is 5 h/day, and expecting that the terminal power can be turned off completely when not in use, the power consumption reduction of 22~37 % can be expected in the estimation of Fig. 9. Compared to the transceivers that are shared by multiple users within the network, it is expected that the sleep function can be readily introduced to the transceivers of the user terminal. Further, the improvement of the insertion loss of the optical switch and WSS is important. If the insertion loss of the



(a) In case of wavelength endpoint 40 Gbps and sub-wavelength endpoint 1 Gbps

(b) In the case of wavelength endpoint 100 Gbps and sub-wavelength endpoint 2.5 Gbps

Fig. 9 Result of the estimation of the power consumption in DOPN

optical device is reduced, the number of EDFA and signal regenerative repeater needed in the network can be reduced, and the reduction of power consumption particularly in the core NW can be expected.

6 Conclusion

The detailed topology and node architecture for the DOPN were investigated; the scalability of the DOPN was evaluated from the perspective of the number of subscribers, bandwidth per user, and the power consumption; and the validity of the DOPN as a future communication infrastructure technology was clarified in this paper. For the realization of DOPN, further R&D such as the development of a low-loss, compact optical switch, as well as efficient integrated resource management technology is necessary. The target of DOPN is not the application that is available on the current communication network, but is future applications requiring a high realistic sensation that involves remote medical care, remote education, and so on. For the DOPN to truly contribute to society, the development of the peripheral technologies that can utilize the DOPN is necessary, not only from the elemental technologies constructing the network mentioned above, but also to the display and video/sound technologies that can achieve realism almost equivalent to actual experiences, as well as business models to realize new services. Considering the above point, and looking at the device and application to the future, we plan to continue R&D to establish the communication infrastructure technology for the future.

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Terminologies

Term 1. OSI7 layer: The layer model for communication function for data communication that was established by the International Standards Organization (ISO). It is also called the open system interconnection (OSI) reference model. It is composed of the physical layer (layer-1), data link layer (layer-2), network layer (layer-3), transport layer (layer-4), session layer (layer-5), presentation layer, (layer-6), and application layer (layer-7). The IP router used commonly in the wide area network is a communication device that conducts connection and routing in layer-3, while the Ethernet switch used commonly in the local area network (LAN) conducts connection and switching in layer-2. The optical switch that is the main component of DOPN corresponds to layer-1 or the lower layer (sometimes called layer-0).

Term 2. Wavelength selective switch (WSS): This is a device with the basic structure of optical port with one input and multiple outputs. It has the function of switching the input WDM wavelengths to any of the output ports per-wavelength basis. Some switches are fixed to the 50 GHz grid or 100 GHz grid for the wavelength channel bandwidth, and others are flexible grids that can handle consecutive bandwidth every 12.5 GHz.

Term 3. Grooming: A process that enables the handling of small-granular communication requests as a large-granular request by grouping them. Here, the process includes the operation that enables switching the multiple sub-wavelength paths with the same destination as one wavelength path by accommodating them into one wavelength path, or the operation that enables switching the multiple wavelength paths with the same destination as one optical fiber path by accommodating them into one optical fiber.

Term 4. Tunable optical filter (TF): The optical device that transmits a certain wavelength bandwidth and can tune the central wavelength of the pass bandwidth. There is also the central wavelength bandwidth tunable optical filter that can change the central wavelength and the pass bandwidth.

Term 5. Dual polarization quadrature phase shift keying (DP-QPSK): One of the modulation formats for the digital signal, where the polarization multiplexing is applied to the quadrature phase shift keying. Since 2005, it has been developed along with the advancement in digital coherent optical communication technology to improve the spectral efficiency. In 2010, the standard for 100 Gbps DP-QPSK optical transceiver module was announced at the Optical Internetworking Forum (OIF). Currently, the products in compliance with this standard have been launched, and the transmission system with 100 Gbps per channel is developing rapidly. Also, the high-speed digital signal processing enables the linear compensation of various issues in transmission of over several thousand km without regenerative repeating has been reported.

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Discussions with Reviewers

1 Overall

Comment (Naoto Kobayashi, Center for Research Strategy, Waseda University)

This paper investigates the topology structure of the dynamic optical path network (DOPN), which is a method devised to handle the significant increase in power consumption due to increased communication capacity that is essential for the information and communication network in the near future, and demonstrates its efficacy. It is a paper with logical clarity and substantial content. The structure of the paper is also appropriate for publication in *Synthesiology*.

2 Network structure

Comment (Katsuhiko Sakaue, Research Environment and Safety Headquarters, AIST)

I understand that this research is a fine investigation of the network architecture to apply the DOPN, the subject of your research team, to the practical scale of Japan's network. However, you present the requirements of the network in subchapter 3.1, and suddenly you jump to the four-layered topology as the subject of investigation in subchapter 3.2. Although this topology is very practical and I have no objection to it, for *Synthesiology*, you should write out the arguments, or what thought processes and investigations results you went through before you arrived at this topology. Please explain them in the appropriate chapters.

Answer (Kiyo Ishii)

The number one issue when investigating the topology is to provide the path connectivity among tens of millions of users using the switches with several hundred ports as the main components. Also, since the traffic volume transmitted by the user is small or 1/80~1/6400 or less compared to the transmission line (optical fiber) capacity, it is necessary to aggregate the traffic at a point as close as possible to the user terminal to increase the utilization of the transmission line. Not only from the point of compatiblity with the existing network, but also from the port limitations and traffic aggregation, the achievement of DOPN using a flat network topology was difficult, and the hierarchical topology where the user terminals are grouped and hierarchically connected was necessary. In the hierarchical network topology, a simple structure with as less layers as possible is preferred, and the point was how many layers with which roles were necessary for the network, other than the two layers for traffic aggregation (lowermost) and long-hole path establishment (uppermost). For traffic aggregation, we decided to consecutively aggregate the sub-wavelength path to the wavelength path, and wavelength path to the fiber path, according to the users' path granularity. The reason for separating the aggregation to two steps were, to increase the utilization of the transmission line by aggregating the sub-wavelength path to the wavelength path at a position close to the user, and to reduce the number of sub-wavelength path switch port that will be necessary when the paths are aggregated to the fiber capacity. Considering the number of target users and the bandwidth per user, the traffic volume aggregated to the uppermost network will become enormous. In the uppermost network, the number of ports much greater than the wavelength switch can be expected, and the optical fiber switch that can accommodate larger capacity is essential. That is, as it becomes possible to switch by individual fiber, it is necessary to connect to the uppermost network in a state where the wavelength path and the sub-wavelength path are well sorted. As a result of investigating quantitatively the communication node architecture of the aggregation network, from the perspective of the number of optical switch ports and loss of optical couplers, it was difficult to aggregate the traffic demand with the same or nearby addresses to fill the fiber capacity using the aggregation network. It was therefore found that a network for grooming was necessary between the aggregating network and the uppermost network. This meant there would be a four-layered network with two layers of aggregating networks, one layer of a grooming network, and one layer of a long-hole path establishment network. Detailed numerical investigation was done, and it was found that the node architectures and topology set as shown in Fig. 4 would satisfy the requirements for the number of optical switch ports and user capacity. The above discussion was added to subchapter 3.2.

Question (Naoto Kobayashi)

The network structure of Elemental Technology 3 considers the similarity with the existing network structure and control characteristic of the upper and lower layers, and I think it is adequate. However, is there room for options such as other possible selections? If there is any, what kind of topologies or nodes can be considered?

Answer (Kiyo Ishii)

The network structure shown in this paper is the result of accumulation based on the adequacy of the goals and requirements shown in subchapter 3.1. Before arriving at this network structure, various topologies were investigated including the flat network structure, but they could not fulfill the requirements of subchapter 3.1. For example, reducing the number of the network layers is difficult from the perspective of the number of switch ports. Increasing the number of the network layers is not wise because it leads to increased nodes and therefore, increased device cost and power consumption. I think future investigations are necessary for fine modifications and partial changes in category NW and category core NW according to the expected traffic patterns and variations of the contents server allocation. Also, there are variations, such as using the N×M ladder type instead of N×N grid type or other asymmetrical topology, for the core NW according to the geographic condition. However, it is difficult to fulfill the requirements of subchapter 3.1 using a fundamentally different topology, and in such cases, changes in requirements such as the dramatic improvement of the device technology including the increase of the number of optical switch ports, or changes in the goals of the number of users or capacity must occur. Section 3.2.5 was newly added for the above discussion.

3 Elemental technology

Question (Naoto Kobayashi)

In this research, you predict the property of DOPN based on the current specifications of the individual elemental technologies including the optical switch of Elemental Technology 1. Can you give us prospects on which part of the elemental technology should be dramatically changed to greatly improve the network property?

Answer (Kiyo Ishii)

From the perspective of further reducing the power consumption, I can mention the sleep function for the user terminals (transceiver) that dominate the majority of the power consumption. Since the transceiver of the group network is mostly used by a single user, I suppose it is easier to introduce the sleep function compared to the transceiver of the upper network that is shared by multiple users. Assuming that the average use time of the DOPN for each user is 5 h/day, and expecting that the transceiver power can be turned off completely when not in use, the reduction in power consumption of 22~37 % can be expected for the estimation in Fig. 8. Also, if the insertion losses of the optical switch and WSS are improved, the number of necessary EDFA and signal regenerative repeaters can be reduced, which will further reduce the power consumption of the core NW. From the perspective of topology, if the WSS with several hundred ports is realized, the wavelength path grooming becomes easy, the category core NW layer for the grooming process can be simplified, and unifying the category core NW into the core NW may become possible. From the perspective of target service, if the switching speed of the WSS and optical fiber switch increases in the order of sub-milliseconds, the service with holding time of several seconds (HV or 4K VOD download) can be efficiently handled in DOPN, and this may expand the target services. These discussions were added to chapter 5, section 3.2.5, and section 3.2.2.

4 Issues concerning future application

Question (Katsuhiko Sakaue)

You mention in several places that the DOPN can be used in highly realistic video applications including in remote medical care and remote education that are expected to be developed in the future. However, these are being realized in the current IP router network, and in practice, the flexibility of the IP technology seems to surpass the low power consumption and high speed achieved by replacing the L1 switch with the optical switch. What is your expected scale of application that cannot be handled by the current IP router network?

Answer (Kiyo Ishii)

The quality of the video service targeted by DOPN is the ultra high definition (UHD) that is currently being developed. The UHD has 16 times higher definition compared to high vision (HV). It requires the bandwidth of 72 Gbps or more for uncompressed transmission, and compared with the peak connection speed 40.5 Mbps for the current Japanese Internet network, there is a gap of three digits or more. If the DOPN is used, the bandwidth needed for the uncompressed transmission of UHD can be provided stably. Of course, the video compression technology is also being developed, but there is a limit to compression in realizing the high realism equivalent to actual experiences, and the transmission bandwidth of about several Gbps to 100 Gbps that is the target of DOPN will be necessary. This discussion was added to chapter 1.

Question (Naoto Kobayashi)

You expect multiple users for video application in the future. However, in practice, there are extremely large amount of download services on the traffic, and there is a projection that there isn't much real-time video streaming. In section 3.2.2, you write, "It is possible to reduce the blocking rate in the download service by allocating the contents server for each category." In this case, won't the number and capacity of the content server become so large that it becomes inefficient?

Answer (Kiyo Ishii)

As you indicated, there is a tradeoff between the increased power consumption and cost by the allocating content server and the efficiency of the network through traffic localization. Yet, I think achieving high efficiency not only for the network resource but also for content resource is possible by appropriate server placement and topology design. The optimization of this tradeoff is also related to business models and resource management methods, and these are future topics of study. For content server placement, while connection between the servers is important, this can be accommodated efficiently with the DOPN that can handle the large-capacity paths, since large-capacity demand will occur as the requests from multiple users are aggregated. The above discussion was added to section 3.2.2.

5 Future usability

Question (Naoto Kobayashi)

In the future, the users will hope to use the existing IP network and the proposed DOPN seamlessly, without ever thinking about the differences. Is this actually possible? Or, since there is a reservation task to obtain the optical path when using the DOPN, will that make it less usable?

Answer (Kiyo Ishii)

For the operation management of DOPN, the introduction of a new resource management system to conduct the comprehensive reservation management from network to storage resources will be necessary. From the perspective of the concurrent use of the IP network and DOPN, the resource management system will automatically select the network to be used according to the application, such as web or mail using the IP network, while large-capacity file transfer such as high definition VOD using the DOPN, and the optical path is reserved as necessary. Also, as in the remote teleconferencing service where the user normally makes reservations beforehand, the resource management system will make prior reservation of the optical path based on the user's reservation. In this case, the user reserves the teleconferencing service, while the reservation of the optical path will be done by the resource management system, so the user does not have to be conscious of using the DOPN. The resource management system is being studied in collaboration with the Information Technology Research Institute, AIST. The above discussion was added to chapter 1.

Editorial Policy

Synthesiology Editorial Board

Objective of the journal

The objective of *Synthesiology* is to publish papers that address the integration of scientific knowledge or how to combine individual elemental technologies and scientific findings to enable the utilization in society of research and development efforts. The authors of the papers are researchers and engineers, and the papers are documents that describe, using “scientific words”, the process and the product of research which tries to introduce the results of research to society. In conventional academic journals, papers describe scientific findings and technological results as facts (i.e. factual knowledge), but in *Synthesiology*, papers are the description of “the knowledge of what ought to be done” to make use of the findings and results for society. Our aim is to establish methodology for utilizing scientific research result and to seek general principles for this activity by accumulating this knowledge in a journal form. Also, we hope that the readers of *Synthesiology* will obtain ways and directions to transfer their research results to society.

Content of paper

The content of the research paper should be the description of the result and the process of research and development aimed to be delivered to society. The paper should state the goal of research, and what values the goal will create for society (Items 1 and 2, described in the Table). Then, the process (the scenario) of how to select the elemental technologies, necessary to achieve the goal, how to integrate them, should be described. There should also be a description of what new elemental technologies are required to solve a certain social issue, and how these technologies are selected and integrated (Item 3). We expect that the contents will reveal specific knowledge only available to researchers actually involved in the research. That is, rather than describing the combination of elemental technologies as consequences, the description should include the reasons why the elemental technologies are selected, and the reasons why new methods are introduced (Item 4). For example, the reasons may be: because the manufacturing method in the laboratory was insufficient for industrial application; applicability was not broad enough to stimulate sufficient user demand rather than improved accuracy; or because there are limits due to current regulations. The academic details of the individual elemental technology should be provided by citing published papers, and only the important points can be described. There should be description of how these elemental technologies are related to each other, what are the problems that must be resolved in the integration process, and how they are solved (Item 5). Finally, there should be descriptions of how closely the goals are achieved by the products and the results obtained in research and development, and what subjects are left to be accomplished in the future (Item 6).

Subject of research and development

Since the journal aims to seek methodology for utilizing the products of research and development, there are no limitations on the field of research and development. Rather, the aim is to discover general principles regardless of field, by gathering papers on wide-ranging fields of science and technology. Therefore, it is necessary for authors to offer description that can be understood by researchers who are not specialists, but the content should be of sufficient quality that is acceptable to fellow researchers.

Research and development are not limited to those areas for which the products have already been introduced into society, but research and development conducted for the purpose of future delivery to society should also be included.

For innovations that have been introduced to society, commercial success is not a requirement. Notwithstanding there should be descriptions of the process of how the technologies are integrated taking into account the introduction to society, rather than describing merely the practical realization process.

Peer review

There shall be a peer review process for *Synthesiology*, as in other conventional academic journals. However, peer review process of *Synthesiology* is different from other journals. While conventional academic journals emphasize evidential matters such as correctness of proof or the reproducibility of results, this journal emphasizes the rationality of integration of elemental technologies, the clarity of criteria for selecting elemental technologies, and overall efficacy and adequacy (peer review criteria is described in the Table).

In general, the quality of papers published in academic journals is determined by a peer review process. The peer review of this journal evaluates whether the process and rationale necessary for introducing the product of research and development to society are described sufficiently well.

In other words, the role of the peer reviewers is to see whether the facts necessary to be known to understand the process of introducing the research finding to society are written out; peer reviewers will judge the adequacy of the description of what readers want to know as reader representatives.

In ordinary academic journals, peer reviewers are anonymous for reasons of fairness and the process is kept secret. That is because fairness is considered important in maintaining the quality in established academic journals that describe factual knowledge. On the other hand, the format, content, manner of text, and criteria have not been established for papers that describe the knowledge of “what ought to be done.” Therefore, the peer review process for this journal will not be kept secret but will be open. Important discussions pertaining to the content of a paper, may arise in the process of exchanges with the peer reviewers and they will also be published. Moreover, the vision or desires of the author that cannot be included in the main text will be presented in the exchanges. The quality of the journal will be guaranteed by making the peer review process transparent and by disclosing the review process that leads to publication.

Disclosure of the peer review process is expected to indicate what points authors should focus upon when they contribute to this journal. The names of peer reviewers will be published since the papers are completed by the joint effort of the authors and reviewers in the establishment of the new paper format for *Synthesiology*.

References

As mentioned before, the description of individual elemental technology should be presented as citation of papers published in other academic journals. Also, for elemental technologies that are comprehensively combined, papers that describe advantages and disadvantages of each elemental technology can be used as references. After many papers are accumulated through this journal, authors are recommended to cite papers published in this journal that present similar procedure about the selection of elemental technologies and the introduction to society. This will contribute in establishing a general principle of methodology.

Types of articles published

Synthesiology should be composed of general overviews such as opening statements, research papers, and editorials. The Editorial Board, in principle, should commission overviews. Research papers are description of content and the process of research and development conducted by the researchers themselves, and will be published after the peer review process is complete. Editorials are expository articles for science and technology that aim to increase utilization by society, and can be any content that will be useful to readers of *Synthesiology*. Overviews and editorials will be examined by the Editorial Board as to whether their content is suitable for the journal. Entries of research papers and editorials are accepted from Japan and overseas. Manuscripts may be written in Japanese or English.

Required items and peer review criteria (January 2008)

	Item	Requirement	Peer Review Criteria
1	Research goal	Describe research goal (“product” or researcher’s vision).	Research goal is described clearly.
2	Relationship of research goal and the society	Describe relationship of research goal and the society, or its value for the society.	Relationship of research goal and the society is rationally described.
3	Scenario	Describe the scenario or hypothesis to achieve research goal with “scientific words”.	Scenario or hypothesis is rationally described.
4	Selection of elemental technology(ies)	Describe the elemental technology(ies) selected to achieve the research goal. Also describe why the particular elemental technology(ies) was/were selected.	Elemental technology(ies) is/are clearly described. Reason for selecting the elemental technology(ies) is rationally described.
5	Relationship and integration of elemental technologies	Describe how the selected elemental technologies are related to each other, and how the research goal was achieved by composing and integrating the elements, with “scientific words”.	Mutual relationship and integration of elemental technologies are rationally described with “scientific words”.
6	Evaluation of result and future development	Provide self-evaluation on the degree of achievement of research goal. Indicate future research development based on the presented research.	Degree of achievement of research goal and future research direction are objectively and rationally described.
7	Originality	Do not describe the same content published previously in other research papers.	There is no description of the same content published in other research papers.

Instructions for Authors

"Synthesiology" Editorial Board
Established December 26, 2007
Revised June 18, 2008
Revised October 24, 2008
Revised March 23, 2009
Revised August 5, 2010
Revised February 16, 2012
Revised April 17, 2013
Revised May 9, 2014

1 Types of articles submitted and their explanations

The articles of *Synthesiology* include the following types:
• Research papers, commentaries, roundtable talks, and readers' forums
Of these, the submitted manuscripts of research papers and commentaries undergo review processes before publication. The roundtable talks are organized, prepared, and published by the Editorial Board. The readers' forums carry writings submitted by the readers, and the articles are published after the Editorial Board reviews and approves. All articles must be written so they can be readily understood by the readers from diverse research fields and technological backgrounds. The explanations of the article types are as follows.

① Research papers
A research paper rationally describes the concept and the design of R&D (this is called the scenario), whose objective is to utilize the research results in society, as well as the processes and the research results, based on the author's experiences and analyses of the R&D that was actually conducted. Although the paper requires the author's originality for its scenario and the selection and integration of elemental technologies, whether the research result has been (or is being) already implemented in society at that time is not a requirement for the submission. The submitted manuscript is reviewed by several reviewers, and the author completes the final draft based on the discussions with the reviewers. Views may be exchanged between the reviewers and authors through direct contact (including telephone conversations, e-mails, and others), if the Editorial Board considers such exchange necessary.

② Commentaries
Commentaries describe the thoughts, statements, or trends and analyses on how to utilize or spread the results of R&D to society. Although the originality of the statements is not required, the commentaries should not be the same or similar to any articles published in the past. The submitted manuscripts will be reviewed by the Editorial Board. The authors will be contacted if corrections or revisions are necessary, and the authors complete the final draft based on the Board members' comments.

③ Roundtable talks
Roundtable talks are articles of the discussions or interviews that are organized by the Editorial Board. The manuscripts are written from the transcripts of statements and discussions of the roundtable participants. Supplementary comments may be added after the roundtable talks, if necessary.

④ Readers' forums
The readers' forums include the readers' comments or thoughts on the articles published in *Synthesiology*, or articles containing information useful to the readers in line with the intent of the journal. The forum articles may be in free format, with 1,200 Japanese characters or less. The Editorial Board will decide whether the articles will be published.

2 Qualification of contributors

There are no limitations regarding author affiliation or discipline as long as the content of the submitted article meets the editorial policy of *Synthesiology*, except authorship should be clearly stated. (It should be clearly stated that all authors have made essential contributions to the paper.)

3 Manuscripts

3.1 General
3.1.1 Articles may be submitted in Japanese or English.
Accepted articles will be published in *Synthesiology* (ISSN 1882-6229) in the language they were submitted. All articles will also be published in *Synthesiology - English edition* (ISSN 1883-0978). The English edition will be distributed throughout the world approximately four months after the original *Synthesiology* issue is published. Articles written in English will be published in English in both the original *Synthesiology* as well as the English edition. Authors who write articles for *Synthesiology* in Japanese will be asked to provide English translations for the English edition of the journal within 2 months after the original edition is published.
3.1.2 Research papers should comply with the structure and format stated below, and editorials should also comply with the same structure and format except subtitles and abstracts are unnecessary.

3.1.3 Research papers should only be original papers (new literary work).
3.1.4 Research papers should comply with various guidelines of research ethics

3.2 Structure

3.2.1 The manuscript should include a title (including subtitle), abstract, the name(s) of author(s), institution/contact, main text, and keywords (about 5 words).
3.2.2 Title, abstract, name of author(s), keywords, and institution/contact shall be provided in Japanese and English.
3.2.3 The manuscript shall be prepared using word processors or similar devices, and printed on A4-size portrait (vertical) sheets of paper. The length of the manuscript shall be, about 6 printed pages including figures, tables, and photographs.
3.2.4 Research papers and editorials shall have front covers and the category of the articles (research paper or editorial) shall be stated clearly on the cover sheets.
3.2.5 The title should be about 10-20 Japanese characters (5-10 English words), and readily understandable for a diverse readership background. Research papers shall have subtitles of about 15-25 Japanese characters (7-15 English words) to help recognition by specialists.
3.2.6 The abstract should include the thoughts behind the integration of technological elements and the reason for their selection as well as the scenario for utilizing the research results in society.
3.2.7 The abstract should be 300 Japanese characters or less (125 English words). The Japanese abstract may be omitted in the English edition.
3.2.8 The main text should be about 9,000 Japanese characters (3,400 English words).
3.2.9 The article submitted should be accompanied by profiles of all authors, of about 200 Japanese characters (75 English words) for each author. The essential contribution of each author to the paper should also be included. Confirm that all persons who have made essential contributions to the paper are included.
3.2.10 Discussion with reviewers regarding the research paper content shall be done openly with names of reviewers disclosed, and the Editorial Board will edit the highlights of the review process to about 3,000 Japanese characters (1,200 English words) or a maximum of 2 pages. The edited discussion will be attached to the main body of the paper as part of the article.
3.2.11 If there are reprinted figures, graphs or citations from other papers, prior permission for citation must be obtained and should be clearly stated in the paper, and the sources should be listed in the reference list. A copy of the permission should be sent to the Publishing Secretariat. All verbatim quotations should be placed in quotation marks or marked clearly within the paper.

3.3 Format

3.3.1 The headings for chapters should be 1, 2, 3…, for subchapters, 1.1, 1.2, 1.3…, for sections, 1.1.1, 1.1.2, 1.1.3, for subsections, 1.1.1.1, 1.1.1.2, 1.1.1.3.
3.3.2 The chapters, subchapters, and sections should be enumerated. There should be one line space before each paragraph.
3.3.3 Figures, tables, and photographs should be enumerated. They should each have a title and an explanation (about 20-40 Japanese characters or 10-20 English words), and their positions in the text should be clearly indicated.
3.3.4 For figures, image files (resolution 350 dpi or higher) should be submitted. In principle, the final print will be in black and white.
3.3.5 For photographs, image files (resolution 350 dpi or higher) should be submitted. In principle, the final print will be in black and white.
3.3.6 References should be listed in order of citation in the main text.

Journal – [No.] Author(s): Title of article, *Title of journal* (italic), Volume(Issue), Starting page-Ending page (Year of publication).

Book – [No.] Author(s): *Title of book* (italic), Starting page-Ending page, Publisher, Place of Publication (Year of publication).

4 Submission

One printed copy or electronic file (Word file) of manuscript with a checklist attached should be submitted to the following address:

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c/o Website and Publication Office, Public Relations Department, National Institute of Advanced Industrial Science and Technology(AIST)
Tsukuba Central 2 , 1-1-1 Umezono, Tsukuba 305-8568
E-mail: synthesiology-ml@aist.go.jp
The submitted article will not be returned.

5 Proofreading

Proofreading by author(s) of articles after typesetting is complete will be done once. In principle, only correction of printing errors are allowed in the proofreading stage.

6 Responsibility

The author(s) will be solely responsible for the content of the contributed article.

7 Copyright

The copyright of the articles published in "*Synthesiology*" and "*Synthesiology English edition*" shall belong to the National Institute of Advanced Industrial Science and Technology(AIST).

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Letter from the editor

The papers published in *Synthesiology* describe new synthesis methods for products and services that are put to good use in society by integrating individual elements of technologies and knowledge. Perhaps because I have a mind structure of a person from the science and engineering field, I tend to categorize papers under “experiment” that presents specific examples of synthesis, and “theory” that discusses and systematizes synthesis methods. Of the five papers published in this issue, “Practical use of an advanced sewage sludge incinerator, ‘turbocharged fluidized bed incinerator’” by Suzuki *et al.* describes the demonstration of a new incineration system that was developed to optimize the urban sludge treatment to save energy and prevent global warming. It presents a case study of introducing the new system to the local governments, and in this case, the focus is on “experiment.” Of course, the experiment conducted here is a field trial involving a local government. Similarly, “Social system for production and utilization of thermophysical property data” by Baba *et al.* is also a case of a field trial based on a typical synthetic methodology for metrology standards. On the other hand, “Towards large-capacity, energy-efficient, and sustainable communication networks” by Ishii *et al.* attempts to satisfy future demands for information communication by integrating elemental technologies including for a new high-speed optical switch, a sub-wavelength switch, and a combination array theory. The communication system for the entire country is optimized by projecting predicted types of demands. I see glimpses of the attempt to systematize the combination array and demand categorization in this framework, and this seems to provide a “theory.” In the paper “Open foundry to spur open-innovation” by Akinaga, methods for optimizing new values such as sustainable interdisciplinary integration and human resource mobility is presented through a field trial of open management of a foundry facility. “A novel material design method for on-demand material development” by Inada *et al.* describes a case study of a system to support material design using the database for synthesizing semiconductor materials from basic materials, and that itself is a discussion of a synthesis method in a microscopic sense. Moreover, the paper addresses the possibility of optimizing the value of risk supply reduction.

In discussing the synthesis method “theoretically,” it is important to set an evaluation index that may serve as a target of optimization. However, other than the indices for pressing issues such as energy savings, environmental pollution countermeasures, and achievement of high speed, synthesiology study must engage in activities to introduce the systems and products obtained from synthesis into society, and to discern new evaluation indices from the claims that arise as reactions of their customers to such introductions. In this meaning, I think there is increasing significance for accumulating results of field trials that are treasure troves of data for synthesiology. Therefore, it is important to clearly explain to the customers the significance of the trials when debuting a “product and service” to society as a fruit of technological development.

(Mitsuru TANAKA, Senior Editor)

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Messages from the editorial board

Research papers

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