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Synthesiology

English edition

Construction of a traceability matrix for high quality project management

Research and development of a monopivot centrifugal blood pump for clinical use

An analysis method for oxygen impurity in magnesium and its alloys

Analysis of synthetic approaches described in papers of the journal *Synthesiology*

Durable polymer electrolyte fuel cells (PEFC) for residential co-generation application

Synthesiology editorial board

2012

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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, it 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 be active.

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

Note 1 : The period was named "nightmare stage" by Hiroyuki Yoshikawa, President of AIST, and historical scientist Joseph Hatvany. The "valley of death" was 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

Construction of a traceability matrix for high quality project management

— A proposal of a basic theory toward a change from process-centric management to information-centric project management —

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[Translation from *Synthesiology*, Vol.5, No.1, p.1-15 (2012)]

Design information is important for software development projects because it determines their cost and product. In this research, a model has been made which can trace how information moves in a project by paying attention to the design information which is hard to trace by process-centric project management. On the basis of the model, a traceability matrix method has been constructed which quantifies the complexity of the traceability. It has been confirmed that high quality information-centric project management is realized by applying the model and the method to software development projects.

Keywords **:** Traceability matrix, complexity, quantitation, information centric, project management

1 Introduction

According to PMBOK,[1] "a project is an organic work conducted to create some original product, service, or artifact." To create original products and services, it is necessary to synthesize various elements such as technological and human resources. This means that the project itself is synthesis. Under the subject of synthesiology, various efforts have been made to conduct high quality project management and there have been several previous studies. Along with Visualizing Project Management[2] and PMBOK, SWEBOK[3] and Rational Unified Process[4][5] organize know-how into project management and development process methods, and address software development. Nevertheless, the success rates of projects have not improved, particularly in software development. For example, according to a report[6] by the Japan Users Association of Information Systems, the majority of projects on the scale of 500 person-months from 2004 to 2008 are over budget, and this is a trend observed every year. Frank[7] cites the report[8] by the Standish Group that states that "the present status with projects is that 68 % of them are failures," and questions the effectiveness of current management techniques. Specifically, the standards (such as ISO15288, IEEE1220, EIA632, CMMI, INCOSE Handbook, and PMBOK Guide) for project management and systems engineering are reviewed, and the fact that they are all process-centric is indicated. Frank also states, "The current project management technology and system engineering technology seek methodology for better management," and points out the limitations of the current process-centric management.

In the present study, the objective is the construction of methodology for realizing high quality project management. To achieve this object, the whole of the project, and its details, are analyzed to construct the methodology of "seeing both the forest and the trees." As the specific methodology, the architecture (or the organization of elements that compose the system and the relationships among elements) of the project is clarified. The quantitative management of the project is made possible by using the complexity of the project architecture as an index to gain an overview of the whole project, and by creating indices for the difficulty of individual elements and the relationships among the elements (Fig. 1). Finally, the methodology to realize high quality project management is considered by using the project model for which the architecture is shown.

2 Current state of project management and analysis of relevant issues

2.1 Difference between information and objects from the perspective of transfer cost

Information and objects have different properties from the perspective of transfer cost. Hereinafter, information is defined as knowledge and know-how that people have or that have been formalized as products or texts; and an object is defined as a physically tangible thing. In this way of thinking,

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work progresses when the person in charge finishes one task and hands the object over to the next worker, for example, in the case of an automobile factory where the object is assembled in steps. However, in a software development project, the main subject of transfer is information, which is different from objects in terms of transfer cost characteristics. The information transfer cost is defined as the total expense required to transfer information in a form that can be used by the information seeker (receiver).[9] To control the information transfer cost, the difficulty of transferring implicit knowledge, the difficulty of transfer due to different capabilities between the receiver and sender of information, and the difficulty of transferring high-volume information must be considered (Table 1).

It is difficult to maintain the accuracy and details of the information without the worker checking the original information transferred by the previous worker. Unlike objects, it is difficult to conduct information transfer by clearly segmenting the process as in object transfer, and there is the characteristic that the same process must be repeated several times to transfer information.

2.2 Necessity of shifting from process-centric to information-centric project management

In a software development project, the main work is the transfer of information rather than a physical object. To improve the production efficiency of an information-centric software development project, mere process-centric improvement is limited to pursuing a smooth workflow according to a set procedure. The issues that arise from the information transfer characteristics (the difficulty of transferring implicit knowledge, the difficulty of transfer due to different capabilities between the receiver and sender of information, and the difficulty of transferring high-volume information must be considered) will not be solved by a process-centric approach. Accordingly, a change from process- to information-centric is necessary

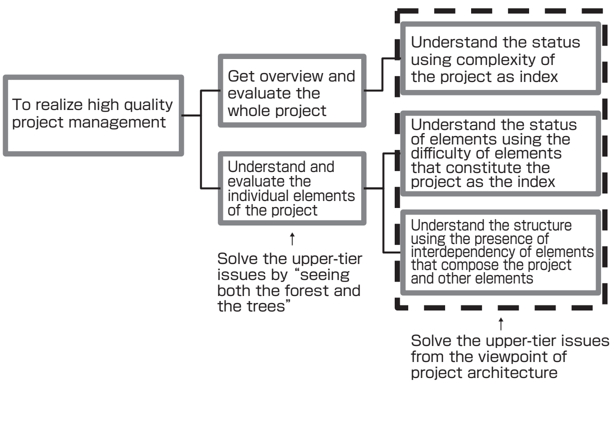


Fig. 1 Research aims

Table 1. Difference in the transfer cost of information and object

Determining factor of transfer cost	Information	Object
Characteristic of transfer subject	Large transfer cost is necessary due to implicitness of information (such as know-how).	Transfer cost does not depend on the characteristics of the object itself (instead, the cost depends on transfer conditions such as rate and volume).
Attributes of the sender and receiver	Information transfer cost varies according to the capabilities of the sender and receiver.	Not dependent on sender/receiver attributes (transfer is completed when it is handed over from the sender to receiver).
Amount to be transferred	Transfer cost increases because more information exchange becomes necessary as complexity and information volume increase.	Transfer cost increases as volume increases (even if the volume is high, it takes only one session to complete the transfer activity).

2.3 Characteristics of information: equivocality and information stickiness

The information transfer cost will be reconsidered from an information-centric perspective. Focus will be placed on the following two concepts pertaining to information. The relationships between the information transfer cost and the two concepts will be explained.

Information stickiness: the difficulty of information transfer[9]

Equivocality: the characteristic where the information may be given diverse meanings

Information stickiness is a term that describes the difficulty of transferring information from the sender to the receiver due to stickiness, a characteristic of information. Stickiness indicates that the element and its information are indivisible, and the information transfer cost arises due to this stickiness. There are three decisive factors of stickiness as shown in Table 1. When the sender and receiver of the information have a 1:1 relationship, the information transfer cost is governed by the information stickiness that arises from the three factors. For example, many companies work on formalizing implicit knowledge; this is done because the information stickiness of implicit knowledge is high and the information transfer cost, or the cost needed to teach the know-how of a worker to another within the company, is very high. It may be necessary to exchange the information several times to extract or to learn the information. It may be impossible, to begin with, to transfer information to other workers. As a result, it may become a barrier in raising the basic capacity of the company as a whole. Therefore, it is necessary to reduce the information transfer cost by reducing the number of information exchanges by formalizing the worker's knowledge (or making it visible).

On the other hand, information stickiness is insufficient to explain the information transfer cost in a 1:n relationship in an organization or a project. That is because if there are separate senders, the relationship with the receiver will be determined uniquely, and the information transfer cost can be calculated as the sum total of the information stickiness of the sender. However, if the sender is the same, the cost to modify the sender's information stickiness to individual receivers must be added. In other words, considerations must be made for the cost of preparation to change the destination of the information transfer from one receiver to another. To add this into the cost, the concept of equivocality is introduced.

Equivocality means that certain information may take on several meanings according to the receiver's perspective. For example, when information is transferred to one receiver, one piece of information may be given two meanings A and B. However, in the case where there are multiple receivers, the meaning may be not only A and B, but also C and D. As the number of information transfer destinations increases, the equivocality increases. Attempting to ensure that the multiple receivers arrive at the correct meaning, the sender of the information may add preliminary information that can be correctly understood by multiple receivers, for example, in instructional material, or the material may be rewritten to match the receiver. If the receiver is specified and the information transfer starts, this can be addressed as the issue of information stickiness. However, in the case where the receiver is not specified, or before the information transfer, it is necessary to consider the transfer cost of equivocality rather than information stickiness. As seen from above, the cost of equivocality arising from the 1:n relationship is dependent on the number of receivers. To control equivocality, it is necessary to reduce the number of receivers. Next, in the case of n:1, it is necessary to organize the thought by integrating the number n of transferred pieces of ambiguous information to provide one meaning. By maintaining a consistent meaning of n pieces of information, the information is integrated to have one meaning. The information transfer cost is expected to change since the integration work is dependent on n, and like 1:n, it is desirable that n be as small as possible.

Moreover, in a project conducted under limited budget and time, there may be cases where the activity is conducted before the information transfer is completed, due to the limitations of higher information transfer cost. To avoid such a situation, it is necessary to create and manage a condition where the transfer cost is minimized as much as possible within the project. Therefore, in an information-centric software development project, the management of information stickiness and equivocality is expected to promote accurate information transfer between the sender and receiver, and is important in realizing high quality project management.

3 Construction of the project architecture (traceability matrix)

In managing information stickiness and equivocality in an information-centric project, it is necessary to see what elements constitute the project and to organize the relationships of each element. For this purpose, a model will be constructed.

3.1 Concept of element extraction

The elements are extracted by object-oriented business modeling. According to requirements engineering,[10] which incorporates the concept of object orientation, needs,[Term 1] feature,[Term 2] and requirement[Term 3] elements are extracted to constitute the system called a project. The needs are related to features, and features are related to requirements. Function[Term 4] and component[Term 5] elements are extracted according to "all things have functions."[11] The components are related to functions. From process flow, artifact,[Term 6] activity,[Term 7] and team[Term 8] elements are extracted. Teams are related to activities, and activities are related to artifacts.

3.2 Concept for organizing relationships among elements and examples of relationships

In defining the architecture for a whole system called a project, focus is placed on two concepts: "axiomatic design"[12][13] of mechanical engineering, and "business architecture"[14][15] of organization science. In designing the organizational activity, enterprise architecture (EA) may be similar, but the EA method does not indicate the reference architecture.[Term 9 [16]] Therefore, it is necessary to define the elements that compose the system and their relationships. These two concepts have the major characteristics that they consider the manufacturing process and the organization involved in manufacturing as well as the customer requirement of what should be manufactured in the first place, and provide a guideline for the relationships among the elements.

The thinking of axiomatic design is the concept that the information is mapped between the domain of customer, functional, physical, and process, and the design activity takes place. It is the thinking where, for example, the information for requirements in the customer domain that concerns design is mapped as the specification of the function in the functional domain, to realize the function. Likely, the same information is mapped in each domain, and then it is translated and processed in the optimal form in each domain. The mapping of that information is thought to occur interactively. When the elements extracted in subchapter 3.1 are applied to this concept, it is as follows. Since the customer domain designates the customer's requirements, it is composed of needs, feature, and requirement elements. The functional domain is composed of function elements as stated above. The physical domain designates the design solution or the product itself, and therefore it is composed of component or physical elements. Since the process domain designates the production conditions, it is composed of artifact, activity, and team elements. This designates the architecture of the organization system called the development project, and the elements of the development project and their relationships are clarified.

3.3 Concept for realizing information transfer tracing

Figure 2 shows the organization of relationships of the elements that are analyzed and extracted by object orientation, based on the theories of axiomatic design.

To understand the condition, first the needs are understood and then organized as features (these two items are eliminated for simplification in Fig. 2), and are then defined as requirements. The component with implemented function to fulfill the requirement is necessary, and to create the component, there must be an artifact that is a summary of the design content. The development activity to create the artifact is executed by each team.

The transfer of information mapped in the software development project includes, for example, the following case. When realizing the function for “checking the number of input characters when the user ID (UID) and password (PW) are entered,” how and where the function is implemented must be designed. For example, let us consider the following two structures: (1) the character number check is implemented as separate built-in functions within the UID and PW systems, and (2) the character number check is implemented as a standalone function that can be shared by the UID and PW systems. The component design will differ accordingly. If the shared character check function is employed, its development cannot be started until both the UID system and the PW system are established. However, when implemented as a built-in function within those individual systems, the design can be started when one of the ID systems is established. Therefore, the function, component, and activity elements translate, transfer, and influence the design information into a necessary form, and the cost of information transfer affects the quality of the project.

Next, the information transfer cost is considered. The left side of Fig. 2 shows the linear interdependency of each element, and the right side shows the mesh structure. With the mesh structure, multiple elements and information are exchanged; thus, it is thought that more information transfer cost will be needed, as explained in the example of equivocality. Also, on the right side of Fig. 2, for the element activity, the information transfer cost increases because information stickiness increases as difficulty increases. When using the original notation to summarize the content of the design, there may be some content that cannot be expressed as design information. As a result, design information may be lost and design mistakes may be induced. This is a case where high transfer cost is generated due to the factor, or the original notation, that makes the information transfer difficult. Therefore, in terms of the relationships

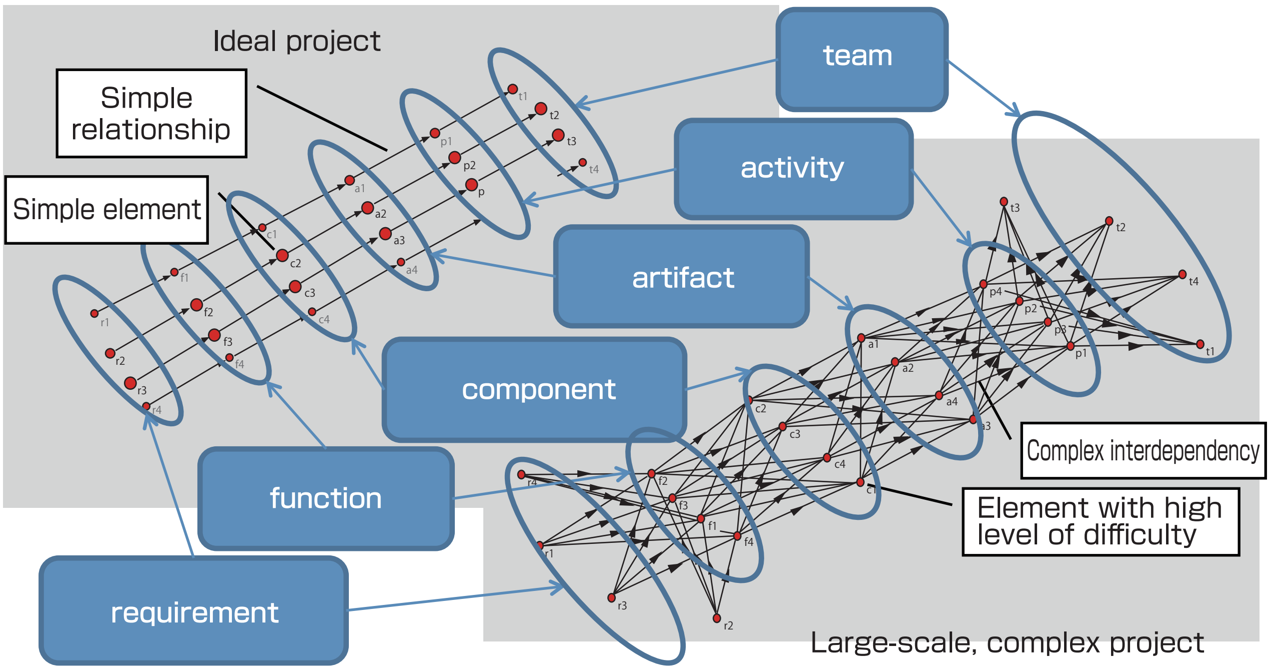


Fig. 2 Network model of an ideal project and large-scale, complex project

among elements, to reduce the information transfer cost, it is necessary to maintain independence as much as possible, or more specifically, to approximate the diagonal matrix with the highest independence when organizing the relationship between two elements using the matrix, and to reduce the difficulty (the concept that designates the difficulty of the aforementioned activity; details are explained later) of the element itself. In other words, to reduce the information transfer cost and to transfer the information accurately in the project architecture, it is necessary to control information stickiness and equivocality by using the interdependency between the elements and the difficulty of the element itself.

3.4 Project architecture

Figure 3 shows, as basic concepts, the relationship expressed as a matrix in Fig. 2.

This relationship agrees with the following matrix calculation (Equation 1) when the vector is used.

$$\begin{pmatrix} r1 \\ r2 \\ r3 \\ r4 \end{pmatrix} = \begin{pmatrix} \text{Requirement-} \\ \text{Function} \end{pmatrix} \times \begin{pmatrix} \text{Function-} \\ \text{Component} \end{pmatrix} \times \begin{pmatrix} \text{Component-} \\ \text{Artifact} \end{pmatrix} \times \begin{pmatrix} \text{Artifact-} \\ \text{Activity} \end{pmatrix} \times \begin{pmatrix} \text{Activity-} \\ \text{Team} \end{pmatrix} \times \begin{pmatrix} t1 \\ t2 \\ t3 \\ t4 \end{pmatrix}$$

$$\vec{r} = A\vec{t} \quad \cdots\cdots \text{(Equation1)}$$

$\vec{r}$: requirement vector $\quad$ $\vec{t}$: team vector

A : system matrix

In this study, the traceability matrix obtained as a result will be called the system matrix as it designates the properties of the whole system. By multiplying the matrix, the traceability matrix (system matrix) that clarifies the relationship between the team and the requirement can be obtained

4 Index for seeing both the forest and the trees

To promote accurate information transfer among elements and to realize high quality project management, it is necessary to manage information stickiness and equivocality as mentioned earlier. To manage equivocality, it is necessary to control the relationships among elements between and within the team, activity, artifact, and other regions (i.e., to control "interdependency," hereinafter). This is because the probability of error in information transfer increases along with the number of related elements. This also means that equivocality increases with increasing interdependency. When the cost of equivocality is forcefully decreased, the possibility that multiple receivers attach the wrong meaning to a piece of information increases. In addition, to manage information stickiness, it is necessary to control the factors that inhibit accurate information transfer of the element itself (i.e., to control the "difficulty," hereinafter). Depending on the property of the element itself, the essential information that must be understood is not conveyed when transferring the information, and the possibility of error in information transfer increases. This means that information stickiness increases as difficulty increases, and the transfer may be finished before the necessary information is absorbed.

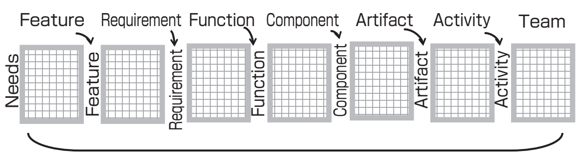


Fig. 3 Traceability matrix of project

From the above, the accuracy of information transfer is determined by interdependency and difficulty. Overall, the possibility that information is transferred accurately within the whole project is determined by the sum of the probabilities of (1) accurate information transfer by controlling interdependency and (2) accurate information transfer by decreasing the difficulty. Therefore, for the whole project, it is necessary to define the sum of the interdependency and difficulty as the complexity, and to use complexity as the control index.

4.1 Quantification of interdependency

The overall perspective improves as it nears the diagonal matrix. Moreover, equivocality decreases from the perspective of information transfer. Therefore, to evaluate the interdependency among the elements that may be factors of equivocality, the distance between the system matrix and the unit matrix can be measured. In comparing the unit matrix, it is necessary that the increasing equivocality be expressed as the increasing value of the non-diagonal component. Therefore, the linear Euclidean norm is used to measure the distance. The unit matrix is subtracted from the system matrix to be evaluated, and the Euclidean norm of that matrix will be the interdependency. However, the component value of the system matrix with respect to interdependency will be set as 1 when there are relationships among elements, and 0 when there are none. This will be called system matrix **s** hereafter.

4.2 Quantification of difficulty

The difficulty of the elements from their information stickiness will be expressed by the component values of the system matrix; the system matrix that has difficulty as the component value will be called system matrix **n**. The quantification of difficulty is made possible by evaluating the magnitude of the entire system matrix **n**. Therefore, the evaluation will be done according to how many times the matrix is greater than the unit matrix, or the Euclidean norm of system matrix **n**. However, the component value of system matrix **n** with respect to difficulty is determined by evaluating the difficulty of the elements (guideline for difficulty setting: Reference Material 1). The standard value is 1, and the value becomes greater than 1 at higher difficulty, or less than 1 at lower difficulty.

4.3 Definition of complexity

The complexity of information transfer is defined as follows:

Complexity = difficulty × interdependency

However, difficulty is given by the Euclidean norm of system matrix **n**, and interdependency is given by the Euclidean norm of system matrix **s** minus the unit matrix (sample calculations: Reference Material 2).

The difficulty and interdependency are variables that reflect the situation of the individual elements and relationships among elements of the project. Therefore, by understanding their indices, it is possible to understand the elements of the matrix and the relationships among them. At the same time, the whole project can be understood via the changes in complexity obtained by multiplying indices.

4.4 Obtaining a square matrix

The relationships among the elements are not necessarily in a square matrix. In such a case, it is necessary to form the square matrix for the diagonalization that is necessary for the calculation of interdependency. To form the square matrix, the component value 0 is given. Since the component value is 0, the interdependency value changes as much as the degree added to the square matrix formation (this is because the diagonal component is subtracted for the row or column added by the square matrix formation, and the additional diagonal component becomes -1). However, considering that complete independence is expressed by the square matrix called the unit matrix, the change in the interdependency value by adding the component value 0 in the non-square matrix must be understood as the index that indicates the independence of the non-square matrix. From the above, the square matrix formation by adding the component value 0 is set as the rule.

5 PDCA cycle of project management using the traceability matrix

This chapter explains the methodology for understanding the whole of a project, and its details, and for “seeing both the forest and the trees.” For explanation, the PDCA (plan → do → check → act) cycle will be used as the scenario (Fig. 4).

First, to create the traceability matrix, specific elements are organized and the matrix is created. The complexity of the project as a whole is reduced by improving the difficulty and interdependency in the created traceability matrix. The actual development activity is conducted in the project, and the progress is checked. The complexity of the project is used as the index of progress, and an overview of the state of the project is gained by looking at the change. If the change of complexity is on an increasing trend, it is because some problems have developed in the project, and the causative element is sought. The difficulty and interdependency of the elements are changed by simulation, and the element that

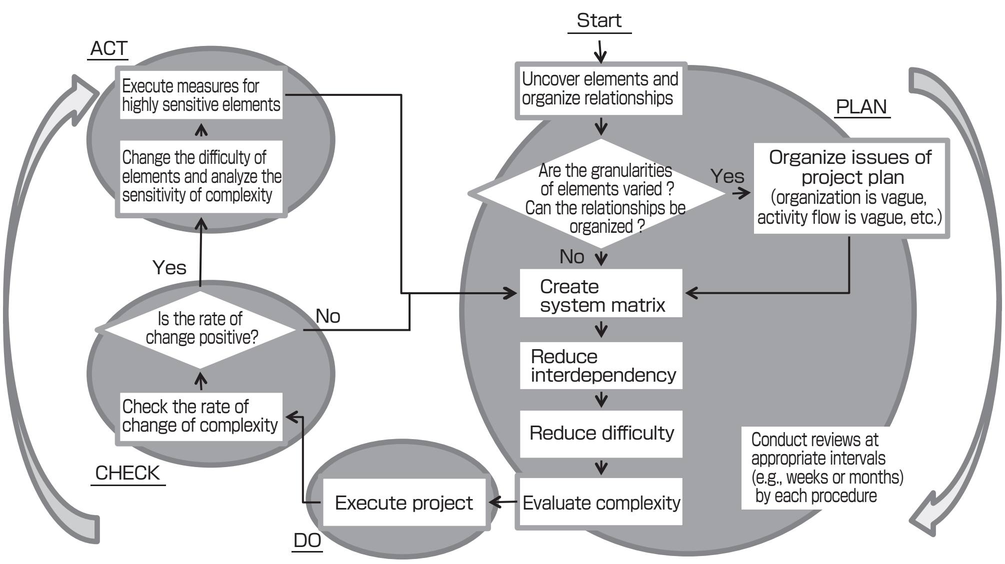


Fig. 4 PDCA cycle of project management

is most effective for reducing the complexity of the whole project is found in order to improve the project status. What follows is an explanation following the PDCA cycle.

5.1 PLAN

5.1.1 Uncovering the element and organizing the relationships

The analysis of the project status is conducted as shown in Fig. 4, the elements needed for the creation of system matrix are uncovered, and their relationships are organized. However, it can be expected that the system matrix cannot be created because the granularity of the elements may vary or the relationships are unknown. In that case, it can be assumed that there is some sort of problem in the project plan itself, and the solution is sought.

5.1.2 Organize the issues of the project plan

For example, if there is a team where the organization is loose and capable of being described in large granularity only, it is necessary to reorganize such a team. In another example, when elements are uncovered in the upstream process, the component and function may not be clear in the downstream process. In such a case, it is necessary to check the basis of the estimate. There must have been some basis when making the estimate, and if the basis is unclear, it is necessary to review the plan quickly, as an issue in establishing the project plan.

The above points are organized, and system matrix **s** and system matrix **n** are created.

5.1.3 Reduction of the interdependency and difficulty of individual matrices and the evaluation of complexity

Improvements are done to diagonalize the individual matrices. However, there may be cases where the difficulty of an element increases as a result. Moreover, there may be cases where the difficulty of the elements of the non-diagonalized matrices may increase. Therefore, it is always necessary to check the degree of influence on the whole project by calculating the complexity, to maintain the overview of the project.

As shown in Fig. 3, the system matrix that shows the project structure is calculated by the multiplication of seven matrices. Due to the properties of matrix multiplication, the solution of the calculation for the full matrix or one that contains a triangular matrix will always be the full matrix or the triangular matrix. To obtain the diagonal matrix as a solution, it is necessary to make each matrix into a diagonal matrix.

In step 1, the relationships of each of the seven matrices that constitute system matrix **s** are organized, and the interdependency is reduced by approximating the diagonal matrix. In step 2, the difficulty of the matrix is reduced by reducing the relationship with highest component value among the relationships organized in the matrices that compose system matrix **n**, or the relationships with high degree of difficulty. The complexity (= interdependency × difficulty) of the whole system matrix is reduced by the above technique.

However, in a real project, it is difficult to diagonalize all seven matrices of system matrix **s**. Therefore, the design of the project is improved (reduction of interdependency) by, for example, forming the triangular matrix for each matrix. The relationships among the elements are more simply by, for example, introducing some development tool, in order to reduce the component value of system matrix **n** (reduction of difficulty). There is also a plan to reduce the complexity of the whole project. As an alternative plan for effective improvement, the full matrix is concentrated into one or two matrices of the seven matrices of system matrix **s**, the remaining five or six matrices are diagonalized, and thereby the component value of system matrix **n** is made as low as possible. In this way of thinking, while some parts of the full matrix may have high complexity, by reducing the complexity of the diagonalized area, the complexity of the whole is reduced. However, since some cases may not necessarily be effective for decreasing the complexity, it is necessary to conduct a comparative review by simulation at the design stage of the project.

For example, in planning scratch development[Term 10] where software is all made by hand, the case of using the tool to automatically generate the source code (hereinafter, called "generator") or the case of using the package software (hereinafter, called "PKG") are considered to reduce the complexity. The flow of this review will be explained (Fig. 5). The relationship of the whole elements when scratch development is done is shown in Reference Material 3. The elements that are considered particularly important are extracted in Fig. 6. The figure deals with only the screen

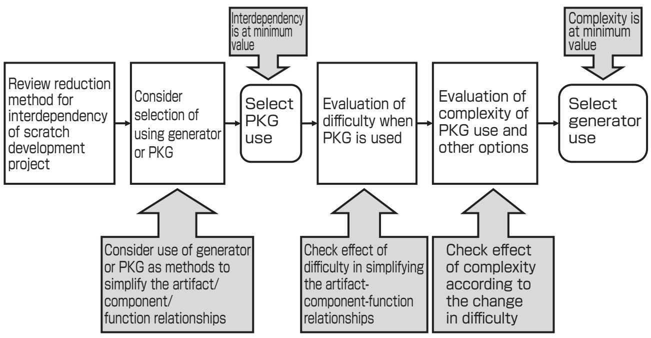


Fig. 5 Evaluation flow of complexity considering the interdependency and difficulty

Table 2. Team-activity matrix

		Team				
		Requirement management team	Architecture design team	Detailed design team	Implementation team	Test team
Activity	Screen design	2.25	2.25	2.25	2.25	2.25
	Work logic design	1.5	2.25	1.5	1.5	1.5
	DB design	1.5	2.25	1	1	1

Table 3. Final evaluation of each plan

	Interdependency	Difficulty	Complexity
Scratch development	77.79	78.18	6081.42
Generator	64.40	64.75	4169.44
PKG (low skill level)	57.16	104.89	5995.12

transition (the presentation layer of the so called three-layer model). The activity elements are the screen design; artifact elements are the screen specification and screen transition diagram, and their source code; components include the login screen and menu screen; and functions include the UID input function and PW input function.

Since there are many elements with high interdependency, improvement is attempted. Since the PKG includes all of the functions within the product, the designer and programmer do not think about the individual components or functions, and therefore, the component is the screen control PKG and the function is the screen control function only (Fig. 7).

For the generator, the structure of the components and functions is the same as in the case of scratch. Since the source code is generated automatically from the design diagram, the designer and programmer do not have to think about the source code. Therefore, the difference from scratch in terms of element is the presence of the source code (Fig. 8).

When the above three types are compared and evaluated, it is thought appropriate to select the PKG, which has the lowest interdependency. However, the effect of peripheral elements when such a selection is made is reconsidered. This means that according to the level of proficiency in the PKG, the difficulty of some other elements may increase. The component value of each system matrix **n** is set to a standard value of 1, but as the proficiency of this PKG is considered, the component values are set as in Table 2 (the component value of other matrices such as relationships of function and component remain 1). In Table 2, difficulty levels (1

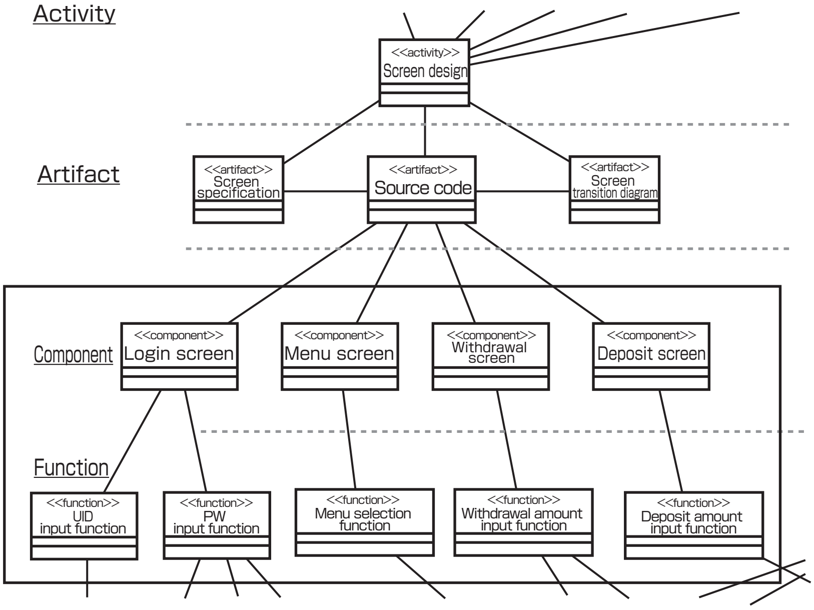


Fig. 6 Network model of scratch development (for screen transition only)

or 1.5) are assigned to each team and activity element, and the component value of the matrix is set by multiplying the difficulty of the row and column.

As a result, it is found that a difficulty level of 104.89 is obtained for the whole project (Table 3). This is greater than the value of 78.18 in scratch development, and is also greater than the difficulty level of 64.75 when the generator is used as an alternative plan.

Based on the above data, the complexities of the project when PKG, generator, and scratch are used are reevaluated. The results are shown in Table 3, and the conclusion is that the use of the generator is optimal.

5.2 DO

The project is executed as planned, and the development is carried out. For example, in the aforementioned case, the development is conducted using the generator.

5.3 CHECK

Up to the previous subchapter, the comparison of multiple projects is discussed, but in this subchapter, the discussion will be focused on one project and on its changes over time.

The complexity decreases as development progresses. This is because the interdependency disappears between elements where information transfer has been completed, and ultimately the value of matrix elements that initially showed interdependency will reach 0. At the same time, the difficulty decreases with the change in progress over time, owing to the effect of proficiency. However, the complexity does not necessary become an elemental value of 0. For example, it is normally difficult to understand all the specifications of the package software and to become proficient in skills that allow dealing with any kind of situation within the limited development period. However, the interdependency becomes 0 when the information transfer is completed. Therefore, by setting the system matrix that expresses difficulty as Sn and the order of the system matrix as N, in the matrix component

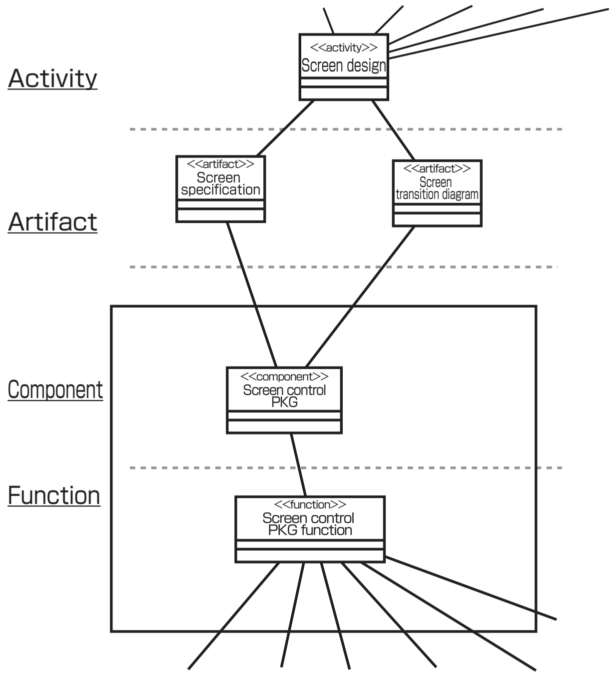


Fig. 7 Network model of PKG development (for screen transition only)

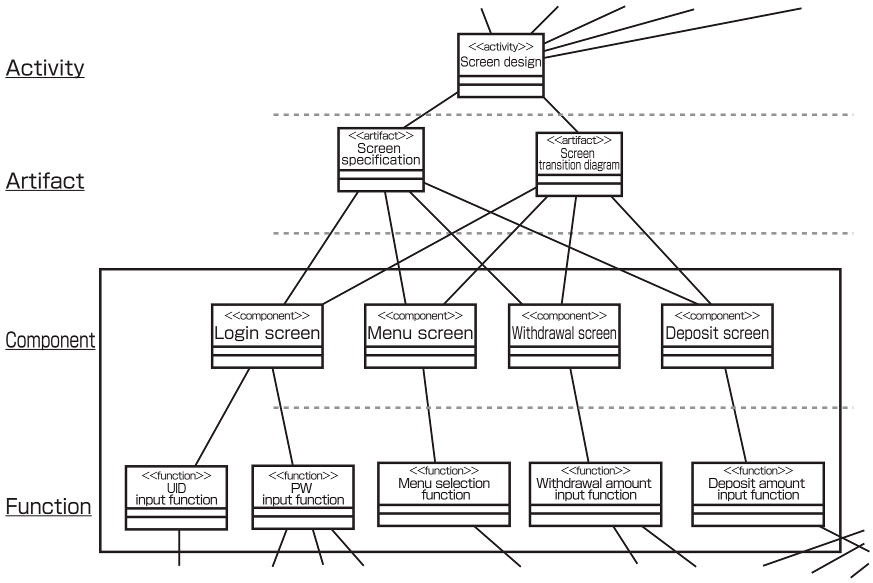


Fig. 8 Network model of generator development (for screen transition only)

where the unit matrix is subtracted from system matrix **s**, all diagonal components will be -1. Therefore, the norm will be $\sqrt{N}$, and the complexity will converge to the following value (Equation 2).

$$\text{Complexity} = \sqrt{N} \times \|Sn\| \quad \cdots \text{(Equation2)}$$

A system matrix that is perfectly diagonalized is considered a singularity, and is not subject to Equation 2. A perfectly diagonalized system matrix is an ideal project according to Fig. 2, and is not a subject of discussion in regard to complexity.

Therefore, two perspectives can be considered as ways to manage the progress status of the whole project.

One perspective is gaining an overview of the whole project (seeing the forest), and progress is monitored by using the complexity as the managing index. If the complexity is decreasing, it shows that the development is progressing smoothly, whereas if the complexity is increasing, it shows that some problem may be occurring in the project (Fig. 9).

The other perspective is managing the individual elements of the project (seeing the trees), and progress is monitored by using interdependency as the managing index. For example, the element allotted to each team is determined, and the interdependency of the elements is managed. One proposal is to use the number of interdependencies and the rate of change as indices of progress.

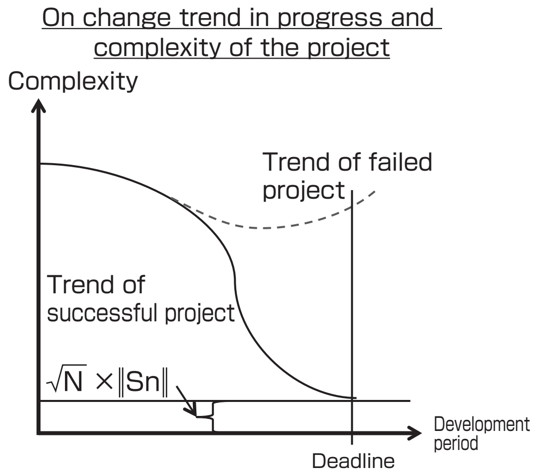


Fig. 9 Successive change of complexity and project status

5.4 ACT

From the perspective "seeing the trees" of the project, if there is a positive rate of change in complexity, an overview of the problems is gained from the model and the issues are uncovered. If the problem can be solved directly and the difficulty and interdependency can be reduced, measures are implemented. If the measures cannot be taken directly, simulation is done for other elements and a sensitivity analysis is done (Fig. 10). In this example, it can be seen that element a is more effective for reducing the complexity than element b.

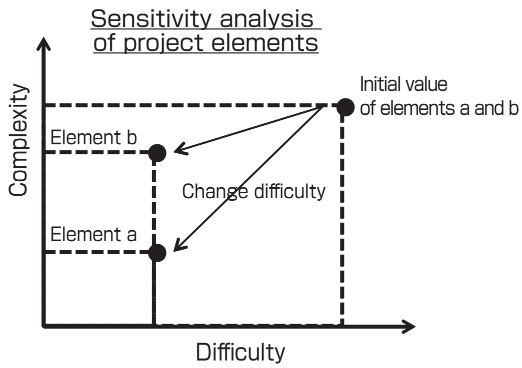


Fig. 10 Example of sensitivity analysis for project complexity

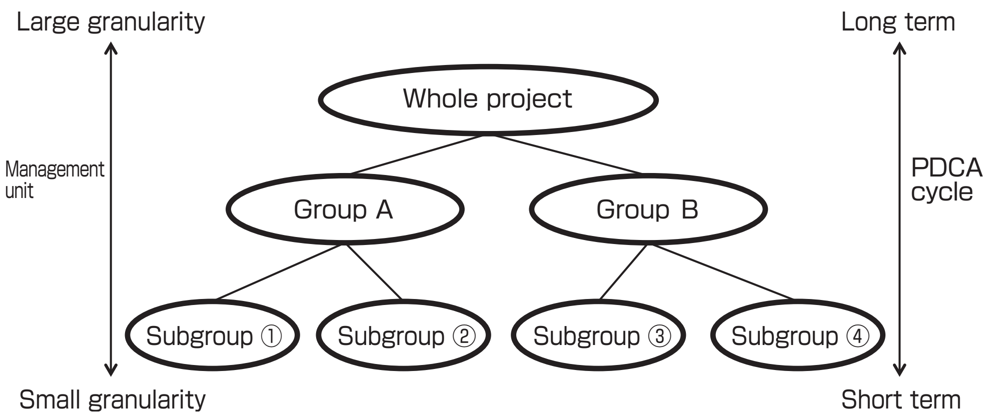


Fig. 11 Management unit and frequency

The element effective for reducing the complexity is uncovered through the reduction of difficulty of the element, and the elements to be dealt with are narrowed down. When the element is determined, necessary measures are implemented to reduce the difficulty of that element.

5.5 Notes in executing the PDCA cycle

From the perspective of project management operations, the following points must be taken into account when executing the PDCA cycle.

First, it is necessary to review the granularity of the elements that constitute the matrix and the management unit of the system matrix. One must determine whether to create the system matrix to gain an overview of the whole project, or to create the system matrix with groups and subgroups within the matrix. If the elements are too detailed, management operations will be overwhelmed by the maintenance and management of the matrix, and proper management will be impossible. Next, it is necessary to consider iterations of the PDCA cycle. In regard to the above, as the management unit of system matrix or the granularity of elements increases, the cycle should be longer. If the granularity is low, the cycle should be short (Fig. 11).

Specifically, the management unit of the system matrix should be set so that the number of elements will be 10 to 20 for each regional unit such as team, activity, or artifact. For a greater number of elements, the understanding of the current project status will be more difficult when using the system matrix and the network model, and improvements will be difficult to implement. To keep the number of elements to 10 or 20 in each region, it is necessary to limit the number of PDCA cycles as well as the management unit of the matrix. For example, when the elements for the total development process are uncovered at the subgroup level, the number will be great and will be far more than 10 to 20. From this perspective, it is necessary to limit the number of cycles.

Information-centric project management can be executed by considering the above points.

6 Conclusion

A traceability matrix was constructed as a framework for managing a software development project. For the scenario of the PDCA cycle of management in an information-centric software development project, the method using the traceability matrix was explained. Also, it was explained that this method enables gaining an overview of the project and understanding its detailed status as a whole. Furthermore, this method was shown to be an information management method for realizing high quality project management.

Acknowledgement

This research was conducted as part of the Global COE Program “Center for Symbiotic, Safe and Secure System Design” of the Ministry of Education, Culture, Sports, Science and Technology. The authors thank Professor Ryuichi Teshima and Project Professor Toshiyuki Yasui of the Keio University Graduate School for discussions of this research.

Reference materials

Reference Material 1: Guideline for setting the difficulty

◆ Setting the standard of difficulty of the element as 1, ranking is provided according to the following indices.

No.	Element to be surveyed	Subject of measurement	Measurement index (example)	Difficulty ranking policy
1	Team	Skill of each team or personnel	Years of experience, proficiency level (skill) Role (leader? assistant? etc.)	Highly skilled team → Low difficulty
2	Activity	Importance of each activity	Is this activity a critical point? (Is it supplementary activity?) Is it standard activity?	Important activity → High-difficulty standard activity → Low difficulty
3	Artifact	Importance of each artifact	Is special technology needed in creating the artifact? (Is it necessary to learn special language, etc.?) Is it frequently referenced while conducting other activities? (assumed that important artifact will be referenced many times) Is the number of pages or lines greater for the measured artifact than the others? Reusability (Is the artifact reused from another project?), or expandability of base by prototyping, etc.	Important artifact → High difficulty (special technology necessary → high difficulty, high referencing → high difficulty, amount of artifact→ high difficulty, high reusability → low difficulty)
4	Component	Importance of each component (basic function, frequency of use, etc.)	Is the component essential to realize a high-priority requirement? Is the component frequently used to realize the requirement? (assumed that major component will have high number of interfaces with other components) Reusability (Is it a reuse of artifact from another project?), or expandability of base by prototyping, etc.	Important component → High difficulty (high priority → high difficulty, used many times → high difficulty, high reusability → low difficulty)
5	Function	Importance of each function (basic function, frequency of use, etc.)	IIs the function essential to realize a high-priority requirement? Is the function frequently used to realize the requirement? (assumed that operation frequency of major function will be high) Reusability (Is it a reuse of artifact from another project?), or expandability of base by prototyping, etc.	Important function → High difficulty (high priority → high difficulty, used many times → high difficulty, high reusability → low difficulty)
6	Requirement Feature Needs	Importance and priority of requirement	High or low priority of requirement to be realized	High-priority requirement, feature, and needs → High difficulty

• In setting the ranking, the following should be noted.
The standard is set as 1, and it is necessary to assign values from 0.1 to 1.9 by dividing by the number of elements to be surveyed within the same category. For example, if there are 10 elements but there are only three difficulty values, the difference of the difficulty level of the ten elements will be rounded off when the values are assigned, and as a result, the difference will be hard to see. Of course, there is no problem in setting the difficulty in three steps, if it is determined that the difficulty levels are truly the same. The figures are set from 0.1 to 1.9 because the upper and lower limits are set within the same range when 1 is set as the standard.

Reference Material 2: Example of complexity calculation

(r1, r2) is the vector that indicates the requirements, while (t1, t2) is the vector that indicates the teams.
The complexity of the development project expressed by this system matrix is calculated. For interdependency, the component value of the matrix is set to either 0 or 1 according to the presence of the relationship (system matrix **s**). For difficulty, the figures are set according to the difficulty level of each element to determine the matrix component value (system matrix **n**). The complexity of the whole development project is calculated by multiplying the interdependency by the difficulty, and the result is as follows.

$$\begin{pmatrix} r1 \\ r2 \end{pmatrix} = \begin{pmatrix} \text{Requirement-} \\ \text{Function} \end{pmatrix} \times \begin{pmatrix} \text{Function-} \\ \text{Component} \end{pmatrix} \times \begin{pmatrix} \text{Component-} \\ \text{Artifact} \end{pmatrix} \times \begin{pmatrix} \text{Artifact-} \\ \text{Activity} \end{pmatrix} \times \begin{pmatrix} \text{Activity-} \\ \text{Team} \end{pmatrix} \times \begin{pmatrix} t1 \\ t2 \end{pmatrix}$$

$$= \begin{pmatrix} 1/2 & 1 \\ 1 & 1/2 \end{pmatrix} \times \begin{pmatrix} t1 \\ t2 \end{pmatrix}$$

$$\text{Difficulty} = \| \text{system matrix } \mathbf{n} \|$$

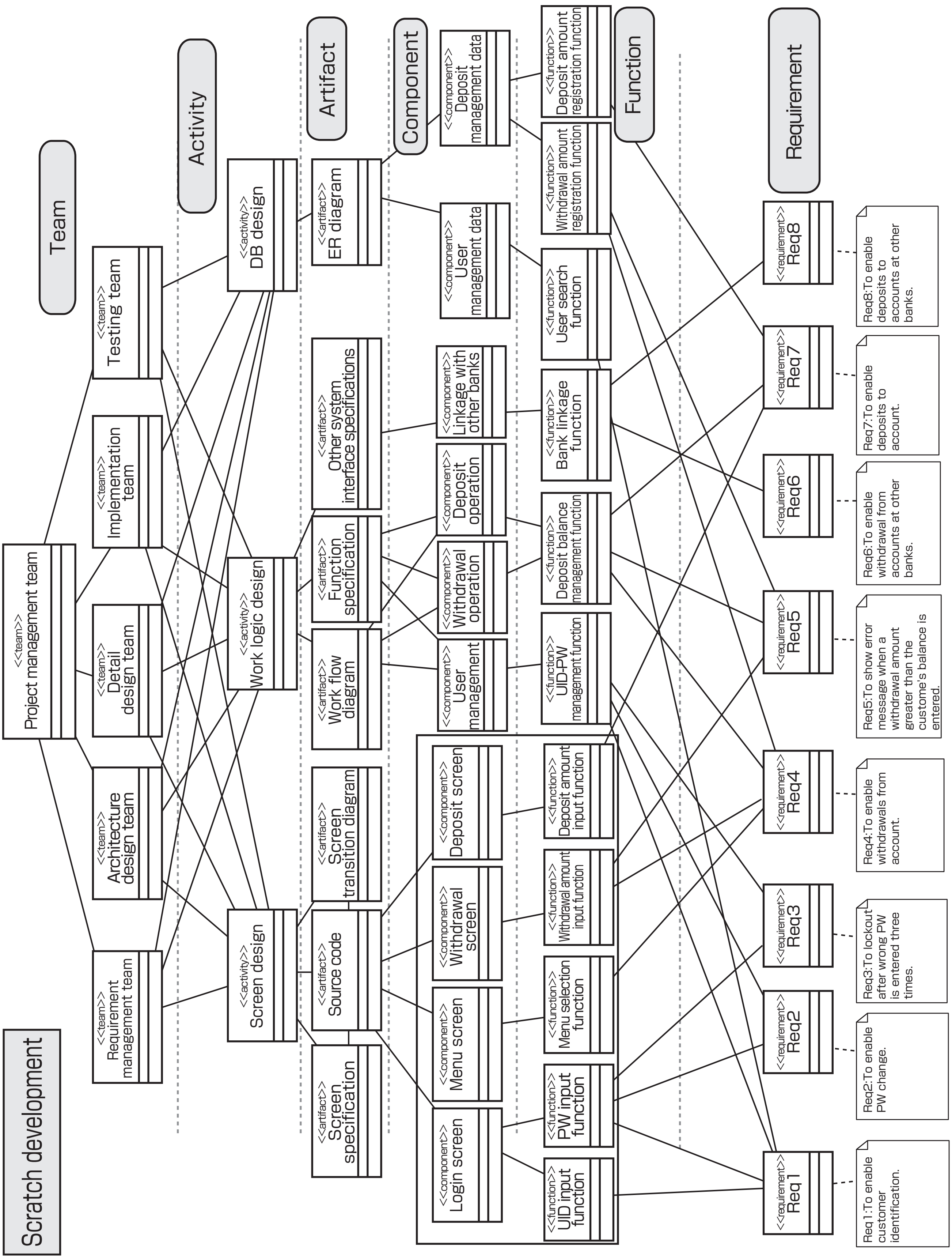
$$= \left\| \begin{pmatrix} 1/2 & 1 \\ 1 & 1/2 \end{pmatrix} \right\| = \sqrt{5/2}$$

$$\text{Interdependency} = \| \text{system matrix } \mathbf{s} - \text{Unit matrix} \|$$

$$= \left\| \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix} - \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \right\| = \left\| \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \right\| = \sqrt{2}$$

$$\text{Complexity} = \sqrt{5/2} \times \sqrt{2} = \sqrt{5}$$

Reference Material 3: Network model of scratch development project



Terminology

Term 1. Needs expressed, for example, as "we want x."
Term 2. Feature: expressed, for example, as "system is to realize x."
Term 3. Requirement: expressed, for example, as "x is done by the system, and y is output."
Term 4. Function: indicates the roles of the substance or component in realizing the requirement.
Term 5. Component: has implemented artifact and has function.
Term 6. Artifact: produced by activity; for example, a design plan.
Term 7. Activity: indicates work done by the team, produces artifact.
Term 8. Team: individual or group assigned to various roles within the organization.
Term 9. Reference architecture: architecture created especially for a certain region, and used as reference in conducting the system design for that region.
Term 10. Scratch development: development in which the developer implements everything

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Discussion with Reviewers

1 The paper as a practice of synthesiology

Comment (Motoyuki Akamatsu, Human Technology Research Institute, AIST)

I understood this paper as a proposal for a traceable modeling method of how the design information for software is communicated or how the information travels in an organization. It shows how quantitative evaluation can be done for the level of complexity of a project, using this method.

To create software quickly and accurately, it is important to design a project eliminating complexity, and in that sense, this is a paper related to synthesiology. However, it focuses on the explanation of the method for traceability matrix to evaluate the information communication efficiency. Although it is shown that the matrix can be used as a comparative tool of complexity, there is no example given where it is used directly, for pointing out the relevance to synthesis. Please add this point.

Comment (Hideyuki Nakashima, Future University Hakodate)

Please indicate specifically how the method proposed here is useful in synthesis.

Answer (Akihiro Sakaedani)

The point is explained in “5.1.3 Reduction of the interdependency and difficulty of individual matrix and the evaluation of complexity.” I explained how the individual matrix of the traceability matrix should be based on the properties of matrix calculation, and used specific examples to describe how to create the best synthesis using interdependency and difficulty.

2 Utilization of this method in management

Comment (Motoyuki Akamatsu)

I can intuitively understand that the management becomes difficult as the complexity of the organization increases. However that is a hypothesis only, and I think you should describe how much management would become easier if this method is used. Since the specific management method is an important point in synthesiology, please indicate specifically how management will become easier by using this method, and how management should be done based on the indices obtained in this method.

Answer (Akihiro Sakaedani)

I described the PDCA cycle of management using the traceability matrix in “5. PDCA cycle of project management using the traceability matrix.” An explanation is added from the perspective of evaluating the project status using complexity as the index, and from the perspective of evaluating the status of individual elements by focusing on the difficulty and interdependency.

3 PDCA cycle

Question (Motoyuki Akamatsu)

You write about the method of turning the PDCA cycle using the traceability matrix, but I imagine that calculating the complexity by rewriting the relationships and difficulties on the system matrix while turning the cycle is a rather troublesome task. I don’t think it is easy to see where the element of a certain region is used in another region, or how to determine the magnitude of the difficulty value. I think you need some maneuvering to turn the PDCA in a realistic manner. Can you please present your thoughts on this point?

Answer (Akihiro Sakaedani)

I added the point you indicated. An explanation is given of reviewing the unit of management and selecting the appropriate granularity of the elements, and of setting the PDCA cycle that matches the granularity. Below, I give a detailed view of the setting of component values of the system matrix below.

• On setting the difficulty

There are two types of difficulties in the difficulty setting. One is to understand the difficulty of an element qualitatively, and the other is to quantify that qualitative understanding.

First, I shall explain the qualitative understanding of difficulty. Understanding the difficulty qualitatively also involves entering information such as the progress and risk of the project. Since progress management and risk management are done by using conventional project management technology, they can be organized, without a problem, as input information in setting the difficulty level. In fact, the project manager, architect, or team leaders have an intuitive understanding of the changing difficulty of each element. For example, in many projects, in the everyday conversion that takes place during the project, there are many discussions pertaining to the difficulty of elements that constitute the project, such as who is the key person, which tool has problems, or which activity is critical. Therefore, there should not be a particular barrier in understanding the difficulty qualitatively.

However, there are issues in quantifying the risk items into difficulty levels. I have yet to verify whether independent evaluations can arrive at equivalent results based on the guidelines indicated in the paper, and this is an area targeted for future research.

• On setting the interdependency

In a project without some sort of activity standard, it is reasonable to expect difficulty in organizing the interdependency. In a project without an activity standard, current process-centric management is difficult in the first place. In that sense, using the proposed model may appear cumbersome due to lack of experience, but I believe it can function effectively as a tool for understanding the status of the project. In a project that already has an activity standard, in general, it defines activities and artifacts, as well as the roles of each team, and it is possible to organize the interdependency in that phase. Once the organization is done, each project can be customized by using the template, and there should be no problem in reusing such a template.

• Overall

As you indicated, this proposal may, at first glance, be a very difficult management technology. In conventional project management, the main method is the management of progress status centering on process and the management of budget based on process. Therefore, the problems that arise from those perspectives were analyzed and measures were taken against the cause of the problems. However, the concept of this method is to understand the problems arising in the project through the difficulty and interdependency of individual elements based on the model, and then taking measures after gaining an overview of the whole project. This means that conventional project management relied on an individual optimal solution centered on individual elements because it was analytical, but what is proposed here is a tool to consider a solution that is optimal for the whole project. In that aspect, while there may be cases where a difference in thinking may become a barrier, if a shift in thinking can be made, no major problem is expected. As I mentioned in the section on difficulty, project managers and leaders have intuitive understanding, and I believe the proposed method is much easier than the execution of something like earned value management (EVM).

4 Completed project

Question (Hideyuki Nakashima)

You say, “The interdependency disappears among the elements when the information transfer has been completed.” Does this mean there is no information dependency between completed projects? However, for example, if some new technology is discovered and the product of Project 1 is improved, isn’t it the case that the same thing can be applied to the product of Project 2?

Answer (Akihiro Sakaedani)

Consideration of the presence of interdependency changes according to how the unit of the project is defined. If you consider Project 1 that established a new technology and the subsequent Project 2 as a single large project, the interdependency will not disappear. However, if you consider Project 1 and Project 2 to be two different projects, interdependency in Project 1 disappears, and information transfer is reflected in the evaluation, such as in setting the difficulty of the team lower in Project 2 than in Project 1, due to the improved skills of the team, for instance.

Research and development of a monopivot centrifugal blood pump for clinical use

— Collaboration for a product between medical and engineering teams —

Takashi Yamane*, Osamu Maruyama, Masahiro Nishida, Ryo Kosaka

[Translation from *Synthesiology*, Vol.5, No.1, p.16-24 (2012)]

AIST succeeded in developing a circulatory assist centrifugal pump, which can be used as a bridge-to-bridge device of a period within four weeks before a long-term use of ventricular assist device. The adopted mechanism of monopivot bearing was originally proposed by AIST. As design verification, flow visualization was performed to evaluate the geometry and the in vitro antithrombogenic testing, proposed originally by AIST, was applied to evaluate the antithrombogenicity. And then, the animal testing was conducted in collaboration between medical and engineering teams. AIST not only succeeded in developing a product with original seeds, but also established and distributed engineering evaluation methods and the R&D guidance for industries.

Keywords : Artificial heart, centrifugal pump, monopivot bearing, flow visualization, in vitro antithrombogenic test

1 Historical background of R&D of artificial hearts

Population Statistics of the Ministry of Health, Labor and Welfare (MHLW) in 2010 indicates 350 thousand people died of cancer, 190 thousand died of heart disease, and 120 thousand died of brain/vessel disease. The second and the third causes sum up to 300 thousand people in total. Among them there are 195 heart transplantation nominees as the most serious patients. Even though the transplantation law was improved to include donors based on family agreement and the number of donors increased from 6 to 40, 150 donors are still lacking. The possible remedy for this situation is an artificial heart or regenerative medicine. However, in emergency cases, the artificial heart is the only choice for heart patients.

History of the artificial heart technology is as follows:

1) Initiation as the total replacement artificial heart with large-scale pneumatic pumps,
2) Change of the purpose from heart replacement to heart assistance (paracorporeal use),
3) Out-of-hospital pumps with implantable ventricular assist devices (VAD),
4) Reduction of size by using rotary blood pumps,
5) Durability enhancement with non-contact bearings: the maximum period of use at present is 7.5 years.

As surgical pumps

6) Roller pumps or centrifugal pumps are limited to one-day use,
7) The circulatory assist pumps with catheters are limited to one-week use,
8) A new category of care, bridge-to-decision, is emerging, which is used for 1 to 12 months before the implantation of a long-term VAD.

The history of the artificial heart is that of overcoming thrombosis and infections. Dr. Kolff and Dr. Akutsu initiated animal experiments of an artificial heart in 1957 at the Cleveland Clinic Foundation Hospital. It was not before the development of antithrombogenic materials in 1981 that a clinical study started for a total replacement artificial heart. The subsequent clinical applications moved to implantable ventricular assist devices (VADs) from 1987. It enabled patients to go out of hospitals and reached the number of 4600 cases. The first generation of VADs was mainly large-size pulsatile pumps which weighed more than 1400 grams.

Small-size rotary VADs were introduced in 1998 and an innovation occurred. They are called the second generation VADs, which use mechanical bearings. Clinical study for axial-flow pumps started in 1998 and the total number has reached 6500 up to now. Their merits are the small size for implantation, such as 200-500 g, and the reliability due to reduced number of components.

The second innovation occurred when they introduced non-contact bearings in combination with the rotary mechanisms. They are called the third generation VADs and their clinical study started in 2004. They are using the magnetic bearing, which levitates the impeller with position sensors and electromagnets, or the hydrodynamic bearing, which levitates the impeller with grooves on the surfaces accompanied by high pressure spots, or the mechanical seal, which block the invasion of blood with thin liquid films. Most of them are centrifugal pumps, which are featured with hyper durability

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Table 1. Purpose of use, driving mechanism, mission life, and product information of artificial heart/circulatory assist device

Purpose of use	Driving mechanism	Mission life	Product information
1) Total replacement artificial heart	Pneumatic pulsatile pump	1 year (Endurance limit)	Jarvik 7 by Symbion
2) Paracorporeal ventricular assist device	Pneumatic pulsatile pump	1-12 months (Endurance limit)	Toyobo VAD by Nipro
3) Implantable pulsatile VAD	Electro-magnetic pulsatile pump	1 year (Endurance limit)	Novacor、HeartMate XVE
4) Implantable rotary VAD	Motor-driven rotary pump (mechanical bearing)	5 years or more (on going)	DeBakeyVAD=HeartAssist5、Jarvik 2000、HeartMate II
5) Implantable rotary VAD	Motor-driven rotary pump (non-contact bearing)	7 years or more (on going)	DuraHeart by Terumo, EVAHEART by Sun Medical Tech.Res., VentrAssist by VentraCor, HVAD by HeartWare
6) Surgical extracorporeal pump	Roller pump or Centrifugal pump	6 hours	BioPump by Medtronic, Capiox by Terumo, HPM15 by Senko Medical, etc.
7) Circulatory assist during/after operation	Centrifugal pump (mechanical bearing)	4 days	RotaFlow by Maquet, etc.
8) Bridge-to-decision (new category)	Centrifugal pump (non-contact bearing)	1-6 months	Not approved yet

though the size is a little larger than axial flow types. An axial flow pump with hydrodynamic bearings has also been developed by the National Cerebral and Cardiovascular Center (NCVC)/the National Institute of Advanced Industrial Science and Technology (AIST)/Mitsubishi Heavy Industries, Ltd./Nipro Corporation.

The second and the third generation VADs enabled patients to go out of the hospital. The controllers are portable and the batteries can be used for 8-10 hours, and the patients can use showers at home. The recent implantations of VADs are almost all rotary pumps in the US. The patients can return to their factories or campuses even in Japan.[1]

At present a necessary device for patients is a bridge-to-bridge pump applicable up to the next diagnosis such as the eligibility for implantable VADs or the sufficient recovery of lung function. However, the presently available product is a pneumatic ventricular assist device whose price is more than 30,000 US dollars. A circulatory support pump applicable up to four weeks is necessary whose price is less than 5,000 US dollars. We, at AIST, have been studying the second and the third generation VADs and, based on the research, have succeeded in developing a product for a circulatory support pump for four-week use. In the present paper we describe the scenario of the R&D process and the collaboration between the medical and the engineering teams (M/E collaboration).

2 Research of a monopivot centrifugal blood pump

When we started the research of artificial heart in 1991, rotary pumps for open heart surgery were requested to eliminate shaft and seal structure. Among seal-less pumps we proposed the "monopivot" mechanism[2] (Fig. 1), which supports the impeller on a point contact, had it patented and started collaboration with the School of Medicine of University of Tsukuba. The pump made by former technology was such that the pump impeller was supported with a shaft and two ball bearings and, therefore, it easily induced hemolysis or thrombosis due to the leakage of blood from the seal. A double pivot pump was also proposed by other facilities. Then we proposed a one-point support mechanism because it was expected to reduce the contact area as well as the hemolysis.

An important advice from the clinical side (Professor and Dr Tatsuo Tsutsui, University of Tsukuba) in the collaboration was that, saving animal experiments, engineering evaluation, or in vitro testing, should be conducted first to obtain scientific evidence and then we can proceed next to the animal experiment. It can be called a concept of evidence-based medicine. We joined the national project of NEDO totally implantable artificial heart which started in 1995 and set a tentative goal of developing an implantable VAD.

First, we repeated redesign and verification alternatively at each stage of the design through flow visualization. A visualized model was made with a 3 times scale-up acrylic model and the circuit was filled with 64 wt% NaI water solution (specific gravity: 1.9) whose refractive index (1.49) matches with the acrylic model. As tracer particles silver-coated glass beads (average size: 10 μm, specific gravity: 1.4) were used. The particle images were taken by a high-speed video system (Phantom), and were illuminated with Ar ion laser light sheet (output: 4 W). The images were analyzed with 4-frame particle tracking method for in-plane motion and with 3-frame particle tracking method for out-of-plane motion because the particle immediately disappeared. Centrifugal blood pumps are often provided with washout

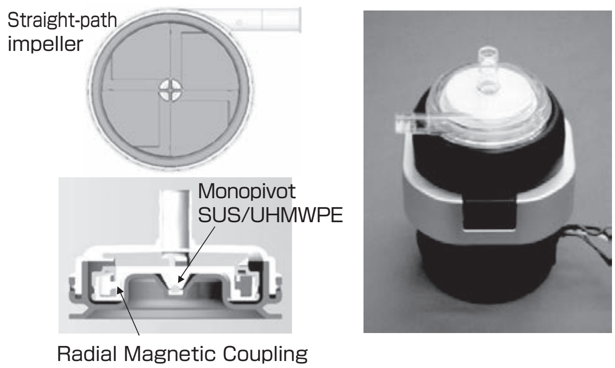


Fig. 1 Structure and picture of a disposable monopivot centrifugal blood pump as a product
(MERA centrifugal pump HCF-MP23, Senko Medical Instruments Mfg. Co. Ltd.)(Made of mainly polycarbonate, an impeller of 50 mm in diameter, a washout hole of 8 mm in diameter, a spherical pivot of 3 mm in diameter of a combination of a stainless ball and ultra high molecular weight polyethylene)

holes, penetrating the impeller to recirculate the fluid in a pump and to prevent thrombus formation, because the fluid behind the centrifugal impeller would not exchange automatically. The results of flow visualization verified that washout holes should be concentrated to a single hole with a small area compared to separate large holes[3] (Fig. 2).

Hemolysis testing using bovine blood revealed that the contact area governed the level of hemolysis; namely the smaller the contact area is, the lower the hemolysis level becomes[4] (Fig. 3).

Based on these evidences of flow visualization experiments and hemolysis testing animal experiments were conducted at University of Tsukuba, and the results were verified.

3 Reset of the goal of development based on clinical needs

When we were conducting animal experiments, a company, Senko Medical Instruments Mfg.Co.Ltd., joined the research collaboration. Generally medical device companies are often small/medium scale businesses, and they often join the development after animal experiments from the view point of risk management. Selecting AIST as a partner may be because the AIST team was not deeply connected to any companies then. Then the goal of development was switched from an implantable VAD of NEDO goal to a circulatory assist/extracorporeal pump for 4-week use based on the proposal of the company. The concept of monopivot centrifugal pump proposed by AIST was adopted for the product.

Clinically available blood pumps for cardiac surgery and cardiac assist at present can be classified into four categories as follows:

(1) Short term use (made of polymer, structure with seal, usable for 6 hours)
The pharmaceutical price is around 60,000 yen and the total number of production is 40,000 in Japan.
(2) Long term use (made of polymer, structure without seal, usable for 4 days)
The pharmaceutical price is around 100,000 yen though insurance does not cover the open-heart surgery use.
(3) Paracorporeal pulsatile VAD (placed outside the body, made of polyurethane, usable within a month)
The pharmaceutical price is 3,160,000 yen though the durability proof is within a month.
(4) Implantable VAD (made of Titanium, no limitation for period of use)
The pharmaceutical price is 18,100,000 yen and the insurance covers for implantation.

As an economic estimation, if an extracorporeal pump of 60,000 yen covers 25 % of the share of the market of 40,000 sales a year, the total sale would be 600,000,000 yen. In contrast, if an implantable VAD of 18,100,000 yen covers 50 % of the share of the market of 100 sales a year, the total sale would be 900,000,000 yen a year, which is almost the same as that of the extracorporeal pumps. Therefore, the former was selected as the goal of the development. The present pump features the cost of 60,000 yen and realizes a similar performance as the pneumatic VAD for one-month use of 3,160,000 yen. The goal of the product was set not only for surgical use but also for bridge-to-bridge use before long-term implanatble VAD, namely the performance is over (2) and the cost is (1).

The product of the monopivot centrifugal pump is composed of an impeller of 50 mm in diameter with straight paths, a monopivot bearing of a 3 mm sphere made of stainless steel/ultrahigh molecular weight polyethylene, and a washout hole

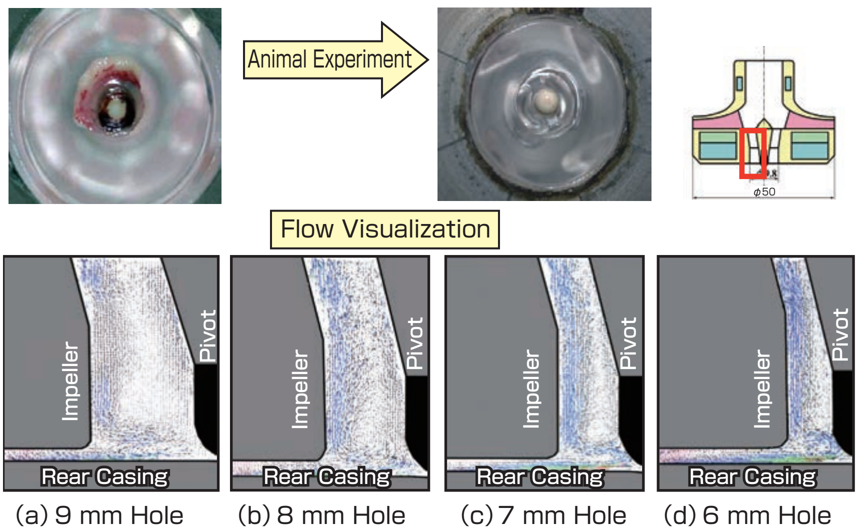


Fig. 2 Comparison of wash by washout hole through flow visualization for improvement of antithrombogenicity

of 8 mm in diameter. Though the pump is made mainly of the usual material, polycarbonate, the straight path structure and the assembling method without seals or adhesive materials are the original ideas of the company.

4 Role and fruits of AIST in the product design and the design verification

4.1 Engineering evaluation in the laboratory

Before the application to Pharmaceuticals and Medical Devices Agency (PMDA), the efficacy, safety, and quality designated in pharmaceutical law should be evaluated. The company was in charge of the evaluation of safety and quality. AIST was in charge of the evaluation of efficacy and conducted a flow visualization test, an in vitro thorombogenicity test, and a durability test for design evaluation.

The AIST empirical standard for thrombus formation is shear rate of less than 300 s^{-1}. As a result of flow visualization, since flow region of less than 300 s^{-1} was found at a sharp corner of the pivot support, a geometrical modification was performed for the corner[5][6] (Fig. 4).

In the durability test the impeller axial displacement was continuously measured with a laser confocal displacement meter. It was verified that the axial wear rate of the female pivot was as small as 1.1 μm/day. Though the geometry of the wear section generally becomes the letter W for rotational wear tests, the trace of wear was not observable. The operation was found to be sufficiently silent.

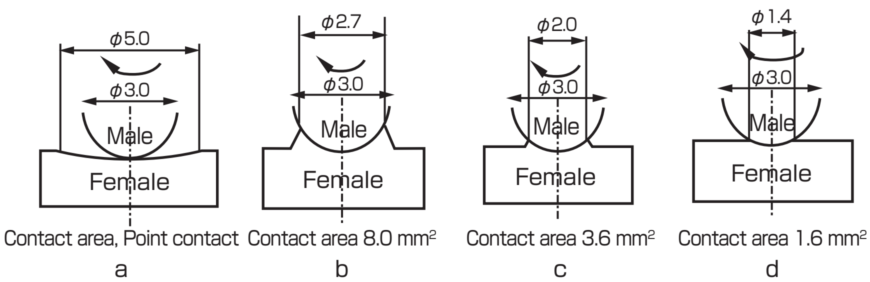
The in vitro thrombogenic test was proposed by AIST to investigate whether thrombus forms or not before animal experiments.[7] The closed circuit including a test pump was filled with purchased bovine blood, and sodium citrate and calcium chloride were used to maintain the active clotting time (ACT) to be around 200 s and the temperature at 37 °C for two hours. As a result of this method, the thrombus induced by a small difference of male/female pivot radii was successfully removed by adjusting the radii (Fig. 5).

4.2 Animal tests as M/E collaboration

We repeated more than 20 animal tests with sheep at University of Tsukuba with prototype blood pumps to eliminate thrombus and finally found no thrombus in a five-week animal experiment. The mass production models were also tested at Tohoku University and no thrombus were found in a 4-week animal test (Fig. 6). As mentioned above, the medical team advised us of the concept of evidence-based medicine, namely we do not go directly to multiple animal experiments but utilize *in vitro* testing to obtain scientific evidences. We conducted sufficient flow visualization experiments and *in vitro* thrombogenic tests and minimized the number of animal experiments. The important advice led to an efficient development and this can be regarded as the fruit of the M/E collaboration.

Generally speaking, M/E collaboration has two patterns. One is where a hospital supports a company to test a product based on a company's seed. This is because a company cannot be a user of medical products by itself. The other is where a university, a hospital, or a research facility offers a seed and a company joins to realize a product. The case presented in this paper corresponds to the latter case. Former cases of similar patterns for VADs are as follows and most of them are accomplished products:

- a pulsatile VAD with pneumatic driver of Xeon Medical/University of Tokyo
- a pulsatile VAD with pneumatic driver of Toyobo/National Cardiovascular Center
- a rotary VAD with a magnetic bearing of Terumo/Kyoto University
- a rotary VAD with a mechanical seal of Sun Medical



Hemolysisi Indices of Monopivot Pumps (g/100L)

Geometry	Hemolysis Index	Hemolysis index of control	Relative ratio
a	0.001	0.003	0.3
b	0.010	0.003	3.3
c	0.012	0.004	3.0
d	0.002	0.002	1.0

Fig. 3 Difference of hemolysis levels due to difference of pivot geometries

Technology Research/Waseda University
a centrifugal blood pump of Nikkiso/Baylor Medical University
a centrifugal blood pump of Kyocera/Baylor Medical University

4.3 Summery of outcomes

As mentioned above, AIST conducted R&D mainly on the hemocompatibility and durability of the design. The monopivot centrifugal pump features:

1) Small wear, silent sound, durable over four weeks.
2) Thrombus free, low hemolysis, hemocompatible over four weeks.
3) The product can be offered with a low price as a surgical pump in addition to having the above performance.

The following AIST original technologies were useful in the development:

1) "Monopivot bearing" is a mechanism AIST proposed internationally.[2] Wear, hemolysis, and thrombus formation occur at the monopivot and it was theoretically and experimentally verified that the contact area has a close relation to them.[3] The hemocompatibility and the durability were verified to be effective over 4 weeks.
2) We proposed "flow visualization technique" which can predict quantitatively the hemocompatibility.[5][6] After our presentations flow visualization sessions were increased in international conferences and ISO 14708-5 adopted flow visualization as an ANNEX. As mentioned later the obtained data of the flow visualization was used as the application for the PMDA or for US Food and Drug Administration (FDA) and they were approved.
3) "*In vitro* thrombogenic test" was a method we proposed for evaluation of hemocompatibility before animal experiments.[7] Though this method is still under development, there are several companies doing collaborative researches with us.

On the other hand, the original technologies of the company were as follows:
1) Cost reduction by adopting an assembling method without seals or adhesive materials.
2) Cost reduction by removal of permanent magnets or ceramic components.
3) Inhouse manufacturing of a motor driving unit with a radial-flux magnetic coupling.

As a result, the equivalent function to a pneumatic driven VAD of 3,160,000 yen was realized with a centrifugal pump of around 60,000 yen. Furthermore, AIST inhouse program for patent application to a product was useful especially for establishing the business plan.

5 Outcome as a product

Senko Medical Instrument Mfg. Co. Ltd. started the collaboration research with us in 2002, submitted the pharmaceutical application at the end of 2008 regarding "MERA centrifugal pump (HCF-MP23)" and obtained the approval in January 2011. The pump was launched into the market in April 2011, and the total number of clinical applications was more than 100 at the end of November

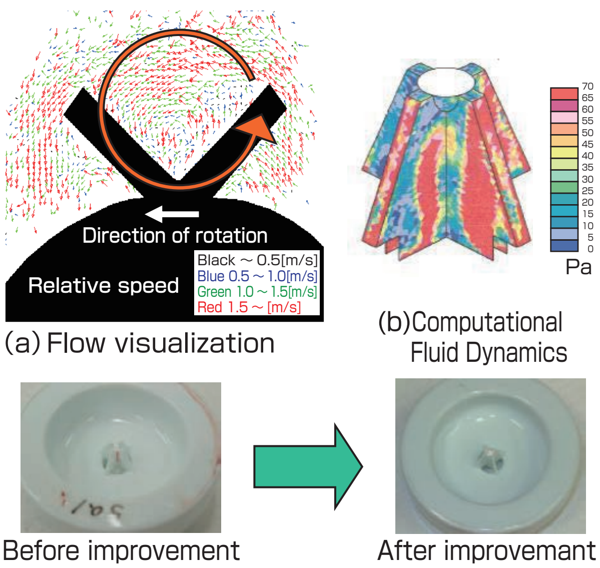


Fig. 4 Prevention of thrombus formation through flow visualization and computational fluid dynamic analysis
Elimination of thrombus formation by predicting thrombus at the corner of the pivot support

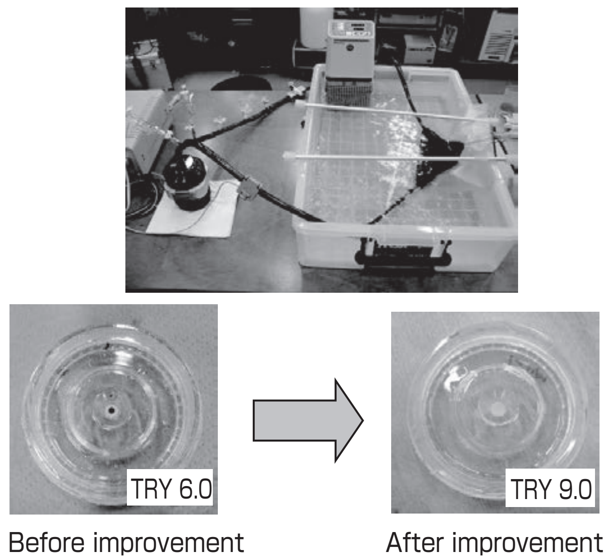


Fig. 5 Prevention of thrombus formation through in vitro thrombogenic test
The closed circuit including a test pump was filled with purchased bovine blood, and sodium citrate and calcium chloride were added to maintain the active clotting time (ACT) to be around 200 s and the temperature at 37 °C for two hours

2011. The approval covers an extracorporeal pump use for cardiovascular surgery and the name "MP23" denotes monopivot bearing, which shows the contribution of AIST. The pump features silent operation and less wear. The necessary time for development was 9 years. We kept the number of animal experiments low and accumulated sufficient engineering data which could become bases of design and could be used as descriptive material for users. Though the approved duration of use was 6 hours, AIST has done research to verify the durability and hemocompatibility for 4 week use, and therefore, it is expected to be used in the future for the new, bridge-to-bridge care before the implantation of a long-term artificial heart. Further collaboration with hospitals would expand the application field.

6 Future contributions of AIST to industries

Our research made contributions not only to a company product but also to other facilities or companies with our technology evaluation technique. AIST also made contribution to the Guideline Program of METI/MHLW to promote speedy approvals of medical devices for industries.

Among two implantable VADs approved in December 2010, we conducted flow visualization for EVAHEART by Sun Medical Technology Research and the data was submitted to premarket approval of PMDA and to the investigational device exemption (IDE) of FDA. The approvals have been successfully obtained. For DuraHeart of Terumo, we contributed to making VAD guidelines to establish a consensus for evaluating items and to shorten the review period.

Recently our research collaboration has expanded to overseas companies. AIST will make contributions to domestic and overseas industries using our development technology as well as our evaluating technology.

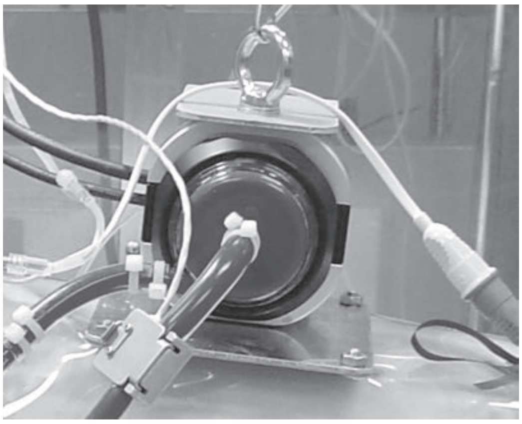


Fig. 6 Animal experiment using monopivot centrifugal blood pump
Conducted for 4 weeks at Tohoku University, paracorporeal application as left heart bypass

7 To the researchers who wish M/E collaboration

Our experience clarified that the followings are necessary for making a product in medical engineering.

1) Medical engineering researches are team studies which cover mechanics, fluid, material, and electo-mechanical engineering, as well as medicine, manufacturing, regulation, insurance reimbursement. The Japanese situation should be understood that instead of buyers the insurance pays for the devices based on the national health insurance.

2) The project should have research leaders who watch the project and connect different teams with each other for a long period, though the administrators may change, since the development needs roughly a decade. As the results or remedies of medical or engineering subjects appear at random, synthesizing the solutions into a system is similar to building with blocks. We kept steady M/E leaders for twenty years.

3) Research collaboration among a research institute, a medical facility, and a manufacturing company should be as equal partners. We see many cases where a medical team governs the project and where the project tends to do research instead of making products. However, balancing the purpose, design and materials is important to be accepted by the maximum number of patients. Therefore, the activity and the experience of the company should also be respected. The academia often tends to pay attention to a total replacement heart (TH) first, a VAD second, an extracorporeal pump third. The present case is a model case where the economic aspect was taken into account with assistance of academia or a research institute.

4) A good product goal should be made instead of a good research goal. AIST should seek for a goal of social needs instead of seeking its own research goal. Though obtaining research budget is important, "research for research sake" does not lead to social acceptance.

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Discussions with Reviewers

1 Overall structure

Comment (Motoyuki Akamatsu: Human Technology Research Institute, AIST)

The purpose of *Synthesiology* is to publish papers that allow readers to gain knowledge of how to poceed with research. It is expected that the papers would explain, for example, at what timing of the research and development process the researcher decided on what was needed, to what the attention would be given and what were the reasons behind the decisions. With this in mind, in chapter 2, goal setting a goal is mentioned, but is it possible to write about the scenario of what kind of development was to be conducted for that goal?

Answer (Takashi Yamane)

In chapter 2, we explain the logic of research, and extract the important phenomena of designing for “2.Research of a monopivot centrifugal blood pump.” In chapter 3, we point to the revision of target of product development as “3, Reset of the goal of development based on clinical needs." We restored chapter 4 to cover the development results as it did originally.

2 Relevancy between design verification of the pump and experiments

Comment (Motoyuki Akamatsu)

At the beginning of subchapter 4.1, it is written that design verification was efficiently conducted to solve problems. Please explain why the flow visualization test and the in vitro thrombogenicity test were necessary so that the readers outside of the field may understand. Please explain the degree of advantage by comparing with the research and development of other pumps.

Question (Jun Hama: Energy Technology Research Institute, AIST)

In the chapter concerning design verification of the pump, the flow visualization test, the *in vitro* thrombogenicity test and the durability test are explained. What is the whole picture of design verification of pumps? Please write your response to each category of verification of the three tests in more detail.

Answer (Takashi Yamane)

I added the following to subchapter 4.1.

"Before the application to Pharmaceuticals and Medical Devices Agency (PMDA), the efficacy, safety, and quality designated in pharmaceutical law should be evaluated. The company was in charge of the evaluation of safety and quality. AIST was in charge of the evaluation of efficacy and conducted a flow visualization test, an in vitro thrombogenicity test, and a durability test for design evaluation."

These evaluation techniques were requested by the clinical side and I added what kind of effect there was in subchapter 4.2.

"As mentioned above, the medical team advised us of the concept of evidence-based medicine, namely we do not go directly to multiple animal experiments but utilize *in vitro* testing to obtain scientific evidences. We conducted sufficient flow visualization experiments and *in vitro* thrombogenic tests and minimized the number of animal experiments. The important advice led to an efficient development and this can be regarded as the fruit of the M/E collaboration."

Moreover, I added its effect in chapter 5.

"The necessary time for development was 9 years. We kept the number of animal experiments low and accumulated sufficient engineering data which could become bases of design and could be used as descriptive material for users."

3 Standard for approval of assist pump

Question (Jun Hama)

How is the standard of approval for assist pumps for cardiovascular surgical procedure stipulated?

Answer (Takashi Yamane)

Basically, there are standards for safety in pharmaceutical law; however there is no standard for efficacy. Efficacy is determined not by numerical evidence but by the duration of evidence (data taken during 6 hours in this case).

4 Development of evaluation technique

Question (Jun Hama)

How should we understand that the evaluating endpoints and verification experiment would be approved in Japan and overseas as a method of evaluation? For example, what kinds of measures are you taking in order that these methods of evaluation would be recognized more widely as a conventional evaluation technique rather than a specific evaluation method of artificial heart design?

Answer (Takashi Yamane)

We included visualization tests in the evaluation method of the artificial heart of ISO. Evaluation methods vary depending on how far the companies want to file. Examples are explained in chapter 6. In December 2010, we conducted flow visualization for EVAHEART by Sun Medical Technology Research and the data was submitted to premarket approval of PMDA and to the investigational device exemption (IDE) of FDA.

5 Decision for productization and resetting of target

Question (Motoyuki Akamatsu)

One of the points of this paper is the decision made when Senko Medical Instrument Mfg. Co. Ltd. joined the research aiming for productization and the resetting of the target later. Although there must have been many other researches for artificial hearts, please write the reason why this company chose to commercialize this monopivot centrifugal pump, or why it saw the possibility of productization.

Question (Jun Hama)

It can be presumed that the difficulty of productization related to medical fields is the reason why the target to develop an artificial heart in collaboration with a university was changed to extracorporeal circulatory pump in the productization efforts with a company. Would you explain to us the reason for that change in detail?

Answer (Takashi Yamane)

The reason for the decision the company made for the productization of monopivot centrifugal pump was based on an introduction by a university professor who was a research partner of the monopivot centrifugal pump development. There were only five groups which had reached animal experiments among the institutes researching rotatary type artificial hearts in 2002.

It seems to me that among these groups, only AIST was in a position where the company could easily participate in.

We mentioned the process of resetting the development target in chapter 3. Doing business with inexpensive, low-risk products or disposable products is the basic stance of the collaborating company. This company can easily procure polymer material and is good at processing it. With our design, it assembles the pump with little adhesive, using a cheap manufacturing method that does not use O ring or screws often used for ordinary products. There was a prospect that, if the monopivot mechanism of AIST was used, an inexpensive product without ball bearings and shaft seals could be made. That was the reason for aiming at productization of a circulatory assist pump based on the AIST's method.

6 Medicine-engineering collaboration

Comment (Motoyuki Akamatsu)

Concerning medicine-engineering collaboration, as of medicine, there is the basic research point of view of medical doctors of research and the clinical view from treatment and diagnosis of patients at hospitals. As for engineering, there are university professors and researchers of public research institutions in the field of engineering, and engineers involved in productization at companies. I think if you can organize the parties involved, it would be of use to the readers.

Answer (Takashi Yamane)

There are usually two types for the medicine-engineering collaboration. One is where a company and a hospital collaborate as a manufacturer and a user, to realize a product because the law prohibits medical device manufactures from being users themselves, which is different from general industry. The other is where universities, hospitals or research institutions offer seeds and companies join them to realize productization according to the needs. The case presented in this paper is the latter case. I added the examples of successful productization of artificial assist hearts (VAD) in subchapter 4.2.

An analysis method for oxygen impurity in magnesium and its alloys

— International standardization activity in parallel with R&D —

Akira Tsuge * and Wataru Kanematsu

[Translation from *Synthesiology*, Vol.5, No.1, p.25-35 (2012)]

A simple and reliable analysis method has been developed to measure oxygen impurity in magnesium (Mg) and its alloys. Instead of directly analyzing oxygen impurity of an analyte, a multi-step heating-up method has been invented, in which oxide, compound of oxygen impurity with metals, is first separated from an analyte and then oxygen content analysis is carried out. The oxygen analysis of the oxide has been performed by Inert Gas Fusion-Infrared Absorptiometry widely used as a method for oxygen analysis in metals. We verified that analysis with adequate accuracy can be achieved with temperature calibration of each equipment. In parallel with R&D of the analysis method, we performed international standardization activity. It has been shown that consistent data can be obtained both in Japan and Korea through our technical assistance to Korea, and a proposal to the ISO technical committee for Mg and its alloys has been submitted smoothly.

Keywords **:**Magnesium, magnesium alloy, oxygen analysis, inert gas fusion-infrared absorptiometry analysis, multistep heating procedure, international standardization

1 Introduction

Magnesium (Mg) is a light metal with specific gravity 1.8 g/cm^3, which is one-fourth of iron (SG 7.8 g/cm^3) and two-thirds of aluminum (SG 2.7 g/cm^3). It is expected to have a major effect in reducing carbon dioxide when used in transportation machineries such as automobiles. The carbon dioxide emitted annually by the transportation machineries in Japan is estimated to be about 250 million ton, and 55 % thereof is dominated by private automobiles.[1] If the weight of the automobile is cut down to three quarters by reducing the weight of various structural members, the fuel consumption is expected to improve about 20 %, and the carbon dioxide emission can be reduced to 27.5 million ton (= 250 million ton x 0.55 x 0.2) for private automobiles alone.

The researches for the use of Mg material that is excellent for reducing the environmental load have been done as major national policies in Europe and the United States. Some of the well-known projects are the “EUCAR Project” of EU, the “SFB390 Project” of Germany, and the “USCAR Project” of the US. However, the use of Mg per automobile is only 6 kg even in Europe as of 2005, and the use in Japan is much lower at 2 kg.[2]

Mg has high oxygen affinity, and it is known that the oxygen impurities present as oxides (nonmetal inclusions) cause adverse effects on mechanical properties such as strength and fatigue life.[3][4] These prevent increase in the Mg use in various structural components such as those for automobiles. The industrial oxygen analysis method has not yet been established for Mg, and the evaluation is currently done by methods that are neither precise nor accurate, such as microscopic observation of casting surface of the sample or visual inspection of oxides from the CT scan image. This is a barrier against building the recycling system, and it makes increasing the Mg use in products more difficult.

In Mg with high oxygen affinity, the oxidation of surface tends to occur readily in the process of fabricating or being used as the structural component. Therefore, in the recycling of reuse parts and scraps produced in component fabrication process as raw material, monitoring of oxygen content and the oxide removal process based on the evaluation results are essential. However, the lack of the oxygen analysis method that can be employed at production fields is an obstacle to promoting the recycling practice.

Japan has an advantage in the manufacturing technology of Mg materials and components, and particularly in both the melting and casting under oxygen shielded condition and the injection molding in semi-molten state. In these fabrication technologies, in principle, the increase in oxygen content during the process does not occur, and the components manufactured thereby are known to have low oxygen content.[5] In the international market for Mg, Japan can be positioned as the “raw-material-importing and products-exporting country.” In Korea, which is positioned similarly, there are

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several large companies that manufacture basic materials such as sheets by twin-roll and rods by extrusion.

On the other hand, as shown in Fig. 1, about 85 % of the world share for Mg metal is dominated by the Chinese heat refined metal. Although China is currently positioned as the “raw-material-exporting country,” it is expected to put more effort in the manufacture of alloys and components[2] in the future. Currently, the major East Asian countries are entering the global market in various ways, and one of the characteristics of the Mg material industry is that although these three countries are rivals, there is potential for getting together to build a cooperative and collaborative relationship.

From the perspective of environment protection, there is no question that the use of Mg material should be expanded. The prevalence of the oxygen analysis method is expected to facilitate the verification of quality and reliability of the materials and components and eventually leading to the improvement thereof. At the same time, it is possible to appeal the excellence of the products of Japan, which has an advantage in Mg components manufacturing technology. Therefore we began to develop an easy yet highly reliable oxygen analysis method that can be used for process management at manufacturing plants. In this study, disseminating research results to industry was built into its objectives from the beginning. At the start of the R&D project, we set the final goal to proposing a developed method as an international standard. It was expected that the international standard would serve as a yardstick for product properties in the global market. In this paper, we will present the development of the element technologies of the oxygen analysis method, the process in which the reliability of the method was verified, and the background to international cooperation for the proposal of the standard.

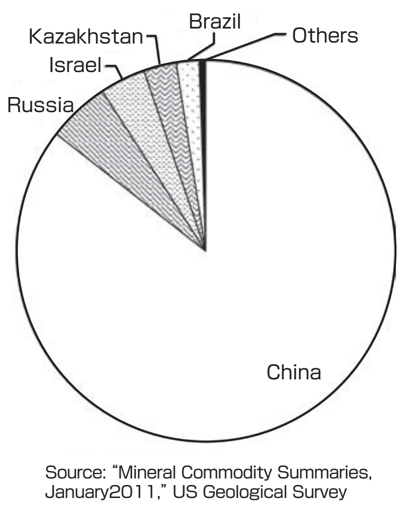


Fig. 1 Share of international market of magnesium metal

2 Element technologies and remaining issues for international standardization

2.1 Development of the basic technology

In standardizing the analysis method of industrial materials, versatility is a factor to be considered in addition to a stand point only from analysis technology. For example, radio activation analysis that is known as the analysis method for oxygen is excellent in terms of the accuracy of results, but the use of nuclear reactors and accelerators for activation is strictly regulated, and hence this method cannot be used for routine on-site analysis. Also, the wet chemical analysis, which was mainstream in the past, tends to be avoided because the analysis personnel must be highly skilled, and such method is adopted in a standard only when no other instrumental analysis is available.

Under these circumstances, inert gas fusion infrared absorptiometry (IGF-IRA) is generally employed as the industrial measurement method of oxygen content in metals.[6] The oxygen analysis by IGF-IRA is used widely in industries including iron and steel, and there are many commercially available automated devices. There are also many companies that can contract the oxygen analysis. From these points, this method is considered to be promising one for the standardization of oxygen analysis for Mg.

Figure 2 shows the schematic of the measurement principle of IGF-IRA method. The sample is placed in a graphite crucible in an inert gas flow such as helium, and heated by applying a current in the crucible. The oxygen in the sample is reduced by reaction with the carbon in the crucible material, and the carbon monoxide formed by the reduction reaction is extracted eventually. The carbon monoxide concentration in the helium flow is measured and accumulated by the infrared absorption detector to determine the oxygen content in the sample. The analysis is done by the reduction reaction of the sample by carbon, and this is the same reaction used in refining iron from iron ore. This derives from the fact that IGF-IRA method was originated and developed in the iron and steel industry.

It is expected to respond quickly to the demand for oxygen analysis in Mg, if the measurement of oxygen in Mg is enabled using an established method. However, in general, the IGF-IRA method has not been considered applicable to

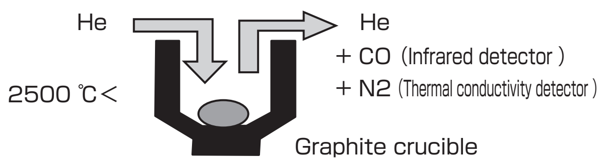


Fig. 2 Conceptual diagram of the inert gas fusion method

the oxygen analysis in Mg, because Mg has a low boiling point and high oxygen affinity.

Figure 3 shows the result of monitoring the extracted amount of carbon monoxide (or the temperature-increased inert gas fusion profile) when the magnesium oxide was placed in the graphite crucible with increase in the applied power. Although the carbon monoxide extraction started at around 2,400 W, the temperature of the graphite crucible corresponding to the applied power was estimated to be about 2,000 °C, being much higher than the boiling point of Mg, 1,090 °C. It implies that before the magnesium oxide in Mg starts to react with carbon, the matrix material Mg begins to boil at lower temperature. When the sample boils, the molten sample in the crucible causes boiling out due to the force of generated Mg vapor and eventually makes the analysis impossible.

To solve this issue, we adopted the "multistep temperature increase method" where the oxide included in the sample is separated and followed by the oxygen analysis. This method is inspired by the refining method of iron and Mg.

As mentioned earlier, the IGF-IRA method uses the reduction reaction of the sample by carbon. This is an irreversible reaction where the gaseous reaction product, carbon dioxide or carbon monoxide, desorbs from the reaction system. It can be considered that oxygen analysis corresponds to obtaining the gas phase product (carbon monoxide), contrary to obtaining the liquid phase one (metal) in iron refining.

In the Pidgeon method, which is the major thermal refining method for Mg, the raw material of magnesium oxide ore is mixed and heated with the powder of iron-silicon alloy (ferrosilicon). When the oxygen in magnesium oxide transfers to the ferrosilicon, the metalized Mg evaporates and desorbs from the reaction system. This reaction is not associated with reverse reaction, where the oxygen transfers to the ferrosilicon, and resulting in the collection of the evaporated Mg by coagulation in the low temperature area. In other words, the metal Mg is refined from the gas phase product of the irreversible reaction. Therefore, we reached a conclusion that analysis of the residual liquid phase, in which the oxygen was remaining, provides the oxygen content.

When certain metal with higher boiling point than Mg is mixed with the Mg sample as the oxygen receptor, the oxygen would remain in the metal even after Mg evaporated from the sample. The oxygen that desorbed from the Mg sample could be measured as the oxygen in the receptor metal.

At the beginning of the research, we believed that it was necessary to transfer the oxygen of the oxide in the Mg sample to the receptor by redox reaction, and that a metal with strong oxygen affinity like aluminum was considered as a receptor candidate. However, we eventually came across an idea that the magnesium oxide, which is the primary oxide in the sample, can be directly transferred to the receptor. Consequently, tin (Sn) was selected as the candidate of oxygen receptor metal. Since Sn has a low melting point of 232 °C but has a high boiling point of 2,602 °C, it mixes with the molten Mg in a liquid state, and the oxide was expected to be received into it easily. Also, Sn is often used as the metal bath material in the inert gas fusion process and has advantages of low oxygen content as well as ready availability. On the other hand, aluminum is not usually used as the metal bath material, and specimen of low oxygen content is not readily available.

Figure 4 shows the conceptual diagram of the newly developed analysis method in which Sn is used as the oxygen receptor metal. After 0.3 g of Mg was melted with 0.5 g of Sn at about 900 °C, the temperature was increased gradually to 2,000 °C in more than 1,000 seconds. The residue found at the bottom of the crucible was slightly less than 0.5 g. As the vapor pressure of Sn at 2,000 °C was a few kPa, it is considered that Sn evaporated resulting in the weight loss from the original amount. This temperature also surpassed the boiling point of Mg, and it is inferred that Mg was almost thoroughly evaporated off. The appropriate heating condition for separating Mg from a receptor was determined through weight measurement of the eutectic material with systematic changes in temperature increasing rate and heating duration.

The residue in the crucible was considered to be composed

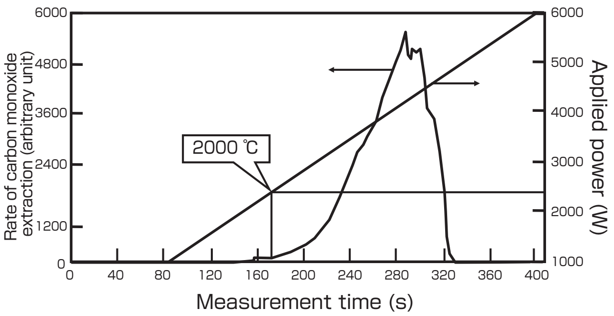


Fig.3 Temperature-increase inert gas fusion profile of magnesium oxide

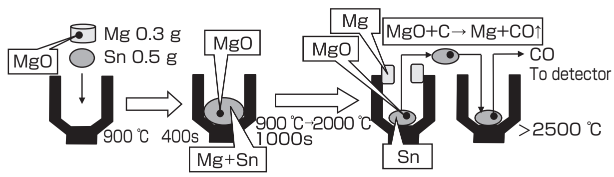


Fig. 4 Conceptual diagram of the analysis method for oxygen in magnesium by multistep temperature increase method

of Sn and magnesium oxide originally contained in the Mg sample. As shown in the profile of Fig. 3, it was expected that the oxygen could be extracted completely as carbon monoxide when heated with power of over 5,000 W. Therefore, we studied the percentage (recovery rate) of the amount of oxygen in the carbon monoxide extracted and detected against the 4 mg of oxygen predicted from the added magnesium oxide (the stoichiometric composition of oxygen in magnesium oxide is 39.7 %) when Mg was separated using the model sample where 10 mg of magnesium oxide was added to a mixture of 0.3 g Mg and 0.5 g Sn. The residue was heated at 5,000 W. In this experiment, however, the recovery rate remained at about 20 %, and much time was consumed to figure out the cause of discrepancy. Finally, we found that the Mg rebonded with the oxygen in the carbon monoxide that was produced from the residue when the crucible was heated with evaporated Mg remaining in it. We reached a simple procedure to prevent the rebonding: the residue is removed from the graphite crucible in association with the removal of the remaining Mg by opening the furnace and followed by the oxygen measurement with a new graphite crucible.

Since the reactivity between the Mg vapor and the generated carbon monoxide was unexpectedly high, we were possessed by a bias that the analysis procedure had to be done under inert gas flow in the IGF-IRA method. As a consequence, much time was wasted to find the cause of discrepancy in oxygen analysis. There was a concern that the sample may become oxidized when the residue was exposed to the atmosphere during analysis, but the effect of the oxidation was ruled out by conducting the blank test, analysis without placing the sample in the crucible.

2.2 The method of sampling

In commercial transaction, analysis values measured according to a standard are considered to be representative ones of traded merchandises. Therefore, in standardizing the analysis method, it is necessary to specify a sampling method to have the analysis value representing the characteristic of the entire sample, in conjunction with basic analysis procedures. Normally, a larger amount of sample than that actually used in the analysis is taken from several parts of the object to be measured and then these samples are mixed well to homogenize.(homogenizing process) At the beginning of this research, we tried the "chip sampling method", which is used widely in the chemical analysis of the major component and impurities of metal, allowing homogenization of the sampled material. In this method, homogenizing process was done for the chips sampled by drilling several areas of the object to be measured.

Mg is, however, readily oxidized and the oxidation of the samples during the chip sampling procedure could not be avoided only with simple and practical oxygen shielding. Consequently, we examined the core drill sampling method which has only a small effect of oxidation, but lack of homogenization. The results of examination of the sampling methods and additional findings expected to contribute to the standardization will be described below.

2.2.1 Chip sampling method

In the ordinary chip sampling method, the sample will have a large surface area in the chip formation process. The surface oxidation of the chip cannot be avoided in materials with high oxygen affinity like that of Mg. Direct application of the chip sampling to Mg was expected to be quite difficult.

Considering these results, we attempted to apply the chip sampling with a simple oxidation resistant treatment. Figure 5 shows the schematic diagram. Using a miniature lathe placed inside a nitrogen-purged glove box, a 10 mm diameter rod was turned and its stock removal ranged 0.2~0.6 mm. The chips formed by turning were measured with a tablet frame, taken out from the glove box through a pass box, followed by forging to form tablet samples. As shown in Fig. 6, the chip sampled under nitrogen purge showed higher oxygen concentration than that of the core of the rod. The oxidation of the chips could not be avoided, the same as those

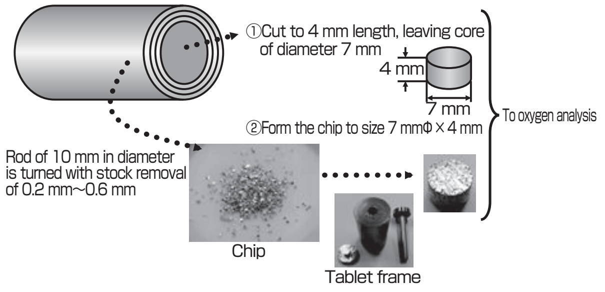


Fig. 5 Chip sampling method and creation of samples for analysis

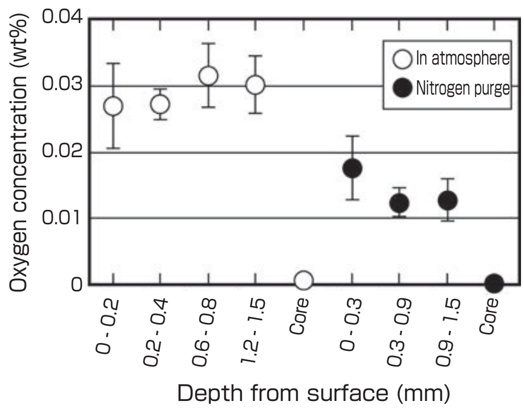


Fig. 6 Effect of surface oxidation by atmosphere during chip sampling

formed in the atmosphere, even though they were formed in the nitrogen-purged glove box.

It is inferred that such oxidation of the chip is caused by a small amount of remaining oxygen in the glove box, resulting from the purging by blowing off the oxygen with nitrogen, without vacuuming.

We reached a conclusion that the chip sampling is not appropriate for on-site analyzing with a simple procedure. To avoid the oxidation, extremely careful operation is necessary. The operation of fabricating the chips and collecting them with a tablet frame placed in the glove box was not only difficult and required skills, but also handling a lathe, which is a rotating machinery, with thick gloves is quite dangerous. Therefore, we considered that the chip sampling is inappropriate for an analysis method to be done easily on site and should not be adopted as a sampling method for a standard.

From the experimental results about chip sampling, we obtained two findings which are helpful for subsequent research. First, as seen in the measurement result of the core of the rod shown in Fig. 6, it is inferred that the effect of oxygen on the bulk surface was almost negligible in the developed analysis method. It implies that the oxidation is limited to the very thin layer on the surface despite high oxygen affinity and susceptibility to oxidation of Mg. It also implies that the effect of surface oxidation could be kept at the same level as the detection limit of the IGF-IRA method if the surface area of the sample was relatively small compared to the volume. This led to the development of the core drill method described below. Second, another finding is that oxygen content could be kept within a certain range if the chip thickness remained roughly constant. This is important for preparing samples for verification of the analysis value and for the joint analysis tests.

2.2.2 Core drill method

As mentioned in 2.2.1, the effect of surface oxidation can be suppressed by using a bulk specimen with a small surface area against its volume. Meanwhile, the sampling method is required to be able to sample the material without bias. In addition, the specimens of a shape suitable for the analysis, have to be sampled from any part of objects which may have various configurations. Another unique requirement of the IGF-IRA method is that the specimen must be placed most certainly in the graphite crucible. In the commercially available IGF-IRA device, the graphite crucible is degassed after conducting the inert gas purge of the furnace, and the specimen is dropped by its own weight through the sample drop path of about 8 mm in diameter. That does not matter for heavy samples such as iron due to its large specific gravity. In contrast, there is the possibility that Mg, which has low specific gravity, will be lodged in the path for some reason. To fulfill these two requirements, the specimen should be made small and spherical as much as possible. However, there is a trade-off between the quantity of the specimen used and the precision of the measurement value. In the case of a spherical sample, the more time will be needed for processing, the more profound influence of oxidation is exerted on the analysis result. In our preliminary study, a cylinder specimen, which enables easy sampling, was adopted. After much trial-and-error, we chose a cylinder with a diameter of 7 mm and a length of 4 mm as the smallest size specimen while maintaining the measurement precision.

To efficiently collect the sample of this shape from the object to be measured, we prepared a custom-made core drill to core a rod of 7 mm in diameter. Using the core drill, the rods were sampled from any area of any depth in the object, and the specimens were cut out at arbitrary depth from the rod. The appearance of the core drill is shown in Fig. 7. Figure 8 shows the case where 130 specimens were cut out systematically from the extruded billet of 170 mm in diameter and 500 mm in length. It should be noted that collecting specimens for distributional analysis from such a large object could be done within two days.

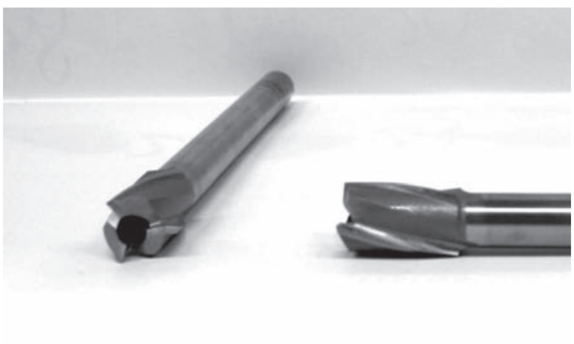


Fig. 7 Core drill for collecting sample (inner diameter 7 mm)

3 Investigation of reliability of the method for international standardization

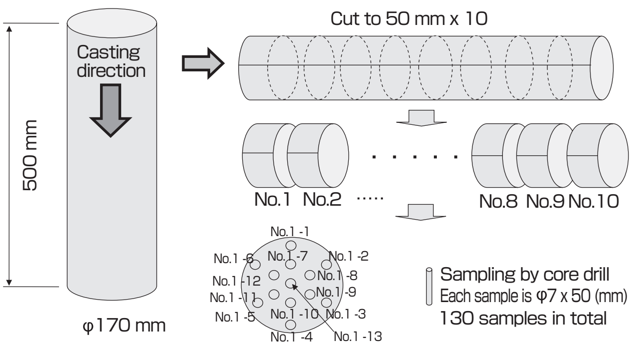


Fig. 8 Example of sample collection by core drill for the measurement of oxygen distribution in the extrusion billet

For international standardization, it is necessary to show that the method to be standardized reach a level required by experts in various countries, in addition to the establishment of the element technologies described above. Specifically, 1) an analysis value should represent the precise oxygen content of the object, 2) the range of the alloys to which the analysis method can be applied should be clear, and 3) results with a good reproducibility can be obtained by this method using a commercially available inert gas fusion device. In the following, we examine whether our proposed method meets these requirements or not.

3.1 Verification of the analysis value

When a new analysis method is developed, it is necessary to examine whether the analysis value accurately represents the content of the analyte in the measured specimen. However, the higher the novelty of developed analysis method is, the more difficult the examination is. For example, if a certified reference material with known content of the analyte is widely available, an analysis value of the new method can be verified by comparison with the certified value by analyzing the reference material. However, in an analysis method for a substance considered difficult to measure, a certified reference material does not naturally exist. In such a case, the widely used practice is to check the validity by comparing the analysis value with that obtained by another applicable measurement method, in compliance to the concept of traceability, validation, and data evaluation described in "ISO Guide 34: General requirements for the competence of reference material producers"[Note 2] issued by ISO.

Here, the "phenol dissolution method" was selected as a standard for comparison. This is a method for quantifying the magnesium oxide in Mg, based on the fact that magnesium oxide in Mg is insoluble in phenol while Mg reacts with phenol and generates phenoxide as it dissolves. The outline of this operation is shown in Fig. 9. This method is applicable only to chip samples which dissolve readily in phenol. In the cases where the phenol or methanol used for dissolving or dilution contains water, the generated phenoxide should be hydrolyzed to magnesium hydroxide. This will cause an overestimate of the oxygen content, and hence it can be asserted that the phenol dissolution method is sensitive to humidity. The phenol dissolution method is considered inappropriate as a standard analysis method to be employed at production fields of Mg components because it requires skills in complex procedures of wet analysis to eliminate the effect of humidity.

Figure 10 shows the comparison between the analysis results of various Mg materials by the IGF-IRA method and those by the phenol dissolution method. While there is a correlation between both analyses, the results of phenol dissolution method are somewhat higher than those of IGF-IRA method. This is attributed to the aforementioned moisture effect.

Next, another standard for comparison was the charged particle activation analysis (CPAA). In this method, the sample is irradiated with helium atom (α particle). The oxygen in the sample is activated as the radioactive fluoride atom, and the oxygen amount in the sample is calculated from the amount of radiation of the fluoride atom. Since an accelerator is necessary in the CPAA, it cannot be used as a routine on-site analysis. It is, however, used relatively frequently in the measurement of oxygen content in Mg in the development stage of alloys, and there are many analysis laboratories experienced in this analysis. The outline of the CPAA is shown in Fig. 11 and the results in Table 1. The samples were extruded pure Mg (no.1), the tablet formed from chips of 0.2 mm thickness by turning of extruded material in the atmosphere (no.2), and the tablet from the chips which were left for 3 days in the desiccators with 100 % humidity to enhance oxidation (no.3). Sample no.1 had oxygen concentration that was close to the lower limit of the IGF-IRA, and therefore had high standard deviation against the average value, while, for samples no.1 and no.2, the analysis values agreed within the standard deviations for

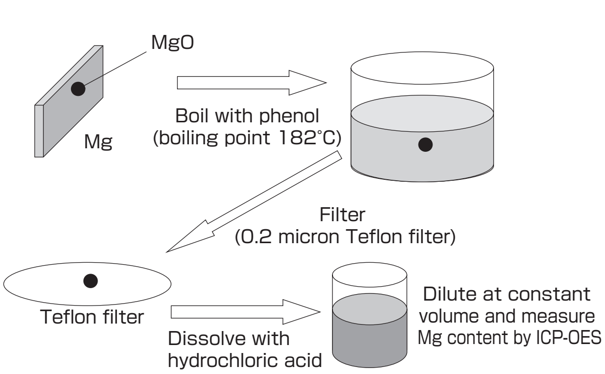


Fig. 9 Conceptual diagram of phenol dissolution method

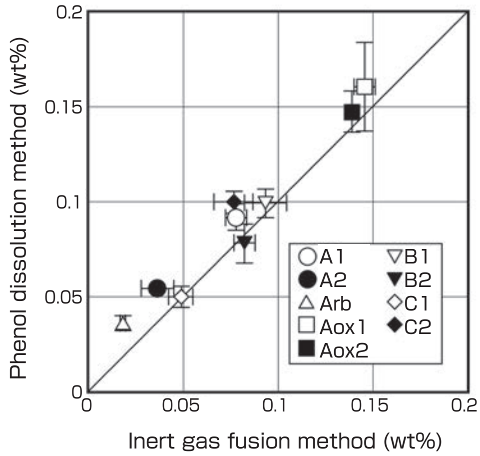


Fig. 10 Relationship between the analysis values by inert gas fusion method and phenol dissolution method

the IGF-IRA and CPAA methods. For the analysis value of sample no.3, the value for IGF-IRA was slightly lower than that from CPAA. From the analysis principle of CPAA, the cause of discrepancy was considered to be the fact that the CPAA detects every oxygen in the sample, even that in water, while the IGF-IRA measures only the oxygen in the form of stable oxides. Particularly, in sample no.3 it is inferred that a stable oxide is not formed because of incomplete oxidation by moisture and that water and hydroxides are contained. Considering these situations, it was asserted that the analysis values of the CPAA and IGF-IRA methods agree within the standard deviations for samples no.1 and no.2, which were not affected by moisture. As a result, the validity of the analysis value of IGF-IRA was considered to be confirmed.

3.2 Applicability range of IGF-IRA for Mg alloy

For Mg alloys, there are many reference materials with known alloy composition and impurity content distributed by several companies. However, there are no reference materials with certified oxygen content. Therefore, we investigated only whether there would be any problems in the measurement procedure of the IGF-IRA method using the commercial reference materials. As a result, as shown in Table 2, the procedure was applicable to most of the commercially available Mg alloys excluding some exceptional troubles in the following. For the samples containing more than 6 % aluminum, after the Mg was evaporated off from the eutectic compound, the residual Sn was found to adhere to the crucible. Furthermore, with increase in aluminum content to more than 9 %, the Sn adhered to a wide area at the bottom of the crucible. This is attributed to the fact that the aluminum tended to form carbide which has good wetness against carbon. Since the residue could be removed by the disruption of the crucible, it was recognized in this standardization that our method is commonly applicable to commercially available Mg alloys.

3.3 Applicability range of the analysis device

The analysis devices of the inert gas fusion method are

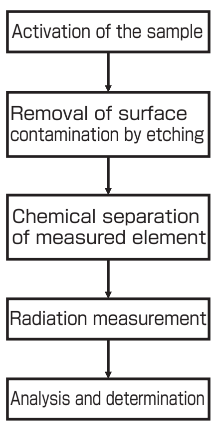


Fig. 11 Analysis flow diagram for CPAA

Table 1. Comparison of the analysis results between the inert gas fusion method and the CPAA method

Sample no.	Inert gas fusion method	CPAA method
No.1	0.0006±0.0005 (mass%)	0.0001(mass%)
No.2	0.0165±0.0023 (mass%)	0.0180(mass%)
No.3	0.0480±0.0052 (mass%)	0.0600(mass%)

Table 2. Applicability of IGF-IRA to various alloys

Name of sample	Form	Alloy composition (concentration)	Yes/no of analysis (○: yes, △: problem, ×: no)
MBH C61XMgp10	Chip	–	○
MBH C61XMgp30	Chip	–	○
MBH C63XMge30	Chip	Mn(2.36 %)	○
MBH C65XMga50	Chip	Al(6.01 %),Zn(0.411 %)	△(Adhesion of molten material)
MBH C66XMgc40	Chip	Zn(6.81 %),Mn(0.166 %)	○
MBH C67XMgf30	Chip	Rare earth(2.4 %),Zn(3.18 %)	○
MBH C67XMgg40	Chip	Zn(5.47 %),Th(1.85 %)	○
MBH C68XMgh40	Chip	Ag(2.05 %),Rare earth(2.4 %)	○
MBH C69XMgy4-a	Bulk	Zn(0.5 %),Mn(0.1 %), Nd(2.4 %),Gd(1.5 %)	○
HMP A-41-T05	Bulk	Al(4.1 %),Zn(0.2 %), Mn(0.4 %),Si(1.2 %)	○
HMP STD1/85	Bulk	Al(9.5 %),Si(1.1 %)	○
Commercial AZ91	Bulk	Al(approx.9 %), Zn(approx.1 %)	△(Adhesion of molten material)
Commercial AM60b	Bulk	Al(approx.6 %), Mn(approx.0.1 %)	△(Adhesion of molten material)
Commercial ZK61a	Bulk	Zn(approx.6 %),Zr(approx.0.7 %)	○
Commercial AMX602	Bulk	Al(approx.6 %),Mn(approx.0.1 %), Ca(approx.2 %)	△(Adhesion of molten material)
Commercial AZX1211	Bulk	Al(approx.12 %),Zn(approx.1 %), Ca(approx.1 %)	△(Adhesion of molten material)

Table 3. Result of the joint analysis test in Japan

Sample	Analysis lab A	Analysis lab B	Analysis lab C	Analysis lab D	Charged particle
No.1	ND	0.0014	Bumping	0.0006	0.0001
No.2	0.0015	0.0212	Bumping	0.0165	0.0180
No.3	0.0021	0.0492	Bumping	0.0480	0.0600

supplied from two companies; one in Japan and the other overseas. There are, however, various models according to their manufacturing year. In standardizing a method using an analysis device, a standard must include as many manufacturers and models of the analysis device used in industry as possible. Therefore, we called for participants in Japan to conduct joint analysis tests. For the analysis devices of the different manufacturer from that of our device, the analysis conditions such as applied power and heating time that suited the device were disclosed through cooperation from the manufacturer. Using the sample described in 3.1, we specified the heating condition according to the voltage applied to the graphite crucible.

The results of the above experiment and the CPAA analysis described in 3.1 are shown in Table 3. Here, the values of the device manufacturer (analysis lab B) based on their own disclosed conditions and those of AIST (analysis lab D) were not far apart from the CPAA results. There was a case where the measurement could not be done because the samples were boiled over the crucible (analysis lab C), and the case where low value was obtained because the Mg vapor was produced during the oxygen analysis of the residue due to incomplete evaporation of Mg leading to the return of the carbon monoxide to form the oxide again (analysis lab A). From these results, it was assumed that the relationship between the applied power and the graphite crucible temperature depends on the device and/or its manufacturing year. In other words, the crucible temperature rather than the applied power should be specified as the heating condition for standardization, and the method for obtaining the calibration curve for temperature versus applied power for each device must be described in the standard.

To obtain the calibration curve, the melting of the metal particles of known melting points in the graphite crucible is monitored under gradual increase in the applied power, as shown in Fig. 12. This method is widely used to measure temperatures in the graphite ohmic-heating furnace of which direct measuring of temperature inside is difficult. Figure 13(a) shows the relationship calculated from the data

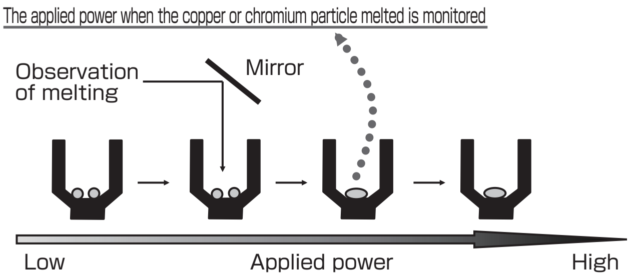
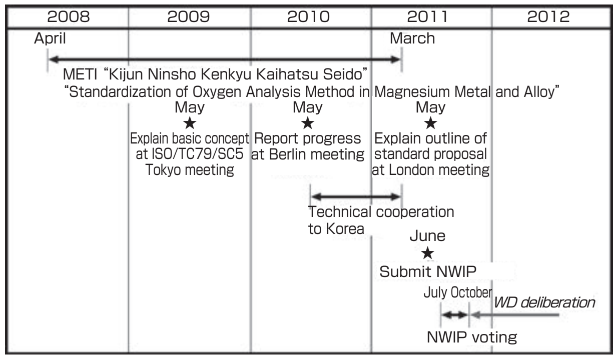


Fig. 12 Conceptual diagram of the temperature calibration of the graphite crucible

Table 4. Activities for international standardization



of five types of metals. In general, the calibration curve exhibits curvature as shown in the figure. In the temperature range 900 °C - 2,000 °C where the Mg is evaporated off, the curvature is sufficiently small and a linear regression is applicable to the data points of the power at which the copper and chromium particles melted, as shown in figure 13(b).

4 Activities for the proposal of international standard

When proposing an international standard of analysis method, it is important to indicate the intention to propose the standard and to let it be known domestically and internationally that the proposal satisfies technological demands which are internationally-recognized, in parallel with the R&D to establish a method for increasing the technological reliability. Our efforts will be described below.

4.1 Representing preferences of industry in Japan by the Japan Magnesium Association

After establishing the elemental technologies for this analysis method, we proposed the R&D project for making the proposal of an ISO standard. To know the preferences in industry, we maintained a close relationship, from the preparatory stage of the project, with the Japan Magnesium Association (JMA), which is the industry association and

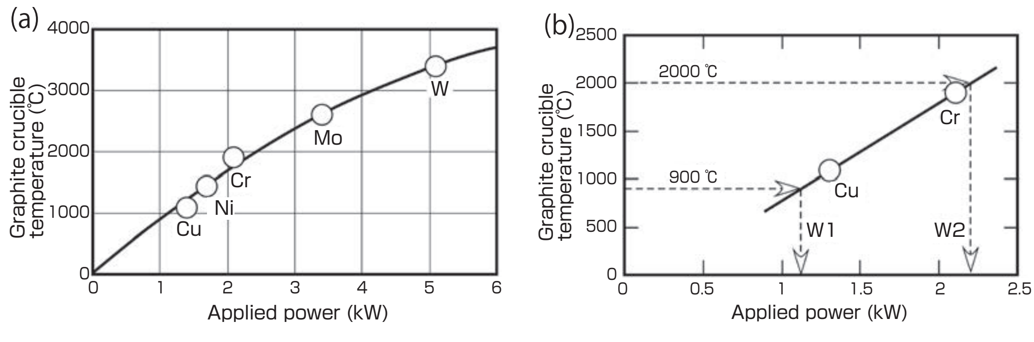


Fig. 13 Relationship of applied power and graphite crucible temperature
(a) Calibration curve by five kinds of metal of different melting points. (b) Calibration method in the range 900 °C ~ 2,000 °C.

the domestic organization deliberating proposals for ISO standard. One of the authors reported the progress of our research as a member of the Analysis Committee of JMA from the early stage of development of the oxygen analysis method in FY 2006 to develop the analysis method satisfying the demands in industry. In FY 2007, a questionnaire survey was conducted on the demands of oxygen analysis among the member companies of JMA. As a result, 20 % of the companies said that the analysis method was “needed immediately,” and 50 % “needed in the future.” The survey indicated the strong demand for oxygen analysis method in industry, and a strong reason for us playing an important role in supporting the process of proposing and carrying out the R&D project.

4.2 Preliminary activities at the ISO technical committee and cooperation with Korea

For three years from the beginning of FY 2008, we conducted the R&D project for submitting the draft standard of oxygen impurity analysis, under ”Kijun Ninsho Kenkyu Kaihatsu Seido” of the Ministry of Economy, Trade and Industry (METI). During this R&D project, we started activities at the ISO technical committee ISO/TC79/SC5[Note 3)] for Mg in advance before the submission of draft. The activities are summarized in Table 4. First, in the meeting held in Tokyo May 2009, the basic concept of this analysis method was introduced as the “Future Proposal to SC5,” and the plan of the ISO standardization proposal using this method was announced. In the meeting held in Berlin May 2010, we reported the progress of the development including the sampling method and the comparison with the result of CPAA. At that meeting, there was a report from Korea that said that the analysis cannot be done well under our measuring conditions introduced in Tokyo 2009. There is a big Korean firm that engages in both the iron and steel manufacturing and Mg components production, and they have deep understanding of the IGF-IRA method frequently used in the iron and steel industry. In addition, major Mg products in Korea are basic materials such as plates rather than components with specific functions. Under these circumstances, they have high demand for quality assurance such as suppressing oxygen content. This seems to be the most likely reason why Korea showed strong interest in the oxygen analysis method and conducted additional testing voluntarily. Recently Korea has occupied a position as a Mg basic material supplier and is enhancing its influence in SC5. It was expected that forming a technological alliance with Korea would be advantageous for the prospective standardization proposal process. Fortunately, at that point we knew the fact that the “applied power – graphite crucible temperature” relationship depends on the device and/or its manufacturing year as mentioned in 3.3, enabling to point out the cause of the problem mentioned above and solution thereof. In February 2011, a mission from the JMA visited Korea and obtained information that Korea was able to obtain stable analysis value by conducting the temperature calibration we suggested and good agreement with the result of CPAA using their original samples. In the ISO/TC79/SC5 meeting in London May 2011, we reported the method for temperature calibration of the graphite crucible and our technological cooperation with Korea. The secretary of SC5 commented, “The new proposal is well considered and we welcome it.”

The early indication of intention to propose a draft standard and giving update of the development status at the ISO technical committee provide a better atmosphere to have constructive discussions. We believe a good impression that the “standardization will go smoothly without major friction” was given to the secretariat and P member countries.[Note 4)] The draft of the analysis method including the calibration of the graphite crucible temperature was proposed at the ISO/TC79/SC5 on June 2011 after the deliberation by the Standardization Committee of the JMA,, and is currently on three-month ballot as a new work item proposal (NWIP).

5 Future prospect

In most standardization of analysis and evaluation methods, they are standardized based on established ones and from time to time, if necessary, differences of measuring conditions are reconciled among countries involved in the standardization. Meanwhile our case is perceived as rare because, we started from the development of basics of our method and eventually led to the proposal of standard to disseminate the method to industry. The dissemination and wide use of the frontier technology for analysis and evaluation is a dream of the researchers and engineers who are involved in the development of the measurement analysis technology. We believe standardization is essential in disseminating the frontier technology.

This analysis method is being applied as the product management technology for heat resistant and fire-retardant magnesium in the project of “Development of Heat Resistant Components of Power Train by Casting of Heat Resistant and Fire-retardant Magnesium” in “Senryakuteki Kiban Gijutu Kodoka Shien Jigyo” (Support Industry Project), METI. To solve the issue of rendering Mg fire retardant, which is a major problem in using the Mg in transportation machineries, an alloy doped with calcium has been developed by AIST.[7] In regard to the improvement of the heat resistance of Mg components to use at high temperature, it is widely known that the addition of rare earth elements or silicon is effective. However, all of these additive metals have high oxygen affinity and are accompanied with the increase in oxides in the alloys. Moreover, although casting is a cost-efficient method for the components manufacturing, the reuse of runner and head, which are wastes in the casting process, as feed stock for casting is essential to prevent cost increase. The reuse of the recycled material in casting may also cause oxide increase in components. The analysis method for measuring the oxygen content of the materials during the plant processes is highly in-demand as a process management and quality control technology. The Support Industry Project has a purpose to support the product development by companies and our analysis method is expected to disseminate into industry and to become popular. Currently, we are engaging in R&D that aims to sophisticate the method as a quality control technology.

Acknowledgement

Part of this research was conducted under the project of "Standardization of the Oxygen Analysis Method for Magnesium Metal and Alloy," sponsored by METI and NEDO. We express our thanks to the members of the execution committee of the project and the Japan Magnesium Association that cooperated in carrying out the project.

Notes

Note 1) The temperature of the graphite crucible during the application of 2,400 W is estimated to be about 2,000 °C from the comparison with Fig. 13(a).

Note 2) Under the assumption that an analysis method as a standard for comparison is greatly different in principle from the analysis method to be standardized, the validity of analysis value by the latter can be assessed by a comparison between them. This is based on the fact that even if both methods have errors from the true value respectively, there is little possibility that the effects of their errors have the same trend. Consequently it can be considered that the effects of the errors are small and that the analysis value is close to the true value when both methods provide similar results. (Corresponding JIS Standard is "JIS Q 0034: 2001 General requirements for the competence of reference material producer")

Note 3) ISO standardization proposal is discussed in the technical committee (TC) for the corresponding technology or the subordinate subcommittees (SC). ISO/TC79/SC5 means the subcommittee no.5 of technical committee no.79, and its name is "Magnesium and alloys of cast or wrought magnesium." The name of TC79 is "Light metals and its alloys."

Note 4) The countries that participate in the TC and SC of ISO are divided into the P (participating) members that are responsible for actively participating in the committee such as voting for the standard proposal and the O (observer) members. There are nine P members of ISO/TC79/SC5: Japan, China, Korea, Germany, UK, Italy, Russia, Spain, and Romania. China is the secretariat.

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Authors

Akira TSUGE

Joined the National Industrial Research Institute of Nagoya, Agency of Industrial Science and Technology in 1983, and engaged in the R&D for chemical analysis method of fine ceramics. After reorganization to AIST, also engaged in the research for industrial standard. In the drafting and revision of JIS R1603, R1616, was in charge of the development of the analysis method for oxygen, nitrogen, and carbon impurities in the powder of fine ceramics material. Currently, senior researcher of the Inhomogeneity Analysis Research Group, Research Institute of Instrumentation Frontier. In this research, worked on the development of the analysis method and ISO draft preparation in the research under the Standard Certification R&D Project, METI, and also worked in the preliminary activities for the standard proposal through participation in the ISO/TC79/SC5 meetings.

Wataru KANEMATSU

Joined the National Industrial Research Institute of Nagoya, Agency of Industrial Science and Technology in 1984, and engaged in research on the mechanical properties and machining damage of structural ceramics. After reorganization to AIST, also engaged in the research for industrial standard. Worked as the chief of committee for drafting JIS R1674, convener of ISO/TC206 (fine ceramics) /WG31, and project leader of ISO/TC206/WG36. Currently, leader of the Inhomogeneity Analysis Research Group, Research Institute of Instrumentation Frontier. In this research, worked on the coordination of the research under the Standard Certification R&D Project, METI as well as the ISO proposal drafting.

Discussion with Reviewers

1 Overall

Comment (Masahiro Okaji, AIST, currently at Chino Corporation)

This research clearly aims for industrial application from the beginning and engages in R&D toward the standardization as an outlet, and I think it is appropriate as a *Synthesiology* paper.

2 International situation

Comment (Yasuo Hasegawa, Energy Technology Research Institute, AIST)

You discuss the situation of Japan, China, and Korea in "1 Introduction," but I think it will become easier to understand the situation of the industry if you add a graph of the share of raw material production and goods production by countries.

Answer (Wataru Kanematsu)

I added the pie chart of the production of magnesium metal by countries based on the report by the US Geological Survey, as Fig. 1 in chapter 1. I also corrected the figures for the world share based on this (95 % → 85 %). For goods production, the market scale is small compared to other non-iron metal products, and the statistics of the industrial organizations do not have magnesium as an independent survey subject.

3 Process of selecting the IGF-IRA method

Comment (Masahiro Okaji)

Please describe the process of choosing the IGF-IRA method among several oxygen analysis methods, from the scenario-driven standpoint.

You start with the inert gas fusion infrared absorptiometry (IGF-IRA) in 2.1. I think it will be logically easier to understand if you start with the comparison of the phenol dissolution method and CPAA method described in 3.1, and show why the IGF-IRA is more appropriate for standardization. Please reconsider the line of reasoning.

Answer (Akira Tsuge)

For the process of choosing the IGF-IRA method, I added the sentences describing the problems of the analyses using activation or wet operation, and the fact that IGF-IRA method is used widely in industry and therefore appropriate for standardization at the beginning of "2.1 Development of the basic technology" to clarify the reason for the appropriateness of standardizing IGF-IRA.

4 Process of the selection of sampling method

Comment (Masahiro Okaji)

As is the case with the preceding discussion, for the sampling method, I think the reasoning is natural and easier to understand if you describe the comparison of the two methods (chip sampling and core drill methods) in the beginning.

Answer (Akira Tsuge)

I added the description at the beginning of "2.2 On the sampling method" and at the beginning of "2.2.1 Chip sampling." I clarified the process by explaining the fact that the effect of surface oxidation in the material with high oxygen affinity like magnesium cannot be avoided in general chip sampling method, and therefore the core drill sampling that has small effect on oxidation was chosen although homogenizing process cannot be done.

5 Justification of agreement with CPAA method

Comment 1 (Masahiro Okaji)

In the last paragraph of 3.1, you explained the justification of agreement between this method and the charged particle method. However, there are assumptions in the description of the cause of discrepancy of the data, and I think a more objective explanation is required here. For example, in the later paragraph, it is written, "Sample no.3 … probably contained moisture and hydroxides." Is this the result of measuring the concentration of moisture and oxides? Also, for the degree of agreement, can you say it is satisfactory in the comparison with the requirement level of uncertainty?

Answer 1 (Akira Tsuge)

The moisture and hydroxides were not measured. These are error factors caused by the assumption that the sample no.3 used in this experiment is a sample oxidized by increasing the humidity of the chips.

For the requirement level of uncertainty, the analysis value of the oxygen in metal by the IGF-IRA method is allowed to have about 2 %~10 % fluctuation by relative standard deviation (this depends on the amount of sample used). This relatively low precision is attributed to the fact that there are many cases where the oxygen analysis value in metal is used for the detection of failures associated with the increase of an order of magnitude in the analysis value in daily product process management. In this sense, this method is considered to fulfill the required standard for uncertainty for use at production sites.

Comment 2 (Yasuo Hasegawa)

You compared the two different analysis methods in chapter 3, and discussed the cause of discrepancy with this analysis method. If you can assume a definite reason, shouldn't you verify whether the degree of agreement improves when the cause of discrepancy is eliminated? If not, I think you can just say that the results agree within the margin of error.

Answer 2 (Akira Tsuge)

Since analysis results for the sample no.3 did not agree within the margin of error, we investigated the cause of discrepancy. In the comparison among the analysis methods with different analysis principle, investigating the differences originating from the analysis principle is necessary even if the result agrees within the error range; in inert gas fusion method, oxygen contained as oxide in the sample is analyzed, whereas oxygen of any form in the sample is done so in CPAA method. In this case, the difference exceeded the error range in sample no.3.

6 Validity of the result of the joint analysis experiment

Comment (Masahiro Okaji)

In 3.3, you mentioned that as the result of the joint analysis experiment by AIST and three other institutions, AIST and one institution were able to have measured values. However, you did not show the data so the reader cannot examine the validity. I think you have to demonstrate how the consistency is improved by knowing the relationship of the "applied power – graphite crucible temperature" using experimental data.

Answer (Akira Tsuge)

The results of the joint test in Japan were summarized in Table 3. I also added the explanation of each analysis value and the reason for ND (not detected).

7 International standardization

Comment 1 (Yasuo Hasegawa)

I think the process for international standardization is informative for people involved in such a project. I think it will help such efforts if you show the process in a chronological table.

Answer 1 (Wataru Kanematsu)

The efforts for international standardization are described in chapter 4 in chronological order. For a better understanding, I organized the contents in Table 4.

Comment 2 (Masahiro Okaji)

In 4.2, the position of Korea is unclear in the ISO standard proposal. Since international cooperation is important, please describe in detail the background and the process to standardization, such as: “Did Korea participate in response to the request for cooperation from Japan, or did they voluntarily raise their hand?”

Answer 2 (Wataru Kanematsu)

Since there is a big Korean firm that engages in both the iron and steel manufacturing and Mg components production, Korean delegations were highly interested in the oxygen analysis from the beginning. Therefore, the check of our measurement procedure was done voluntarily rather than by request from Japan. I added the explanation of the background of their active cooperation in our activities, with some possible implications.

Comment 3 (Yasuo Hasegawa)

What is the role of Korea in SC5? Also, did the positive evaluation by Korea affect the discussions at the technical committee?

Answer 3 (Wataru Kanematsu)

As mentioned in chapter 1, Korea is solidifying its position as a basic material supplier in the world market of magnesium. Therefore, Korea has a great influence as a P-member in SC5. We believe that the P-members other than Japan and Korea were favorably impressed with the fact that Korea verified the accuracy of the analysis method to be proposed to ISO. Some sentences were added to clarify this point.

Analysis of synthetic approaches described in papers of the journal *Synthesiology*

— Towards establishing synthesiological methodology for bridging the gap between scientific research results and society —

Naoto KOBAYASHI[1]*, Motoyuki AKAMATSU[2], Masahiro OKAJI[3], Shigeko TOGASHI[4], Koh HARADA[5] and Noboru YUMOTO[6]

[Translation from *Synthesiology*, Vol.5, No.1, p.36-52 (2012)]

The methodology of synthesis has been studied by analyzing 70 papers published in the academic journal, *Synthesiology*, launched in 2008. As a result, it has been found that each technological field has its distinctive features, e.g. there are many break-through type syntheses in biotechnology and nanotechnology, and the strategic selection types are commonly observed in the metrology and measurement field. In addition, we have found a common synthetic method as a whole. A kind of methodology called "technological synthesis" has been found to be important in the *Full Research*, and continuous follow-up process called "synthesis for social introduction" is also found to be one of the features to introduce the research results to society. Both the former and the latter involve feedback processes, and moreover, in the latter case, a dynamic synthetic method that can be called a spiral-up process is observed, where many feedback processes are repeated successively through social trials.

Keywords : *Synthesiology*, synthetic study, *Full Research*, *Type 2 Basic Research*, technological synthesis, synthesis for social introduction

1 Introduction

The objective of the journal *Synthesiology*[Term 1] is to publish the research papers on the practice of how to integrate the individual elemental technologies and scientific findings and to synthesize the results of the R&D into a form usable in society. Specifically, the journal requires that the papers present the descriptions of the research objectives and social value, the clarification of the scenario to achieve the objectives, the selection and integration of the elemental technologies, and the result evaluation and its future prospects.[1] The knowledge of the research methods obtained through the accumulation of these research papers may lead to practical examples of *Full Research*,[Term 2 [2]] and if such research findings diffuse into society and contribute to innovations, *Synthesiology* can play a major role as a new type of academic journal. The elemental technologies alone do not contribute to creating innovations, but rationally linked with the knowledge of diverse disciplines, they need to be integrated and synthesized to construct a specific technology before introduction to society. We believe it is beneficial to society to clarify the synthesis methodology of the R&D.

Therefore, of the 70 papers published in *Synthesiology* Volume 1 No. 1 to Volume 3 No. 4, we looked at nine papers in the field of environment and energy, 10 in life sciences (biotechnology), seven in life sciences (human technology), 12 in information technology and electronics, 14 in nanotechnology, materials and manufacturing, 12 in metrology and measurement science, and 6 papers in geological survey and applied geoscience. We analyzed the methods of synthetic research scenarios in each research field, and attempted extracting the common methodology. Chapter 2 addresses the basic types of synthesis of the elemental technology, chapter 3 is the analysis of the synthesis method for each field, and chapter 4 presents the characteristics of the field based on the analyzed synthesis method. In chapter 5, we present the "technological synthesis" of which the necessity in the synthesis method has been clarified, and the characteristics of the "synthesis for social introduction."

By the method of analyzing the written papers, this paper attempts to synthesize the new "study" called synthesiology to connect the research results to society.

2 Basic types of synthesis of the elemental technology

Kobayashi, one of the authors, proposed the examples of the basic types of synthesis of the elemental technology: (1) aufheben type (method by which a new concept is created by

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the sublation of two opposing theses),[Term 3 [3]] (2) breakthrough type (method in which the important elemental technology is combined with peripheral technology and grown into integrated technology), and (3) strategic selection type (method in which the elemental technologies are strategically selected and synthesized).[4] These three types were extracted from the 12 research papers published early after the launch of *Synthesiology*.

One example of (1) aufheben type is the research by Nishii "A challenge to the low-cost production of highly functional optical elements"[5] that involves the combination of glass mold and imprint methods. In this research, a new technology was produced by the integration of the two methods that were considered impossible to coexist. Based on this example, in this paper, the aufheben type is used in a wide-ranging sense in this paper to describe the "complex synthesis method among multiple elements that were thought impossible to integrate." The concept specifically contains the integration and synthesis of the "structure," "function," "entity," and others.

The example of (2) breakthrough type is "Development of a small-size cogeneration system using thermoelectric power generation" by Funabashi and Urata.[6] This is an example where the discovery of layered cobalt oxides, an excellent thermoelectric material, became a breakthrough, and the integrated technology was formed by the addition of peripheral elemental technologies.

The example of (3) strategic selection type is the "A strategic approach for comparing different types of health risks" by Kishimoto.[7] In this research, the process of synthesis is the serial selection of several elemental technologies to achieve the research objective that is the risk assessment of chemical substances. Figure 1 shows the conceptual diagram of the basic types of synthesis method. These are extremely basic raw processes in the synthesis method. The processes where these are combined concurrently or in multiple steps, or where the improvements are made through the interaction of demand and actual environment can be observed. These raw processes were kept in mind when the following considerations were made. Table 1 shows the categorization of the types of synthesis by fields, and it includes the categorization of the combined types as well as single basic types. These types will be explained in detail below.

3 Analysis of the synthesis method for each technological field

(1) Environment and energy field

The researches categorized in the environment and energy field include the extremely wide-ranging topics from the assessment technology such as environment and risk assessments, behavior and control of environmental load substances, renewable energy, energy saving, and production efficiency. Diverse methodologies have been proposed in the *Synthesiology* papers. However, following characteristics can be seen: 1) there are clear social demands such as the reduction of environmental load substances, CO_2 emission control, and compliance to social and administrative regulations; 2) to repond to these, "compromising" type or multidimensional technological integration is conducted, such as the multistep linkage of elemental technologies that are supported by science; and 3) the existing technology is further advanced through the review of elemental technologies and re-synthesis from the engineering standpoint.

For example, for the social demand of "comparing the risks of different kinds of chemical substances," it is necessary to express the scale of risk by a common index. However, since the necessary elemental data used in conventional risk assessment are insufficient, the necessary elemental data are determined by breaking down the new social demands, and the method of making estimates from the existing data is considered. The calculation of risk becomes possible based on the common index by re-integrating the elements obtained.[7] Therefore, the method taken is to strategically select the elemental technologies that match the social demands and to integrate them, and this is the strategic selective type synthesis as explained in the previous chapter.

An example of the technological development to reduce the environmental load substance is the development of the catalyst production for clean diesel fuel by Yoshimura and Toba.[8] In the detoxification of the diesel exhaust, there is the social demand to dramatically decrease the sulfur content in the diesel fuel. To do so, it is necessary to develop a high performance hydrodesulfurizing catalyst. The authors identified the breakthrough point as the catalyst preparation method, and broke down the topic into several elements necessary for this technology and clarified the division of roles with the joint researchers (organization). By further breaking down the topic, key elemental technologies were

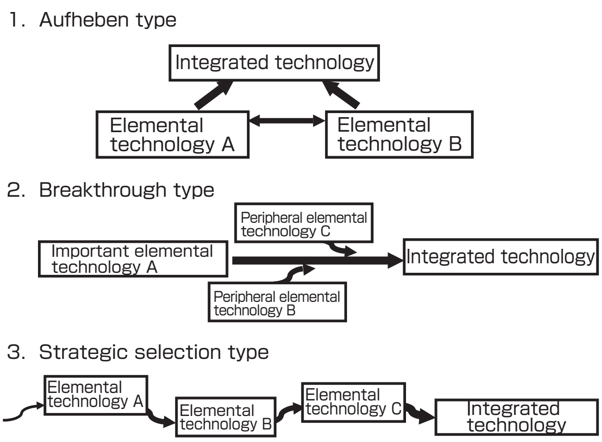

Fig. 1 Basic types of synthesis

Table 1. Categorization of synthesis by fields

	Aufheben	Breakthrough	Strategic selection	Spiral	Aufheben + Strategy	Breakthrough + Strategy	Breakthrough + Spiral	Strategic selection + Spiral	Breakthrough + Strategy + Spiral	
Environment/energy	2	1	3	0		3				9
Life science (biotechnology)		4	2	2		1	1			10
Life science (human life tech)	1		4			1		1		7
Information technology/ electronics	1	2	6				1	1	1	12
Nanotechnology/ materials/manufacturing	2	4	5		1	2				14
Metrology/ measurement science		1	11							12
Geological survey/ applied geoscience			3			1		2		6
	6	12	34	2	1	8	2	4	1	70

reviewed from the chemical and engineering aspects, laboratory level preparation method was completed as the important elemental technology, and commercialization was achieved through joint research with the catalyst producing company. Therefore, the elemental technologies broken down from the social demand had the multistep structure that was an aggregate of detailed elemental technologies. Since the lower level elemental technologies are solved by breakthrough type research and then are integrated, the overall scenario is the "strategic selection type + breakthrough type" synthesis (Fig. 2).

Another example of this type is the "Establishment of compact processes" by Suzuki *et al.*[9] To respond to the social demand of emission control of the environmental load substance from the chemical process, the technology using supercritical fluid of water or carbon dioxide instead of an organic solvent, which was a technology that was theoretically possible but not readily realized, was reviewed by breaking down into individual elemental technologies. It was found that unnecessary reactions occurred before reaching the optimal condition due to slow reaction, and the rapid heating and pressurizing methods were developed to attain the optimal condition rapidly as the elemental technology, and this process was synthesized along with other peripheral elemental technologies. The breakthrough was the process called detuning that involved purposefully withholding the ideal condition to create the optimal condition.

In the environment and energy field, since the goal is to fulfill the social demand by integrating the necessary elemental technologies, the synthesis is essential to meet the specific demand. In general, the strategic selection type scenario can be taken in the cases where the elemental technologies are identified by conducting strategic selection in the first stage and the results of R&D up to a point or their improvements to match the goal are used. This type of synthesis can be seen in three papers. On the other hand, in the case where there are major issues among the elemental technologies, which is shown in the low environmental load technology mentioned above, the breakthrough technology becomes essential, and the social demand can be met only if such breakthrough is realized. In these cases, the general scenario is the "strategic selection type + breakthrough type" synthesis, and there were three such cases.

There were also two aufheben types and one breakthrough type. The categorization is shown in Table 1.

(2) Life science field

The characteristic synthesis method in the life science (biotechnology) field is the cyclical development method. Suwa and Ono developed the comprehensive functional

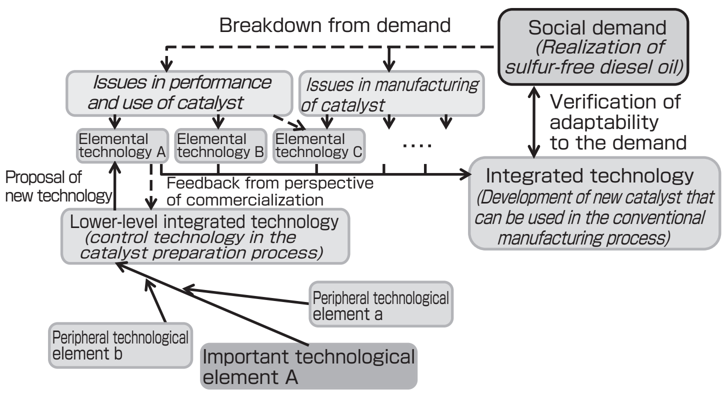

Fig. 2 Strategic selection + breakthrough type synthesis in the environment/energy field

analysis technology for drug design target genes through bioinformatics.[10] In the research that started in 2000, the elemental technologies such as gene identification and functional analysis tools were developed as *Type 1 Basic Research*, the pipeline for gene identification and functional analysis was constructed by combining the elemental technologies as *Type 2 Basic Research*, and the comprehensive database for cell membrane receptor GPCR was opened to the public as *Product Realization Research*. These became *Full Research* and the core technology was synthesized. Then, this core technology became *Type 1 Basic Research* for the next development, and resulted in the development of the new function program. Moreover, this technology contributed to the next development as *Type 1 Basic Research* for the application to organisms other than humans. The core technologies were subject to feedbacks from both the bioinformatics researchers and the experimental bioscience researchers. This helped the spread to society, and long-term maturation is taking place through the sequential development into larger *Full Research*.

Similar cyclical development can be seen in the *Full Research* for the bioluminescent protein by Ohmiya and Nakajima.[11] Ohmiya and Nakajima started from the scientific curiosity for bioluminescence, and discovered the bioluminescent proteins with different colors in fireflies. They decided to use this bioluminescent protein as the breakthrough technology for biofunctional tests. They altered the genetic structure so the protein will glow in the mammalian cells, and developed the technology to simultaneously detect the multiple gene expression in the cell. Since this technology can be used in the mammalian cells, the developed technology led to the product realization as the multigene expression kit to screen the effect of chemical substances on humans at cellular level, through joint research with companies. While this process may seem to be a relatively simple *Full Research* where the *Type 1 Basic Research* led directly to product realization, it is actually the fruit of efforts taken at each step including the demonstration of the correctness of the new concept through *Type 2 Basic Research*, product realization jointly with the companies, and social acceptance of the product. The researchers returned again to *Type 1 Basic Research* from here to handle multiple colors, and emphasized the importance of widening the concept further. Overall, the scenario is a cyclical development after the breakthrough type synthesis.

Although such cyclical development can be seen in other fields, the bio-industries seem to have characteristics unseen in other industries. Professor Gary P. Pisano of the Harvard Business School positions the bio-industry as a business that stands firmly in sciences, and offers the following analysis.[12] First, although bio-industry stands firmly in science, biology, its core discipline, is not as mature compared to physics and chemistry, and it is characterized by the extremely high uncertainty of the foundation technology. For example, it is like making a CPU without knowing the environment in which it will be used. The second characteristic of the bio-industry is the "integral type" nature. Personal computers are "modular types" where the issues can be broken down into modules and the optimization can be done for each module. On the other hand, the issues of automobiles cannot be broken down into modules, and it is an "integral type" that requires simultaneous optimization across the disciplines where the issues reside. The bio-industry is an "integral type." Combining with the first characteristic, it is like building a car where one does not know whether it will run until it is made. In the bio-industry, since the uncertainty where one does not know whether a product is usable unless it is made is greater than other fields, it is necessary to commercialize even a small product in the market. This means that small *Full Research* is necessary to grow to large *Full Research*. The authors call such synthesis method "spiral type" (Fig. 3).

Such spiral type and the combination of breakthrough and spiral type syntheses were seen in three papers. In four papers that deal with biosensors, the breakthrough type synthesis through core technology is taken instead of the spiral type. In two researches, mass preparation of antifreeze protein by Nishimiya *et al*.[13] and practical application of regenerative medicine by Ohgushi,[14] the elemental technologies needed for realization are selected and integrated, and the researches are done by strategic selection scenarios. There is also the breakthrough type synthesis where the chromatography was advanced by a totally novel method of a single system pump using reservoirs, by Iemura and Natsume[15] (Table 1).

In human technology of the life science field, the objective of the R&D is to design a product that takes into account the characteristics of the person who uses the product. There, the basic point is to scientifically understand the human

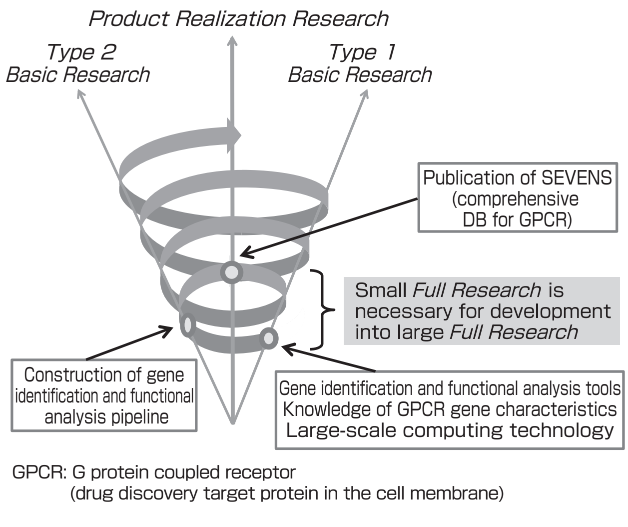

Fig. 3 Spiral type synthesis in the life science (biotechnology) field

functions. Although this is *Type 1 Basic Research*, the shift to *Type 2 Basic Research* becomes difficult if the human understanding is pursued excessively. It is necessary to clarify how the human function under study will be used and to synthesize the research scenario necessary for that purpose.

In the example of the R&D for well-fitting eyeglass frames by Mochimaru and Kouchi, the objective is to provide glass frames that fit each individual, and the technology was developed to help select the frame design that the customer prefers.[16] *Type 1 Basic Research* involves the development of shape design technology to formulate the glass frame that matches the head shape, and the elemental technologies necessary to apply this to the user purchasing the glasses are selected, and the technologies are integrated. The feature of this research is the development of the 3D shape model (homologous head model) that could be used for simple measurement, pattern categorization of the shape, and the perceptual evaluation. The overall goal was achieved efficiently. Therefore, the overall scenario is the synthesis by “strategic selection type + breakthrough type.” In fact, if the breakthrough technology does not occur, the efficiency of the synthesis becomes poor, and the research may stall. The development of the core technology as the breakthrough technology imparts great power to *Type 2 Basic Research*.

In the research on accessible design for the auditory signal that is compatible with the auditory function of the senior citizens by Kurakata and Sagawa,[17] it was important to determine the percentage of the elderly who can hear the auditory signal. Therefore, understanding the human auditory function precisely is not necessary, but the understanding of the distribution of the differences among people is important. This thinking was adapted to the understanding of the condition (auditory condition) at home where the alarm will actually be used. The sounds of the kitchen sink and television that may interfere with the auditory signal were measured, and by knowing the sound distribution, they were able to determine the sound volume that could be heard by the elderly. The property of the living environment must be understood to actually adapt the technology to the life scenes, and such study is necessary for the strategic selection type synthesis (Fig. 4).

The setting of the research scenario is necessary to understand how the human properties can lead to the product design. In the example of the research on eyeglass frames, the scenario taken was to install a device that allows simple shape measurement and style recommendation at the stores, to enable the selection of a frame that matches the individual. On the other hand, as an example of accessible design, there is the scenario where the industrial standard is employed as the tool to be reflected in the product design. If the industrial standard is referred to, product design for the elderly can easily be realized. Also, in the research for providing moving images that do not cause visually induced motion sickness (VIMS) by Ujike,[18] initially the industrial standardization was attempted, but the researchers also constructed the image evaluation system that incorporated the VIMS property that was found in the *Type 1 Basic Research*. This system was to be used by the filmmakers to learn the effects the images might have on the viewers, and corrections were to be made if necessary. The author conducted the elemental researches necessary to construct the tool that could be used by the filmmakers, and this can be considered strategic

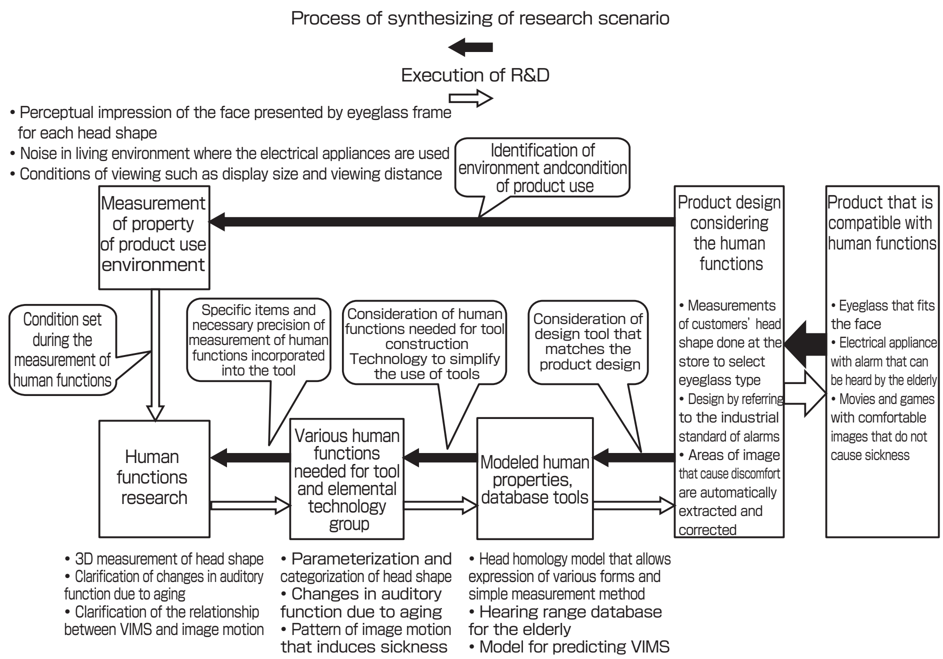

Fig. 4 Strategic selection type synthesis in the life science (human technology) field

selection synthesis. The development of the car navigation system by Ikeda *et al*. is similar.[19] In the field where a thing that is used by a person is synthesized, how the product will be used by the user (end user or the product designer) is estimated, and this is set as the goal. The basic method is to consider the elemental technologies necessary, and to synthesize the whole by strategically selecting the elemental technologies. There is also the aufheben type research by Kubo and Baba where the sensitivity based (kansei) lead user created a value different from the intent of the manufacturer of the IH cooking device,[20] and the strategic selection type and spiral type such as the Cyber Assist product where the users engaged in trials at exhibitions[21] (Table 1). The papers on the theory of service engineering are not included here.

(3) Information technology and electronics field

In the information technology and electronics field, the synthesis methods differ slightly for the device technology field such as electronics and photonics, and for the software field. In the synthesis methodology of the device field, the individual elemental technologies are clear and independent from other elemental technologies. There is a main elemental technology that becomes the breakthrough, and the integrated technology is synthesized as these technologies are combined.

A characteristic example is the research “Creating non-volatile electronics by spintronics technology” by Yuasa *et al*.[22] In this research, in addition to the extremely significant breakthrough where the giant tunnel magnetic resistance (TMR) effect was realized through the tunnel barrier of the magnesium oxide (MgO) crystals, there was a second breakthrough where the mass production technology was achieved by realizing the magnetic tunnel junction (MTJ) element with CoFeB/MgO/CoFeB structure that used an extremely special crystal growth formation. As is shown in Fig. 5, this can be considered a sequential breakthrough type where the scientific breakthrough and innovative manufacturing technology came one after the other. Such breakthrough type synthesis can be seen in the R&D for the cryptographic module by Satoh *et al*.[23] In the fabrication of highly functional optical elements by Nishii mentioned earlier,[5] the imprinting method that used to be difficult under high temperature was combined with the glass mold method that was used in the glass treatment, to realize a highly precise high-function optical element. This can be considered a typical aufheben type in which the two methods that used to be difficult to execute simultaneously are combined. The development of silicon carbonate (SiC) semiconductor power devices by Arai[24] is an interesting process of extracting the elemental technologies and issues that had to be realized, realizing these technologies individually, integrating them, and then realizing a practical technology. This is a strategic selection type synthesis.

In the papers of the software and systems field, the selection of elemental technologies and the interaction with the real society in the process of integration are the keys. In the construction of the system using middleware as in Tanaka’s Grid system,[25] the strategic selective selection and combination of the elemental technologies are shown, and the system construction is relatively clear as in the hardware system. Such strategic selection type synthesis is done in six R&Ds. In Motomura’s research,[26] the Bayesian net was used for modeling human behavior, and while it is a breakthrough type in the sense that sensing and interview technologies are added to the core technology, it is a synthesis of the combination of breakthrough and spiral type in the point that the user interaction is greatly significant as the “social circulation” (as indicated by Mochimaru,[26] Fig. 6).

In the R&D of intelligent wheelchair by Satoh and Sakaue,[27] the breakthrough technology is the omnidirectional stereo camera. Using this technology as the core, other technologies were selected strategically to synthesize the electric wheelchair, and the result of the trial by users was fed back to the development. The combination of the three syntheses is described in the paper (Table 1).

In the hardware field, the definition and selection of the elemental technologies and the synthesis method using them are relatively straightforward and clear, and the synthesis of middleware is similar. However, in the software and application fields where there are greater and more significant interactions between humans and environment, the defined and selected elemental technologies are not integrated in one direction, but they evolve and deepen through the interaction with the social environment.

(4) Nanotechnology, materials and manufacturing field

For the nanotechnology, materials, and manufacturing field, an example is the mass synthesis method of the organic nanotube by Asakawa *et al*.[28] This research involves the development of mass synthesis technology of organic nanotube and this was expected to be applied to wide-ranging fields by filling the tube with nanoparticles and proteins. This technology is a typical example of the seeds driven breakthrough type. However, mass production was made

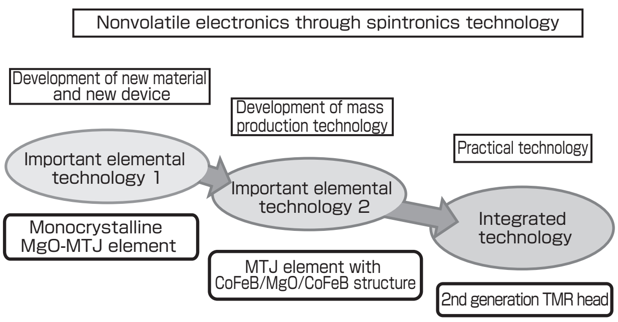

Fig. 5 Breakthrough type synthesis in the information technology/electronics field

possible by extremely fine molecular design and integrated technology, and the practical usages were pioneered through the joint efforts with companies (Fig. 7). Such breakthrough types are seen in four R&Ds including the study of non-combustible magnesium by Sakamoto and Ueno.[29]

On the other hand, in the technological development of large single-crystalline diamond wafers by Chayahara *et al*.,[30] the elemental technologies such as the microwave plasma CVD method, control of abnormally growing particles, and the size increase were strategically selected and integrated. To upsize the wafers, which was one of the elemental technologies, the breakthrough called “repeated lateral growth” was employed, but the overall synthesis is promoted by the strategic selection. Such strategic selection type synthesis is seen in five R&Ds such as of optical catalysts technology. Also, Kobayashi *et al*. developed a material with high hardness and high strength using the Fe-Al intermetallic compound by combining the technologies for casting and powder metallurgy.[31] This is an example of the aufheben type synthesis in which a new method was created by combining the new dry powder metallurgy synthesis and the conventional casting method. Aufheben is also done in the R&D of UV protection cosmetics by Takao and Sando.[32]

A characteristic example in the manufacturing field is the method where various products were developed using the aerosol deposition (AD) method by Akedo *et al*.[33] In this research, the AD method where the ceramics particles were solidified and densified at room temperature became a breakthrough, and through the strategic selective synthesis, the technology was applied to the manufacture of electrostatic chuck and MEMS scanner. The manufacturing method that employed the concept of “minimal manufacturing” with low cost, low environmental load, high function, and low resource consumption was synthesized. The R&D for PAN carbon fiber by Nakamura *et al*.[34] is also a combination of the breakthrough type and strategic selection type.

In the study of the energy-saving process for ceramics manufacturing by Watari *et al*.,[35] focus is placed on the improvement of the binder technology upon carefully investigating the technologies that must be developed for energy saving, and excellent technology was established for evaluation and improvement. This is a combination of “strategic selection + breakthrough” types, in the sense that an improvement technology was established through the scientific approach upon strategic selection of the elemental technologies toward a clear objective. Moreover, in the study of rationalization of resource and energy use throughout the entire manufacturing process by Kita *et al*.,[36] the exergy (Gibbs free energy based on the environment) was analyzed in the entire process of aluminum manufacturing, and important guideline was obtained for the casting process that contributed to resource and energy conservation. This is a strategic selection type synthesis method in the sense that the analysis was conducted by continuously extracting the elements that must be evaluated toward a clear objective.

The characteristics of the synthesis method for the nanotechnology, materials and manufacturing field are not greatly different from the synthesis of the hardware technology such as electronic devices. For materials, the result of the research is seldom launched in the market as a full product but is often used as elemental technology later, and the synthesis method is relatively clear in the case where the demand is the fulfillment of a certain performance or specification. However, in cases where there are interactions with various demands, the feedbacks are likely to be reflected in the synthesis method itself. On the other hand, while there is no major difference in the synthesis method for manufacturing technology, one of its characteristics is that one innovative elemental technology may entirely change the synthesis method. The categorization of this field is also shown in Table 1.

(5) Metrology and measurement science field

As a characteristic of the standard and metrology field, particularly in metrology standard, the main assumption is that a highly reliable metrology standard (physical standard, chemical standard, or reference material) must be delivered to the hands of the end user. It is also assumed that such standards are recognized internationally. Therefore, the scenario is built and the R&D is conducted based on

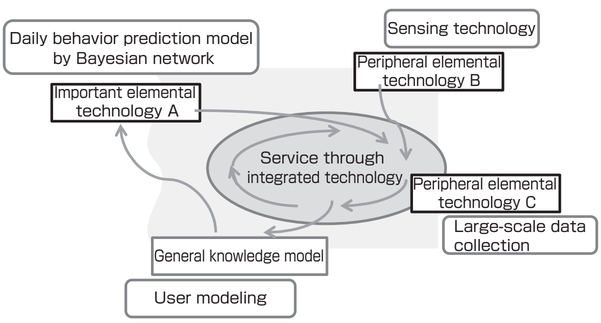

Fig. 6 Social circulation type synthesis (revised Fig. 6 in Reference [26])

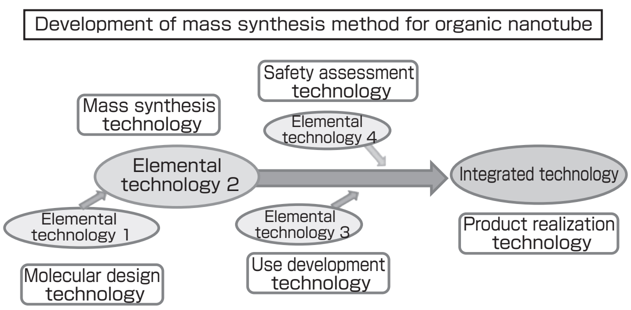

Fig. 7 Breakthrough type synthesis in the nanotechnology/materials/manufacturing field

the three requirements: 1) the establishment of national metrology standard traceable to the international standard (SI), 2) the maintenance of international consistency (through internationally recognized measurement method and international comparison), and 3) the construction of the traceability system that links AIST, the accredited calibration laboratories, and the end users. Requirement 1 corresponds to the "technological synthesis," requirement 3 to the "synthesis for introduction to society," and requirement 2 links the two. Two examples of the R&D for physical and chemical standards are shown below (Fig. 8).

An example of the physical standard is the research of the traceability system for the temperature standard to calibrate the thermocouple in the temperature range of 1000 °C ~ 1550 °C by Arai *et al*.[37] The temperature measurement in this range is particularly important in the industries where temperature management is crucial, including the materials industry such as iron and steel, as well as the parts manufacturing and semiconductor process industries where heat treatment is necessary. The thermocouple is a thermometer used most frequently in such industrial sites, but the reliability of measurement was not very high, and the establishment of the metrology standard and the organization of a traceability system had to be done quickly. The national metrology standards in this temperature range are the fixed points of temperature of pure metals. Specifically, they are the freezing point of silver (961.78 °C), freezing point of copper (1084.62 °C), and melting point of palladium (1553.5 °C). These temperature fixed points were determined by the Conférence Générale des Poids et Mesures (CGPM) comprised of the representatives of the member countries of the Convention du Mètre, based on the thermodynamic temperature scale [requirement 1]. For international recognition, international comparison (APMP-T-SI-4) was conducted with the metrology institutes of various countries, and AIST's calibration values and low uncertainty achieved the highest reliability among the participating institutes [requirement 2]. To construct the traceability system, a transfer standard that can deliver precise standard value between AIST and the calibration labs was necessary, and stability and sturdiness were required for such a transfer standard. Therefore, the highly reliable platinum-palladium thermocouple and the R-type thermocouple were developed to fulfill such conditions [requirement 3]. In this process, it was newly found that appropriate heat treatment contributed greatly to the stability of the thermocouple. Also, the application of the eutectic point as the fixed temperature point, an original technology developed by AIST, is spreading to the metrology institutes of the world, and in the near future, the provision of temperature scale with even higher reliability is expected.

The example of the chemical standard is the study of the development of the reference material to guarantee the reliability of analysis done by testing institutes for the hazardous materials (such as residual harmful substances and agrichemicals) in the food and environment that are directly linked to the safety of the Japanese citizens, by Ihara *et al*.[38] The quantitative NMR method was developed since there were over a thousand types of hazardous material in the food and environment that have been targeted for regulation by law, and there was a need to develop and analyze numerous reference materials quickly. This is an innovative method in which the calibrations of the multiple types of practical reference material are done by a minimum number of standards, rather than the conventional method where the reference materials were prepared for each chemical substance.

The NMR measurement method is normally used to detect unknown substances or to identify molecular structures,

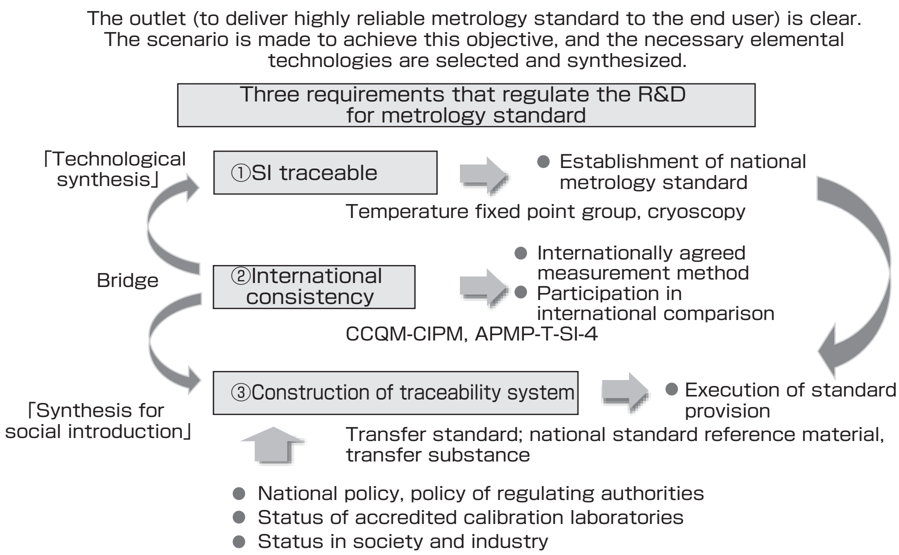

Fig. 8 Strategic selective synthesis in the metrology/measurement science field

while, in this case, the reverse thinking was used where the method was used for the quantitative analysis of known substances. Therefore, the important elemental technology was the search and selection of the measurement conditions totally different from the normal NMR (such as the adjustment of delay time of irradiation pulse or the optimization of audio filter). Also, the selection of the national reference material and the selection of the transfer material that allowed calibration of several substances were important points in constructing the efficient traceability system [requirement 3]. The SI traceability was guaranteed by using the cryoscopic method, a primary measurement method, as the check of adequacy [requirement 1]. Internationally, a proposal was made to employ this method as one of the standard measurement methods at the Comité Consultatif pour la Quantité de Matière (CCQM) of the Comité International des Poids et Mesures (CIPM), and worldwide agreement is being obtained [requirement 2]. As the supply system, through the collaborations (joint research, subcontract research, etc.) among AIST, national research centers, and private companies (manufacturers of reagent and clinical testing agents), the distribution of the reference material valued by this method was started from FY 2008. There are now over 100 kinds of substances tested. The overall structure of this research is summarized in Fig. 6 of the paper by Ihara *et al*.[38]

As shown in the above two examples, the R&D scenario and the execution process are set up with the three requirements as the boundary condition, and these researches can be categorized as typical strategic selection types. Among the papers of metrology and measurement science field published in *Synthesiology*, the research of the x-ray generator driven by batteries for metrology technology by Suzuki[39] is a breakthrough type. There are 11 papers on metrology standard that fulfill the three requirements, and they can be categorized as strategic selection types (Table 1).

(6) Geological survey and applied geoscience field

The characteristic of the researches in geology field is the spiral development through the interaction in response to the various changing social demands, as the integrated strategy is synthesized from the perspective of advancing the understanding of the whole geological phenomenon (Fig. 9). It is not an overstatement to say that the depth of the understanding of nature well into the past determines the social response to the industrial location, resource and environment, and disaster prevention.

As an example of the long-term earthquake prediction (individual strategy A of Fig. 9), Sangawa established paleoseismology through the geological “breakthrough” of the discovery of liquefaction deposits at archeological sites.[40] Moreover, as the focused individual strategy of the research unit, in addition to geology and archeological, different fields such as geophysics and engineering were integrated, and this can be called the combination of the breakthrough and strategic selection types. Based on these results, the understanding of the history of active faults in Japan and the research of the physical model and strong ground motion model of the occurrences advanced. As seen in the study by Yoshioka,[41] these researches are strategically selected and combined and utilized in location selection and disaster prevention. Such methods are applied in the researches of past tsunami deposits by research units, and are contributing to the improvement in the accuracy of predicting long-term

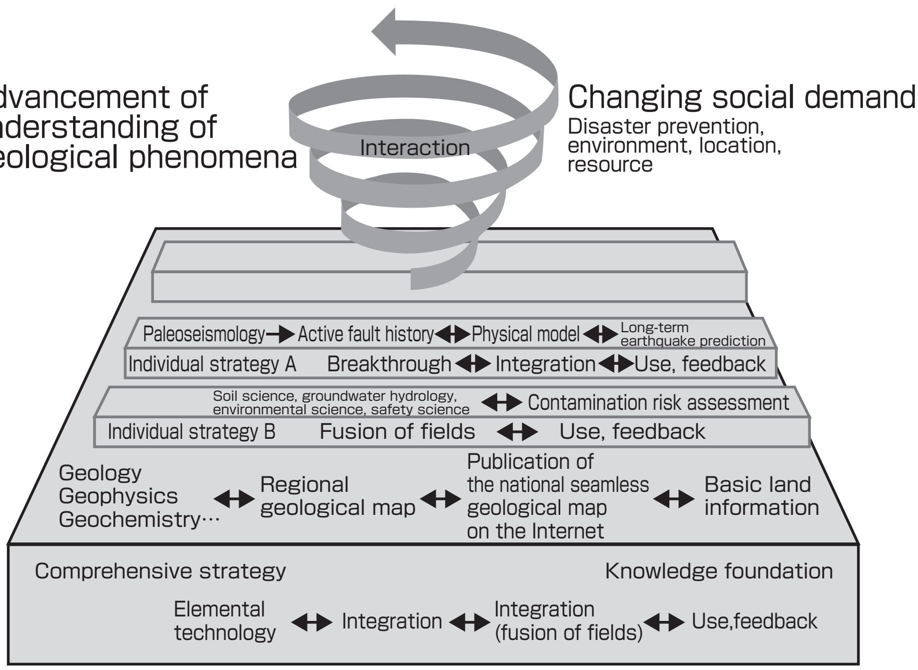

Fig. 9 Synthesis by individual and integrated strategy in the geological field

occurrences of earthquakes and their effects. In the risk assessment of the contamination of soil and ground water (individual strategy B in Fig. 9), as seen in the research by Komai *et al.*,[42] the fields of environmental science and safety science were integrated in addition to the elemental technologies of geology, the feedback was done through use in society according to the stages of advancement of the assessment method, and a refined assessment model was built.

These individual strategies may focus on a target in response to the specific demand of the changing society, and the research based on the integrated strategy for the basic land information and technology is essential as its core. The geological map that is the basic information of the land, as seen in the research by Saito,[43] is the knowledge base in response to the various usages including disaster prevention, environment, industrial location, and resources. By integrating the various elemental technologies (such as geology, geophysics, and geochemistry) based on the integrated strategy of the geology field, the understanding of the geological phenomena is deepened, and the results are provided to society as the public asset in the form of regional geological maps. Also, as seen in the research by Wakita *et al.*,[44] the geological information is joined using the elemental technologies such as information technology according to the demand of society, and the result is provided as the seamless geological map of Japan on the Internet where the updated,latest data can be used any time. With the improvements by feedback, this is the spiral type synthesis.

Many cases in the geological field take the strategic selection type synthesis (Table 1). The empirical model of the geology model is deepened through such research activities, and much deeper understanding of the geological phenomena can be reached by correlating with the deterministic model. Then, the improvement of prediction accuracy that can meet the social expectations may be realized. The research

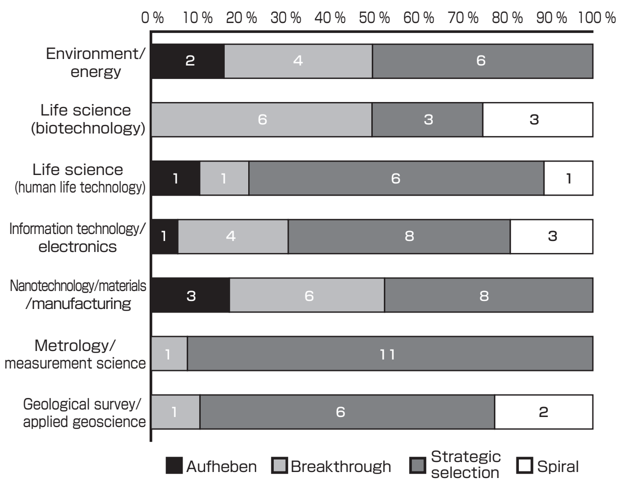

Fig. 10 Result of categorization into four types by fields (combinations types were counted into each type with overlap)

in the geological field advances as the understanding of the geological phenomenon as a complex system takes the spiral interaction in response to the various social demands.

4 Properties of the fields in the synthetic method

From the analysis of the synthetic research in the fields presented in the previous chapter, the characteristics of each field will be described in this chapter, and the common synthesis methodology will be presented in the following chapter. Table 1 shows the categorization of papers into the three types, aufheben, breakthrough, and strategic selection types, as well as the combinations of the three. Since there are not many combination types, to observe the characteristics of each field, it is assumed that combination types are composed of two or three types. The result of the overlapping count is shown in Fig. 10. Although this number is insufficient to present a quantitative discussion, differences by field can be seen. The breakthrough types dominate the fields of biotechnology, nanotechnology, materials and manufacturing, and environment and energy, particularly the R&D for low environmental load technology. These are fields where breakthroughs occur when there is good core technology. On the other hand, there are many strategic selection types in the human technology and the geology field. These are fields where the issues cannot be solved by one breakthrough technology. In all researches except one, strategic selection synthesis is done in the metrology and measurement science field, and it can be seen that multiple elements must be considered to construct the traceability system. On the other hand, spiral type can be seen in the fields of biotechnology, human technology, information technology and electronics, and geological survey and applied geoscience.

In the fields of materials, electronic and photonic devices, manufacturing technology, and in the fields of chemical and physical metrology and measurement science, there are many researches where the elemental technologies are clearly defined and the synthesis methods are relatively clear. However, in the fields of geology, biotechnology, and human

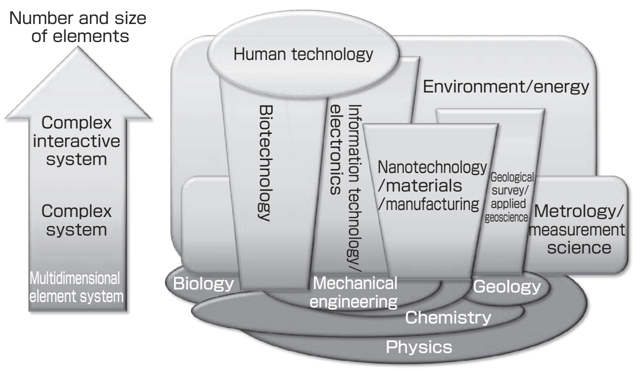

Fig. 11 Properties of the field in synthesis method

technology, the elemental technologies are complex, and the interaction with humans, society, and environment is gaining weight in the synthesis method. Figure 11 is a diagram of tentative thoughts that presents the number and size of the elemental technologies and the relationships among the fields.

The major academic disciplines that form the basis of the technological fields are shown in the basis at the lower part of the diagram. The elements can be defined clearly in the fields of physics and chemistry, and they are thought to form the basis. When the elements are finely analyzed in physics, one reaches quark and lepton, and they synthesize substances as they climb to the higher levels of nucleus, atom, and molecule mediated by interaction. The characteristic of chemistry is that the complex interaction among the electrons creates various reactions and various substances. In mechanical engineering, a main branch of engineering, the main interaction is mechanical or electromagnetic interaction, but the elements are macroscopic and the number of elements is limited. In geology and biology, the number and the complexity of the elements increase dramatically and the descriptions become increasingly diverse.

The fields that are established on these academic disciplines include: the multidimensional elemental systems such as nanotechnology, materials, and electronics that have relatively few elements; complex systems such as geology and environment and energy where, the interaction among the elements can be clearly defined in terms of physics and chemistry although the number of elements increases dramatically; and the complex interactive system such as information technology, biology, and human technology where the interactions among the elements themselves are diverse.

As the number and size of elements increase, the synthetic method becomes diverse, and this is related to the way the scenario is set up and its characteristic. In the multidimensional element system where there are few elements, the scenario can be relatively easy to understand because the elements and the synthesis method are clear. Since the technological synthesis method is clear, the logical development of the scenario can be done readily. It can also be said it is relatively easy to spell out the milestone and roadmap of the technological development. In contrast, in the complex and complex interactive systems, the number of elements increases, the interactions become diverse, and the range of synthesis spreads. The ways in which the scenarios are written are not uniform, but are characterized by the fact that the development changes through the interaction with the real society and users.

The technological fields presented here are the fields for which the R&Ds were promoted by the former Ministry of Commerce and Industry, former Ministry of Posts and Telecommunications, and former Agency of Industrial Science and Technology, Ministry of International Trade and Industry, in response to the demand of industrial promotion since the Meiji era. Although they include a wide range of fields, they do not include all the technological fields. Therefore, it must be noted that the characteristics of the fields presented in this chapter are limited.

5 Synthesis method in *Synthesiology*

(1) Technological synthesis method

Upon analyzing the 70 papers, we extracted the common characteristic of the synthesis method. The synthesis methodology seen in *Synthesiology* involves the series of processes from strategy building and scenario setting → element selection and combination → technological synthesis → trial in society. In addition to such linear process, “feedback” is a characteristic process in some cases.

As an example of individual elemental selection and

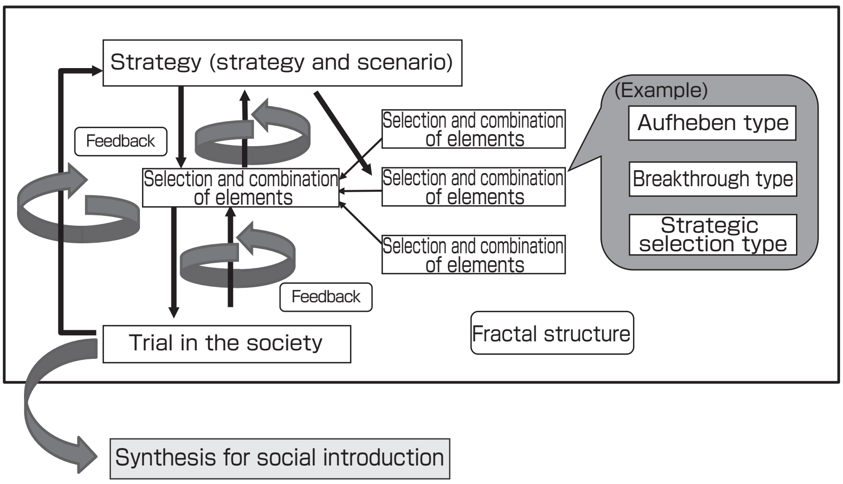

Fig. 12 Technological synthesis in *Synthesiology*

combination, the main description can be given by the aforementioned categories such as the aufheben, breakthrough, and strategic selection types. However, as shown in Table 1, the realistic thinking is that these three types are combined serially or parallelly, rather than existing independently. The synthesis normally takes place over several steps, and in some ways, a fractal structure can be seen in the technological synthesis. An example of multistep synthesis is seen in the environment and energy field as described in chapter 3 section (1). Here, the strategic selection method broken down from the social demand and the breakthrough method of important elemental technologies are combined (Fig. 12).

On the other hand, this synthesis method is conducted based on a strategy. When the elemental selection and combination are done, it is fed back to the strategy and the scenario, it is then fed back again to the elemental selection and combination. There are cases where the combinations are changed or improved, or there are cases where the strategy evolves along with the advancement of the synthesis method as the objective becomes clear. The example of the latter is “Development of real-time all-in-focus microscopes” by Ohba.[45] Here is the process where the elemental technologies were integrated and synthesized to the higher element, the objective that was ambiguous became clear, the technologies were finally integrated as the three-dimensional real-time all-in-focus microscope, and the product was commercialized. Initially, the research started with somewhat vague hypothesis formation of “realization of high-performance optical microscope.” After meeting with several companies and completing the prototype, the hypothesis was advanced, the processes of clarifying the strategy and scenario for its realization were repeated, and the product was finally commercialized. It should be noted that the verification and advancement of the hypothesis occurred through encounters with several companies.

As the synthesis progresses, the synthesized artifact comes into contact with society as a product, and the “trial in society” is conducted. It is extremely rare that the introduction to society starts smoothly. Here is the next feedback loop. When the “trial in society” is conducted, the responses from various stakeholders are offered as feedbacks, and new strategies are proposed. There may be feedback on the selection and combination of the elements rather than the strategy itself. The example of bioinformatics by Suwa and Ono presented in the life science field in chapter 3 section (2) shows the spiral structure where the effective feedback was given by the researchers who used the research result, and this led to the building of strategy and scenario, thereby turning the loop several times. In the example of geology shown in chapter 3 section (6), the understanding of geological phenomena and model building advanced as the social demand gradually changed, and the feedback to the strategy and synthesis method occurred consecutively.

On the other hand, when the feedback to the synthesis result is given through social contacts and on site trials, the dynamic movement of synthesis being conscious of time is necessary. A representative example is the analysis by Chuma on the recent decreased international competitiveness of the Japanese semiconductor industry.[46] The system-on-chip (SoC) is a design method of aggregating the necessary functions as a system on the semiconductor chip. As the clock speed increases dramatically, there are three central issues of the system design: response delay speed among the individual element, transfer speed, and the communication structure that links each job. This means that it is necessary to understand the relationships of the elemental technologies in an extremely dynamic manner. According to Chuma, the decrease in the international competitiveness of the products was because the development system of the Japanese companies could not keep up with this dynamic motion in the world. From the investigation of various case studies in this paper, it was found that in any synthesis method, the relationships among the individual elemental technologies were closely correlated and synthesized, and this correlation was temporally contiguous, and the dynamic movements such as concurrence and interchangeability were not apparent. In the future, as the competition of R&D becomes more severe, the dynamic movement and quick feedback of the linkage among the elements, as well as acceleration of R&D will become necessary.

(2) Synthesis method for introduction to society

As the final major issue, there is the “synthesis for introduction to society.” As described in the research by Ishii,[47] Fujii,[48] and Osawa *et al.*,[49] in cases where the point of introduction to society is the obtainment of traceability as in the metrology standard, it is necessary to build a social system consisting of calibration laboratories, and it is necessary to seek a measurement technology that corresponds to the traceability system. Also, in cases where the demand is clear in society, for example, a specific performance index such as the memory capacity, the technology that can meet that demand will be introduced relatively quickly. As seen in the research by Yuasa *et al.*,[22] the production technology is important as the issue for introduction to society. However, in many cases, the social activity affects the introduction independently from the technological development. For example, giving of values such as subjective sensitivity to a product and impactful concept may promote the introduction to society. Also, rather than pushing the introduction to society in a short time, it may be also necessary to promote autonomous synthesis like sowing the seed of necessary elements. Also, it is important to respond to the feedback from society, rather than the one-way provision of technology.

Table 2. Example of scenario for social introduction

In case where the demand is clarified by industry	• Construction of traceability system for metrology standard • Development of production technology that matches the new technology
In case where the demand is not clarified by industry	<u>Display elemental technology and provide samples</u> • Show impact of new technology by demonstrating the function using the sample • Extract technological and research topics to be solved through feedback obtained from sample trial
	<u>Provision of the product for wide trial opportunity</u> • Rent out prototypes to target users, and extract problems and necessary functions from open prototype • Show impact of realized function by creating the product
	<u>Promote technological introduction to the stakeholder</u> • Take time to obtain understanding of the value of new technology • Promote understanding by seeking problems jointly with the people on site
Establishment and expansion of the industry	• Add use value of the product through perceptive leading user • Collaboration with different businesses, competition by collaboration and standardization with competing companies, construction of joint relationship

As a method to get the evaluation of whether something has become a usable technology, sample provision and trials at exhibitions are done. For example, as in the research by Asakawa *et al.*,[28] the value of the technology can only be understood by having the people use the organic nanotube. Also, as seen in the research of electric wheelchair by Satoh and Sakaue,[27] in the case where the developer and the users are separate, the demands that the developer could not foresee must be incorporated. In the researches by Nakashima and Hashida[21] and Eto *et al.*,[50] the long-term trial in the field is effective in the extraction of technical issues such as reliability in software development. Such feedback through trial use can be a step that determines the additional technical development necessary to realize a product. When the major technical issues are solved and something that can be used as a product is created, still various factors are involved for such a product to diffuse into society. One factor that may be a trigger for diffusion is the technological impact that is highly visible, showing what can be accomplished. As seen in the researches by Ishikawa[51] and Ohba,[45] the standard for length that is portable and the real-time all-in-focus microscope are such examples.

The people who visit exhibitions or request sample provision are those who are seeking new technology, and have an active attitude of incorporating the technology. On the other hand, there may be cases where a major change is not really wanted on site, and people may not necessarily be enthusiastic in solving the problem even if they understand that there is an issue. As seen in the research by Kinoshita and Takai[52] in the technological transfer for system verification, it may be necessary for the provider of the technology to actively enter the field and to work on the solution with the people on site. Also, there may be people who understand the superior technology but are hesitant to introduce the new technology due to the issues in manufacture technology. In such cases, rather than promoting the introduction rapidly, it may be better to obtain gradual understanding of the value of the technology and wait for the people to autonomously initiate the introduction, as stated by Takao and Sando who developed the ultraviolet protective cosmetics using the ceramics powder technology.[32]

In the case where the scale of diffusion is large as in the consumer product, the perceptual impact to the consumer is necessary as well as the performance impact. As described in the study of induction cooking device by Kubo and Baba,[20] people called the sensitivity based (Kansei) lead users who can provide new ways of using the product to the consumer through the mass media may enhance the value of the product.

In the case where the product is composed of an integrated system including the infrastructure, the collaboration within the industry is effective to realize both the performance improvement and cost reduction. As shown in the study by Ikeda *et al.*,[19] the competitive and the collaborative developments by the companies and the common area that would be standardized were strategically laid out in the process of realizing the car navigation system. This pushed the introduction to society.

There are several steps in the synthesis, including the phase of elemental technology development where the technology is incorporated into the product, the phase of assembling from elemental technology to product, the phase of establishment as an industry after product realization is completed to some degree, and the phase where the product is diffused to the consumer. The effort differs in the case where the technological demand is clear and the case where the demand is unclear in industry. In the latter case, much difficulty is expected, and the impact of the product may be presented, active approaches to stakeholders may be done, as well as provision of samples, but there is also the strategy of “wait until the time is right” (Table 2).

6 Conclusion

The synthesis methods were analyzed and characteristics were extracted from the papers of *Synthesiology*. The characteristics of the *Synthesiology* papers are: the researcher clarifies the social objective, sets the issues that must be overcome to achieve the objective, and clarifies the scenario for how to solve the issue; the research is conducted along the scenario; and the process of execution is written as a paper of synthesiology. The contents of 70 papers were analyzed based on Kobayashi’s three basic types, but we sometimes asked the authors to confirm their understanding. Whether the paper was strategic selection, breakthrough, or aufheben types depended on the difficulty of the realization of the core technology, but the decision of whether a paper was a breakthrough or aufheben type relied on our subjective view. In some papers, the overall strategy was emphasized, and in other papers, the breakthrough of the elemental technology was emphasized. Since most of the papers were written by the researchers themselves, we judged that the papers expressed the important points of synthesis from the viewpoint of the researcher.

In *Type 2 Basic Research* conducted to utilize the research result in society, there is the "technological synthesis," and there are several basic types of synthesis. As the characteristics for different fields, although there were differences in diversity due to the number and size of elements, and the difference in the ways of reaching the goal, it became clear that a feedback process by comparing the combination of elemental technologies based on the strategy and the trial in society was necessary. It was recognized that the dynamic synthesis approach called the spiral-up where the feedback process is repeated several times through the interaction with the actual demand in society was extremely important.

In addtion, to introduce the research result into society, it was found necessary to continuously promote something called the "synthesis for introduction to society." While there are several steps in the synthesis phase, different approaches are necessary when the expansion of the industry is attempted, depending on whether the social demand is clear or not. Although the number of case studies is still insufficient, when considering the "technological innovation to society," we must accumulate the examples of such syntheses and analyze their dynamism.

7 Acknowledgement

We express our deep gratitude to the authors of the papers in writing this article. How much we were able to understand the individual research in the limited time is an issue, but we have made our best efforts in trying to understand the scenarios and the methodologies of the researches. However, I think there are cases where we failed to understand the authors' intentions, and we will be glad to have them pointed out. We would also like to express our gratitude for the valuable advices we received from many people, including the comments in the workshops and other opportunities.

Terminology

Term 1: *Synthesiology*: an academic journal launched in 2008 for the purpose of accumulating "what ought to be done" to utilize the research results in society as knowledge. The journal publishes papers that describe the specific scenario and research procedures including the research goal and social value, and the process of integration of the elemental technologies. It shows the readers what approaches can be taken to practice research that may be useful in society, and provides a place for discussion.[1]

Term 2: *Full Research*, *Type 1 Basic Research*, and *Product Realization Research*: "*Full Research*" is a research based on *Type 2 Basic Research* where the process from *Type 1 Basic Research* to *Product Realization Research* is conducted continuously and concurrently, by establishing a system where wide-ranging researchers can participate in specific issues that arise from the scenario in which the research theme is written all the way to the vision of future society.

Type 1 Basic Research is the research for building the universal laws and principles by analyzing the unknown phenomena by observation, theoretical calculation, and *Type 2 Basic Research* is research where various known and new knowledge of multiple disciplines are combined and integrated in order to achieve the specific goal that has social value. It also includes the research that attempts to derive a general methodology. *Product Realization Research* is the research for the practical utilization of the new technology in society by using the result and knowledge obtained from *Type 1 Basic Research, Type 2 Basic Research*, and actual experiences.

Term 3: Aufheben: "aufheben"(in German) is a concept in Hegelian dialectics, where the thesis and the contradicting antithesis are integrated to achieve the synthesis at higher level. In English it is called "sublation."[3][4]

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Discussions with Reviewers

1 Overall evaluation

Comment (Kanji Ueda, AIST)

This paper attempts to establish synthesiology as a science of synthesis through actual practice, and I think it is very interesting and highly significant.

2 Title of the paper and objective

Question and Comment (Kanji Ueda)

The objectives of this paper can be understood as an analysis of the synthesis method from the papers published in *Synthesiology* (main title), and to arrive at synthesiology to link the research result to society (subtitle). Does this mean the positioning of this paper is an attempt to synthesize (or create) a new "study" called synthesiology by the analysis (as a method) of the existing papers, or in one phrase "synthesis by analysis"? If so, I think you should state this clearly.

Answer (Naoto Kobayashi)

Thank you very much for your clear suggestion. As you indicated, the objective of this paper is to "aim for the new study of synthesis" as stated in the subtitle, and that means that the "analysis of the synthesis method" is conducted, as stated in the main title. The meaning is certainly "synthesis by analysis." I added this point to the end of chapter 1.

3 Definition and use of the terms "integration" and "synthesis"

Comment (Akira Ono, AIST)

In *Synthesiology*, "integration" and "synthesis" are central concepts. Since these two terms are used frequently in this paper, I shall comment on their definition and use.

In "integration," the main interest is in the process and the fact of gathering separate elements and combining them into one. What is created as a result of such combination is subordinate. Hence, the direct object of the verb "to integrate" is the element.

On the other hand, in "synthesis," the focus is on the thing that was made as a result, and the main interest is in what elements compose the thing and how its structure is. The interest in the process of combining the elements seems to be subordinate. The object of the verb "to synthesize" is the thing that is made.

If you agree with the above definitions of the terms, please review the use of the terms "integration" and "synthesis" in this paper.

Answer (Naoto Kobayashi)

Thank you very much for indicating this interesting point. As you say, the center of "integration" is the "process" of combining the elements, while "synthesis" can be considered the act of "precisely adjusting" the interaction among the elements concurrently with "integration" "toward some objective." The use of the terms were reviewed from this perspective, and when we refer to "synthesis and integration" in the paper, we reversed the order and said "integration and synthesis."

4 Relationship among the elements and fractal structure

Comment (Akira Ono)

Figure 1 shows the three basic types of synthesis. The diagrams that show the relationship between the elemental technologies and the integrated technologies represent the mutual logical relationship, and they don't necessarily represent the anterior-posterior relationship on the time axis (i.e. time flows along the direction of the arrow). On the other hand, the "spiral" in Fig. 3, "circulation" in Fig. 6, and "feedback" in Figs. 9 and 12 seem to be concepts that represent the anterior-posterior relationship on the time axes.

Also, as shown in Fig. 2, the technological system generally has a multilayer structure, and the integrated technology in the lower level may be repositioned as an elemental technology as it moves to the upper level. In the "fractal structure" in Fig. 12, the relationships between the elemental and integrated technologies seem to be similar to each other regardless of the scale of the phenomena, and have the same logical structures. Also in Fig. 3, it seems that small *Full Research* develops spirally and becomes larger *Full Research* in the upper level. Do the authors agree with this view?

Answer (Naoto Kobayashi)

I think it is as you indicated. The relationship diagram in Fig. 1 does show the anterior-posterior relationship on the time axis. For example, in the case of the breakthrough type, after a certain important elemental technology is created, it may become an integrated technology through addition of the peripheral technologies. However, the peripheral technology may already be in existence, and it does not show a structure with clear temporal flow as in the "feedback." The fractal structure is as you indicated where the integrated technology in the lower level might be positioned again as an elemental technology in the upper level. A similar structure can be seen in the case of *Full Research*.

5 Content of aufheben type

Comment (Kanji Ueda)

In chapter 2, it is stated that the aufheben type is when there are two theses that are in pro-con relationship, a new concept is created through sublation. However, in the similar issues of science and technology, rather than the sublation of strictly opposing antinomy as stated in Hegelian philosophy, I think there are many cases where the opposition entails conflict, trade off, or overall optimization problem among multiple (not necessarily two) elements. I think it will be easier for the readers to understand if you explain the basic types in terms, not only of concept, but of "structure," "element," "requirement," "function," or "entity." Please quote any references in which the authors discussed the basic types.

Answer (Naoto Kobayashi)

As you indicated, the aufheben type described here includes the issues of conflict, trade off, and overall optimization of multiple elements, rather than the sublation of strictly opposing antinomy. We did wonder whether the word aufheben should be used, but we came to a decision when we were considering the example where the combination of two technologies that have very different characteristics and may not coexist together led to an advanced integrated technology. One example is Reference [5] "A challenge to the low-cost production of highly functional optical elements" by Nishii. In this research, the integration of "structures" was done through the glass mold method and the imprinting method. Developing this way of thinking, we have employed the wide-ranging meaning of the "complex synthesis method among multiple elements for which integration and synthesis were considered difficult." Also, I added the description in chapter 2, that it includes the "structure," "element," "requirement," "function," or "entity," rather than being a mere concept.

The description of the basic types was not published in an earlier paper, but it was first presented by one of the authors (Kobayashi) in the discussion with Professor Lester in Reference [4].

6 Utilization of the basic categorization in actual research

Question and Comment (Akira Ono)

I wish that the synthesis methods (categorization into the three types) presented in this paper is useful when executing actual researches. In that point, whether the three-type categorization of this paper is reasonable will be demonstrated by seeing whether they can be used effectively in actual research execution. How do you think the various schemes shown in Figs. 1 to 9 can be used practically in the planning, proposal, organization, management, and evaluation of research projects?

Particularly, referring to the *Synthesiology* paper "Formation of research strategy and synthetic research evaluation based on the strategy - Toward research program evaluation as a creative activity" [N. Kobayashi, O. Nakamura and K. Ooi, *Synthesiology English edition*, 4 (1) 19-34 (2011)] that was written by Kobayashi, one of the authors, what is the possibility of applying the present synthesis methods to the research evaluation?

Answer (Naoto Kobayashi)

Thank you very much for your valuable indication. Certainly, whether the three categories of synthesis presented here and their combinations are reasonable must be verified by seeing whether they can be used effectively in the actual research execution. On the other hand, I think it is possible to use them in the planning, proposal, organizing, management, and evaluation of the research project.

For example, recently, there is a demand for planning and design of research projects with the goal of innovation creation right from the beginning. The points are: 1) to clarify the "logical development structure" where the upper level elemental technologies are synthesized and these will synthesize the even higher level elemental and integrated technologies, by clarifying the elemental technologies that must be developed in research, as well as the characteristics of the elemental technologies and their relationships; and 2) to incorporate beforehand the method of the "feedback process" where the synthesized integrated technology is subjected to actual application including trial in society, and the result is fed back quickly to the next synthesis. In this case, it is possible to utilize the various schemes shown in Figs. 1 to 9, and overall, the developmental structure shown in Fig. 12 can be applied. In cases of research proposals or research organization, we can consider the "elemental concept" and "elemental group" instead of the elemental technology.

In research evaluation, the application to the series of processes for evaluating the research project can be considered. In this case, the elemental group (for example, technological elemental group or managerial elemental group) that produced the research result is extracted, and the "elemental evaluation" is done by evaluating their specific properties. Next, the relationships of such elemental groups and the temporal development relationships are analyzed to conduct the "integration evaluation" where the process that produced a certain bunch of research result is evaluated. Then, the "evaluation from the viewpoint of outcome (feedback)" can be done by projecting the outcome obtained from the research results into the future, by feeding back from the actual application. In the process of analysis in this paper, we did not consider whether this synthesis method can be applied to planning and evaluation, but we have realized that there is potential through the indication from the reviewer.

7 Characteristic of the synthesis method for each technological field

Question and Comment (Kanji Ueda)

In chapter 3, you analyze each technological field and extract some interesting characteristics, but I ask two questions. First, the six research fields at AIST are characterized by the social (or political) demand, unlike the definitions of the general academic field, and perhaps you should explain the definition of the fields or their origin, so external readers can understand and to develop this further as a general discussion.

Second, don't the original characteristics of such fields characterize the synthesis method? That is, for example, aren't you falling into a self-contradictory explanation where the fields with strong strategic characteristic have the strategic selection synthesis method?

Answer (Naoto Kobayashi)

For the first point, it is as you indicated, and we added the definitions of the fields at the end of chapter 4.

For the second point, as you indicated, it was found that the strategic selection type synthesis was used frequently in the metrology and measurement science field because the strategic goals are clear. However, this method was discovered when reviewing the papers of other fields (environment and energy field), but it was also seen frequently in the metrology and measurement science field. Also, please understand that there are many technological breakthroughs in the strategic selection type synthesis.

8 Example of the hypothesis formation in the scenario

Comment (Kanji Ueda)

One of the essences of synthesiology is the hypothesis formation in the scenario where the possible candidates of a solution or the process of reaching an effective solution are presented, since there is no unique solution. I think you should discuss what kind of hypothesis formations were done in the papers analyzed.

Answer (Naoto Kobayashi)

The example where the product realization and commercialization were accomplished by repeating the cycle of hypothesis formation, realization, clarifying the scenario, and then advancing the scenario through the next hypothesis formation, is shown in Reference [45] "Development of real-time all-in-focus microscopes" by Ohba. There, product realization was attempted based on the prospective elemental technologies that were developed earlier. Initially, the hypothesis formation was rather ambiguous "realization of high-performance optical microscope." However, after meeting with several companies, feasibility study was conducted, the product was completed, the hypothesis was advanced, the scenario toward realization was clarified, and this process was repeated. In that process, the strategy became clear and the product was finally realized. The author mentions that it was greatly significant that there were several encounters with the companies before reaching an effective solution. I thought this was an excellent example of synthesiology based on hypothesis formation, and I addressed this point of the paper in chapter 5.

Durable polymer electrolyte fuel cells (PEFC) for residential co-generation application

— Elucidation of degradation mechanism to establish an accelerated aging test method of PEFC —

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[Translation from *Synthesiology*, Vol.5, No.1, p.53-61 (2012)]

Co-generation system using clean and compact PEFC which makes highly efficient power generation possible, promotes considerable energy savings at home since it provides both heat and electricity together. Therefore, its commercialization has been expected. The goal of 40000-hour-operation has been set as a practical target. In order to realize it, the durability of PEFC has been technologically prospected and the accelerated aging test protocol of PEFC has been developed within the frame of the consortium of PEFC makers, energy companies, academia and AIST. AIST has shown the rationality of the accelerated aging test protocol of PEFC through the experimental verification of hypothetical degradation mechanism. The application of the developed accelerated aging tests to actual fuel cells has made it possible to get a clear view of practical durability, and this has led to the commercialization of residential PEFC co-generation.

Keywords : Polymer Electrolyte Fuel Cell, accelerated test protocol, degradation mechanism, co-generation system for resident

1 Introduction (Background of research)

The fuel cell power generation, in which the energy generated in the production of water in the electrochemical reaction of hydrogen and oxygen is used as electricity, is a technology where the chemical energy of a substance is directly converted into electric energy. It is not limited by the Carnot efficiency because it does not involve heat energy as in the heat engine, and high energy conversion efficency can be expected. Therefore, many researches have been conducted for its practical application. Since the fuel cell converts the energy of the chemical reaction between hydrogen and oxygen to electricity, the reaction progresses faster at higher reaction temperature, and this enables improvement in efficiency. Since the produced emission is water, it is clean and is highly environment friendly.

The fuel cell started from the gas reaction experiment conducted by Sir William Robert Grove of Britain in 1839. As shown in Fig. 1, this experiment probably involved two platinum electrodes in dilute sulfuric acid solutions, where one electrode was filled with hydrogen gas and the other with oxygen gas. The electrodes were connected in series, and electrolysis was conducted by the generated electricity. The power generation using the electrochemical process did not advance far compared to the dramatic leap of the generation using the heat engines. However, the basic researches for the high-temperature fuel cell were conducted as one application of this technology to the generation method using coals combustion technology, the major fuel course of that time. The fuel cell researches using the molten salts, oxides, and others as electrolytes were conducted in the early 20th century. In 1921, the high-temperature fuel cell of 1.5 kW was demonstrated using molten carbonate as the electrolyte.

The basic configuration of the current fuel cell in which the porous structures of the cathode and anode are sandwiched between electrolytes was established in 1933 in the Bacon cell that used alkaline water solution as the electrolyte and nickel sintered compact as the electrode. The Bacon cell was significant in presenting a practical fuel cell configuration where the efficient electrode reactions were obtained at the

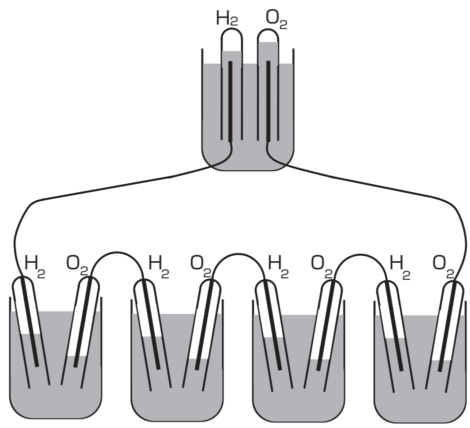

Fig. 1 Sir Grove's gas voltaic battery which was assembled of platinum electrodes in dilute sulfuric acid solution
The upper part is the electrolysis of water. Lower part is the fuel cell.

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three-phase interface composed of gas as the fuel (hydrogen gas) or oxidant, liquid as the electrolyte, and a solid electrode, respectively. The Bacon cell, which achieved the basic design of the practical fuel cell, was put to actual use, although in a special circumstance, as the power generating device for the spacecraft in the American space program. Later, the alkaline fuel cell was installed as the power source of the space shuttle.

On the other hand, the fuel cell used in the actual spacecraft Gemini 5 in 1965 was the type in which the cation exchange membrane was used as the electrolyte, rather than the alkaline type. This fuel cell used pure hydrogen and pure oxygen that were the propellant of the spacecraft. Later, as mentioned earlier, the alkaline type became the mainstream for space use. On the other hand, DuPont developed Nafion, the fluorocarbon cation exchange membrane, and the performance increased greatly. In the 1970s, the development of the fuel cell power system was started as the next generation power generation technology. As the power generation technology, it was preferable to use air as the oxidizing gas due to its simplicity as a system. However, air contains carbon dioxide, and in the fuel cell that uses alkaline solution as the electrolyte, there was the issue of decreased performance due to the production and accumulation of unsolved carbonate salt in the electrolyte. Moreover, the fuel gas of the fuel cell power technology contains carbon dioxide because the hydrogen gas as fuel is produced from hydrocarbon. Therefore, in the development of the fuel cell power technology, it was necessary to add a device for removing the carbon dioxide or to use acid electrolyte. Therefore, both the developments of the fuel cell using alkaline and the one using acid, for example, phosphoric acid were conducted in parallel. Later, from the standpoint of long-term performance stability, the development of phosphoric acid fuel cell progressed. Today, it is developed as the distributed generation system of about 100 kW with lifespan of about 60,000 hours. In terms of system cost, it is competitive as the distributed power generation technology. During the Great East Japan Earthquake, it was used as the alternative power generation system during the blackouts,[Note 1)] and its durability and cost are the issues for practical application.

After the development of the Nafion membrane, the nanotechnology to reduce the amount of platinum in the catalyst to a few fractions was developed in the late 1980s, by utilizing the platinum surface efficiently as a catalyst, by mixing the platinum supported carbon and the cation exchange resin electrolytes. This kicked off the development of the polymer electrolyte fuel cell (PEFC) for power generation in Japan as well as the United States and Europe in the 1990s. The developments were planned for distributed cogeneration and automobile application. Although there is a long history of development of the fuel cell, the cases of its practical application are limited. For its product realization, there are research efforts necessary in the phases from basic research, development, and commercialization. AIST engages in *Full Research* that engages systematically from basic research to product realization. Here, we present the efforts in *Full Research* using the example of the fuel cell.

2 For the practical application of fuel cells

The fuel cell is a power generation device that produces electricity by the electrochemical reaction of hydrogen and oxygen. It is a component of the product used by the end user. Therefore, the fuel cell itself is not the product. For example, considering the product such as the fuel cell automobile, the fuel cell is the engine that propels the automobile, and whether the end user buys this product depends on his/her thinking on the value of the fuel cell automobile. While the fact that the automobile has an efficient power generation system that is clean and environment friendly, which are the characteristics of the fuel cell, as the engine may enhance the value of the fuel cell automobile, the value of an automobile is determined by the combination of driving performance, fuel-savings, and price. In conducting the fuel cell technology development for practical application, the issues of performance, cost, and durability were handled one by one. This arose from the fact that the fuel cell technology was in the technological budding stage where the three issues could not be solved at once. Therefore, it could not get out of the R&D stage. At the same time, this indicated that the fuel cell technology was always the technology of the future against the competing technologies such as the internal combustion engine and secondary batteries. This was not just a problem of fuel cell technology. In the basic research phase of many next-generation technologies, the simultaneous achievement of the solutions that must be solved for practical application is difficult, and the research must concentrate on one issue at a time. Therefore, as the development of the solution to one issue is sought, other technological issues are left behind in terms of practical application. This is a difficulty that faces the researchers conducting the R&D.

In the fuel cell technology, attempt was made to overcome this issue by downsizing the fuel cell in the product to lower the hurdle of technological issues, yet not detracting from the value as a product. While this method may not be effective for all products, there seemed to be opportunities for trials due to the demand of the social situation or due to the marketability of the product. The residential cogeneration system that incorporated PEFC as the generation device could be used in the residential cogeneration where the exhaust water used for cooling the heat produced along with the electricity generated by PEFC at around 70 °C could be used as hot water. This was expected to be the product with the role in global warming countermeasure through energy saving and reduction of CO_2 emission at home. In fact, there was a preceding case where the residential cogeneration system with the gas engine was commercialized and became wide spread in 2003. The generation efficiency of the gas engine was over 20 %, and it was heat-main electricity-sub supply where the main supply would be heat rather than electricity. As the energy utility form at home, the percentage of electric appliances increased, and considering the hot and humid climate in Japan, it was thought that electricity-main heat-sub supply where the percentage of electricity supply was higher would have higher demand. Therefore, high electric power generation efficiency was required in the cogeneration devices. As the generation efficiency of PEFC was expected to surpass 30 %, the potential for the marketability of residential fuel cell cogeneration system was expected to be high. In fact, accompanying the continuous progress in the R&D for PEFC after the 1990s, the generation efficiency was in the 30 % level performance and the conditions for commercialization were being fulfilled. However, the durability of the product was insufficient compared to the competing technologies, and the technological development to maintain the durability for withstanding practical use was necessary.

In this situation, in 2004, the government policy was set to introduce the residential fuel cell cogeneration to expand the use of fuel cells by 2008. The demonstration of PEFC residential cogeneration system started in 2005, and at the same time, R&Ds were conducted for increasing the durability that was necessary for commercialization. The goal for durability of the PEFC in its initial commercialization stage was set at 40,000 hours considering the social acceptability and system cost. Figure 2 shows the thinking of the development in the background of the social shift to low carbon energy society, where the downsized fuel cells would lower the hurdle of technological issues against the competing technologies, and the focus on durability as the development issue for residential cogeneration would enhance commercialization.

The technological development of improved durability was also essential for the automotive and mobile power system uses in which the PEFC technology could be used. In automotive use, the severe usage environment, rapid output shift for the power source device, start-up in a short time, and others were expected, and in practical use, the actual operating time would be shorter than the idle time. Such difference in operating conditions may require different measures when making technological estimates for obtaining durability. However, there is no major difference in the PEFC material configuration, and the findings on degradation phenomenon and mechanism obtained in the investigation for residential cogeneration system can be applied.

3 Objective and necessity of accelerated aging method of PEFC

The development of PEFC technology in Japan was started as the national project and by fuel cell system manufacturers in the early 1990s. Therefore, the system manufacturers accumulated unique technologies for the PEFC material, configuration, and system. As mentioned earlier, around 2004 the direction for the commercialization in 2008 of the fuel cell residential cogeneration was given to promote energy savings and as a measure against global warning. While the companies were aware of the common technological issues for obtaining the 40,000-hour durability, the exchange of technological information did not occur. Particularly, the degradation phenomenon that was the issue in practical use was unclear, although it was expected that the operating condition of PEFC would affect the material, performance, and cell structure.

As part of the establishment of technology pertaining to the durability for the commercialization of PEFC in 2008, the 3.5 year NEDO Project “Fundamental Research of Degradation of PEFC Stacks” was started in October 2004, in the industry-academia-government collaborative consortium consisting of the system maker, energy supplier, universities, and AIST. While 40,000-hours-operation were required as the durability of the fuel cell that would be the main body of the fuel cell residential cogeneration system, the lifetime of PEFC stack in 2005 was about 10,000 hours, and the technology to dramatically increase the durability was necessary. To clarify the common degradation issue for which the fuel cell system makers possessed unique technological information, the makers set the goal of developing the accelerated test protocol for the fuel cells. The project was executed under the scheme of clarifying the degradation phenomenon and mechanism. Since 40,000 hours was about 4.6 years in actual time, the development of the accelerated test to predict the 40,000-hour durability in a year was meaningful to the companies. At the same time, since the accelerated test protocol would be explained by the degradation mechanism, the investigation of degradation

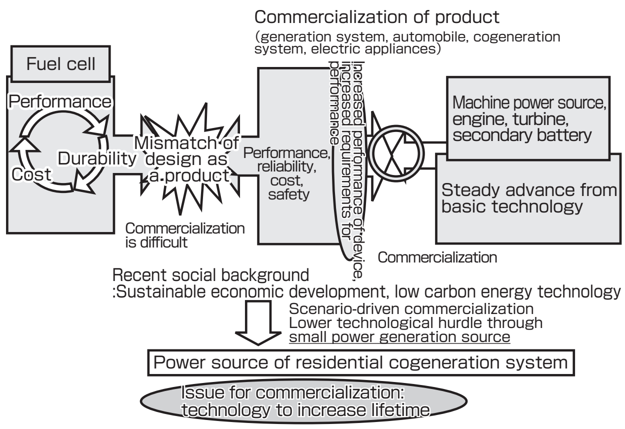

Fig. 2 Past processes of the fuel cell development and the development toward commercialization

factors would progress. In the actual project, the confirmation of 40,000-hour lifetime by the accelerated test was not the only objective, but the clarification of the degradation factors was an important issue of PEFC development.

In this project, to establish the technology for practical accelerated tests for the fuel cell cogeneration system expected to be commercialized in 2008, the accelerated test to estimate the use of 40,000 hours in one year was developed. Led by the energy supply companies that were close to the end users, roundtable discussions were held among the energy supply companies and the fuel cell system maker on the issues pertaining to the PEFC degradation in the fuel cell cogeneration system. The priority issues for the PEFC degradation were extracted, and the objectives were set to clarify the degradation mechanism and to develop the accelerated test method.[1]

4 Investigation of the degradation mechanism

4.1 Degradation factors of the actual cell/stack and the accelerated aging method

Figure 3 shows the data for the time profile of the cell performance that the participating members possessed at the start of the project. The degradation due to the decreased cell performance were categorized into four patterns and investigated.

In the accelerated degradation pattern of (c) the constant output is continued in normal operation, but the folding point cannot be estimated. It was judged to be most fatal for the cogeneration system because the standard output would no longer be obtained immediately after the folding point. In the linear performance decline of (a), the end life can be estimated from the rate of voltage decrease. If this period is

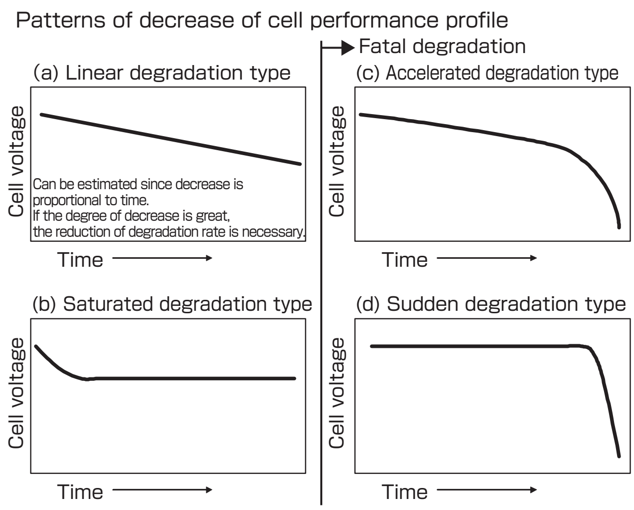

Fig. 3 Types of degradation behavior in the time change pattern of cell property

faster than 40,000 hours, it must be controlled. For pattern (d), it was determined that this is caused by the problems in the management of cell manufacture or the failure in system configuration. Based on the above patterns, and considering the time profile data of the cell performance of the system makers and the information pertaining to the cell material degradation, it was determined that the most important point was to cover the following three requirements, and priority should be given on solving them as well as clarifying the mechanism. The three requirements were: 1) to obtain the accelerated degradation pattern of (c); 2) considering the case of 40,000 hour durability with no saturation in the decrease of cell voltage, the effect is fatal; and 3) at this point, the evaluation method of degradation and countermeasures are not clear. The “decline of CO poisoning resistance” and the “decrease of gas diffusion due to the flooding at the electrode” shown in Fig. 4 were selected as main topics for the practical degradation factors, and were shared commonly as main topics among the members.

As the test protocol to accelerate the degradation factor, we proposed the introduced gas switching method. This test involved the two techniques: 1) the method of introducing air and nitrogen (inactive atmosphere) alternatively to the cathode (air electrode) of PEFC (method 1); and 2) the method of repeating the cycle of hydrogen → nitrogen → air → nitrogen → (hydrogen) to the anode (fuel electrode) of PEFC (method 2). In both methods, it was predicted that the surface of the supported carbon of the cathode catalyst layer would become oxidized by the retention of high potential at the cathode, flooding by water accumulated on the catalyst surface would progress, and gas diffusion at the electrode would decrease. For the establishment of the accelerated test protocol, the clarification of the corrosion reaction mechanism and the carbon corrosion behavior at the material surface was important.

For the “decrease of CO poisoning resistance of the catalyst at the fuel electrode” that was the other degradation factor, we considered including this as the accelerating condition. However, in the actual system, it was confirmed that the effect was seen when the CO concentration in the fuel gas was at several 10 ppm level. It was determined that a practical accelerated test would not be possible unless the factors that caused the CO poisoning could be controlled with high accuracy, and it was also determined that it was not appropriate to conduct the accelerated test on the base of this factor. Since this phenomenon occurred as a result, it could be used as the index for determining the degree of degradation. In the actual PEFC anode catalyst, normally, to add resistance to CO poisoning, the alloy of platinum (Pt) and ruthenium (Ru) is used instead of the Pt catalyst that is readily poisoned. However, the decrease of CO poisoning resistance occurs with this alloy catalyst, and it is thought to occur as the Ru dissolute from the anode catalyst in long-term operations. Also, the behavior of platinum in the alloy catalyst may be related to the durability.

4.2 Degradation observation of the real cell

To observe the fine structure of the real cell to which the aging test was done at micro level, the structural observation of the electrode catalysts was done using the transmission electron microscope (TEM). In the TEM observation, the first issue was to fabricate a sample that could be observed under TEM from the real cell subject to the aging test. The cell with which the generation test was done in the simulated aging condition was disassembled, and the thin EM sample slice of the membrane-electrode assembly (MEA) was made using an ultra microtome. Using this method, the structures of the electrode catalyst and the electrolyte membrane could be preserved and observed. Observations were done for the samples subject to the aging tests under various conditions including lack of fuel, potential flux cycle, and high potential.[2]-[4] From the measurement of the particle size distribution under TEM observation, it was found that the size of the electrode catalyst particle increased, the composition of the Pt-Ru fine particle changed[2] as the Ru eluted from the anode Pt-Ru/C catalyst as seen by energy dispersive X-ray spectroscopy (EDS), and the phenomenon occurred where the metal particles of the electrode catalyst precipitated into the electrolyte membrane depending on the test condition, as shown in Fig. 5. For the particles that precipitated into the electrolyte membrane, it was found that the particle size distribution and the spatial distribution and precipitated particles changed by the influence of the type of gas supplied to the anode and cathode and by the thickness of the electrolyte membrane.[4] Figures 5a and 5b are the TEM images of the surrounding area of the cathode when the cathode potential was retained at 1.0 V, nitrogen gas was supplied, and the electrolyte membranes with thickness 50 μm (Fig. 5a) and 175 μm (Fig. 5b) were used. The lower part of the photo is the Pt/C catalyst layer. In the case of the thin electrolyte membrane, many particles were precipitated near the Pt/C catalysts layer. When air was supplied to the cathode (Fig. 5c and 5d), the precipitated particles were distributed to areas further from the catalyst layer compared to when nitrogen was supplied. It was thought that the concentration inside the membrane of the hydrogen that permeated the membrane from the anode affected the precipitation distribution of the platinum particle in the membrane. In the EM observation, as shown in Fig. 5, the structural assessment of the electrode catalyst fine particles from μm to several nm is possible. The effectiveness of the fine structural analysis in practical materials such as PEFC was demonstrated. As the advancement of the recent EM technology is dramatic, the observation of a single atom of Pt is possible, and we think detailed data on the electrode catalyst structure can be obtained. With the improvement of the spatial resolution of EM, it is becoming possible to study the details of the electron state of carbon with the increased sensitivity of electron energy loss spectroscopy (EELS). Detailed information can be obtained for the carbon degradation of the cathode catalyst.

4.3 Clarification of the degradation mechanism in a model cell

While it was known through experience that the start-stop operation of PEFC enhanced degradation, in 2005, an American researcher proposed the theory that the degradation occurred due to the “reverse current decay mechanism.”[5] This theory states that when the fuel supply

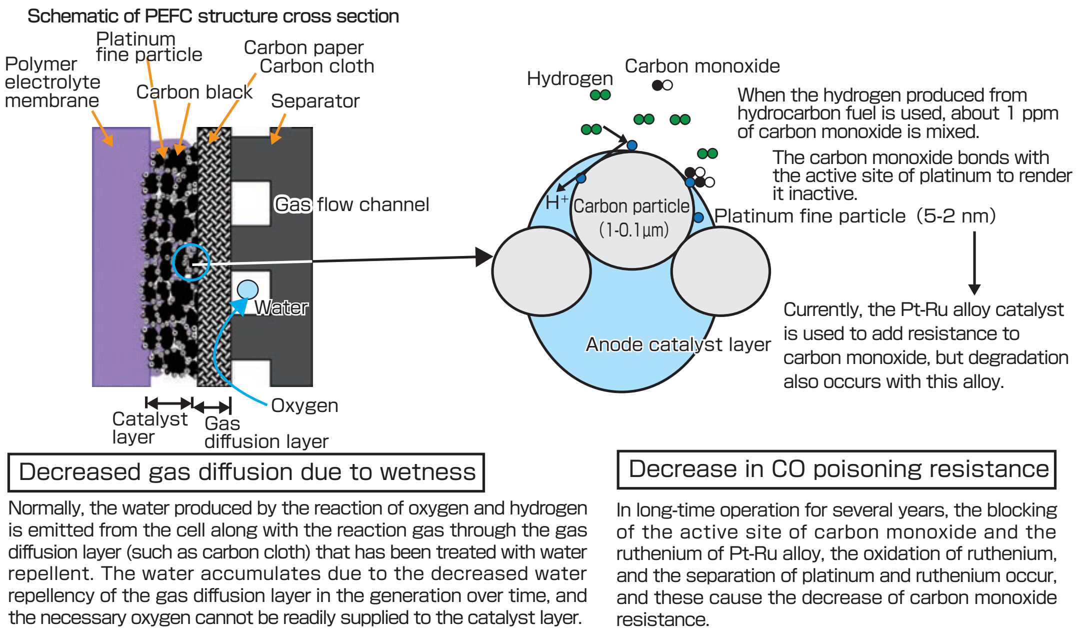

Fig. 4 Two issues on which weight must be placed for stack degradation

Two issues important in the degradation mechanism related to the decrease of cell performance are extracted based on the generation data of the companies participating in the project.

is started when the air is remaining in the anode, a transient state appears where the region with fuel and the region with oxygen exist simultaneously within a cell, the reverse current is produced in some areas with remaining oxygen, and the electrode material carbon becomes corroded as the potential of the cathode becomes high in some areas. Since such phenomenon could not be measured by observing the cell from the outside, to verify the "reverse current decay mechanism," we conducted measurements by fabricating the "100 segment cell" (Fig. 6). The electrode was divided into minute segments, settings were done to measure the time change of the generated current distribution and the local potential distribution within a cell, and transient states were created by switching several types of gases. As a result, we succeeded in measuring the abnormal high potential of about 1.6 V locally (in normal operation, the material will not be subject to potential higher than 1 V) in the transient state in which the "reverse current decay mechanism" was expected to occur.[6] From the measurements of other types of transient states, we found two phenomena that were closely related to the conditions of the proposed accelerated aging test. One was the phenomenon in which the high potential that may cause cathode degradation like the "reverse current decay mechanism" could occur when the anode gas was switched from nitrogen to fuel. Another phenomenon was when the cathode was switched from nitrogen to air, certain anode had high local potential (about 0.7 V) in the potential range of 1 V or less. These results offered logical explanation for the phenomena that occurred in the "accelerated aging method 2" and "accelerated aging method 1" respectively. The phenomenon in which the anode local potential increased, for example, to 0.7 V in the cathode gas switching test was certainly a degradation factor as the ruthenium in the anode catalyst eluted. However, it was considered harmless for the carbon material since it was 1 V or less. However, when a basic test using beaker cells was conducted for the purpose of studying the factors that affected the rate of carbon corrosion, it was found that the change in potential was the factor that promoted carbon corrosion even in the range of 1 V or less that was thought to not cause much corrosion.[7] Combining these findings, it was found that the degradation in the "accelerated aging method 1" accelerated not only the ruthenium elution but also the carbon corrosion.

In the PEFC cathode, the surface area of the effective platinum catalysis decreased with degradation, and this was because of the increased particle size and loss of platinum due to dissolving, as well as the shedding and aggregation due to the corrosion of the supported carbon. To investigate these phenomena, we devised the "identical position observation" that allowed almost "*in-site* observation." Microscopic observation (AFM and SEM) of the shedding and aggregation of the platinum particles on the model electrode was conducted, and the phenomenon where the presence of platinum promoted the carbon corrosion was captured.[8][9] These results made basic contributions in accurately understanding the degradation phenomena that occurred under the accelerated aging condition.

5 From the development of accelerated aging method to commercialization

As the test method for accelerating the degradation process by enhancing the "decrease of gas diffusion by the flooding at the electrode," we proposed two gas switching methods. The phenomenon of flooding due to increasing the wettability of the cathode was hypothesized as being caused by the production of hydrophilic functional group at the surface of the catalyst support carbon. For the production of this hydrophilic group, the carbon oxidation would not be enhanced greatly even if open voltage 1 V was retained, but such functional group might be yielded by shifting the potential by switching

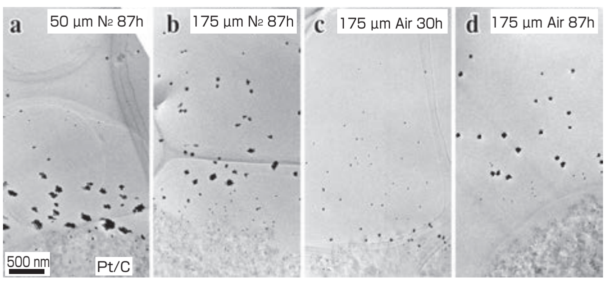

Fig. 5 TEM images of the Pt/C electrode catalyst layer and the electrolyte membrane interface after conducting the aging test by applying constant voltage
(a) Using the 50 µm electrolyte membrane, nitrogen was supplied to the cathode and 1.0 V was applied for 87 hours. (b) Using the 175 µm electrolyte membrane, nitrogen was supplied to the cathode and 1.0 V was applied for 87 hours. (c) Using the 175 µm electrolyte membrane, air was supplied to the cathode and 1.0 V was applied for 30 hours. (d) Using the 175 µm electrolyte membrane, air was supplied to the cathode and 1.0 V was applied for 87 hours.

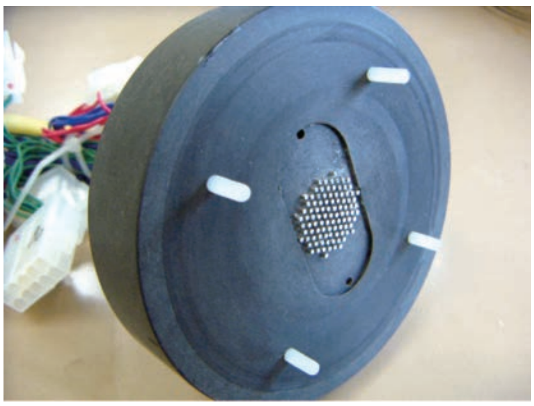

Fig. 6 External appearance of the segmented electrode of the "100 segment cell" fabricated to measure partial current and local potential

Table 1. Introduction of ENE-FARM by subsidy

	City gas type/ unit	LP gas type/ unit	Total / unit
FY 2009	3,681	1,349	5,030
FY 2010	3,969	1,016	4,985
FY 2011	10,526	1,911	12,437
Total	18,176	4,276	22,452

(For FY 2011, the number is for the application received by December 27, 2011)

the cathode or anode gases. Also, high potential of about 1.6 V could be induced depending on the condition of gas switching according to the model cell experiment, and this could offer the rationale for the accelerated test protocol by gas switching. The decrease of gas diffusion in the catalyst layer was thought to arise from the electrochemical reaction of the catalyst supported carbon. The dissolution of ruthenium of the anode catalyst was confirmed in the analysis and observation of the electrolyte membrane and the electrode catalyst layer after cell operation. These behaviors were thought to decrease the CO poisoning resistance of the Pt-Ru alloy catalyst over time. The increase of anode potential was confirmed in the anode gas switching condition. It was thought that such aging condition would not occur under normal operation, but since the local distribution of the gas composition caused the potential increase, the dissolution of ruthenium of the anode catalyst was accelerated.

The PEFC residential cogeneration system uses the fuel cell of about 1 kW as the power source. The durability was evaluated by applying the accelerated test protocol to this fuel cell by gas switching method. As a result, for the fuel cells of the various fuel cell system manufacturers, about seven-fold acceleration rate was obtained in the cathode gas switching method, and about 100-fold acceleration effect was observed for the anode gas switching method. In this project, the companies that manufactured the PEFC residential cogeneration system were able to confirm the 40,000-hour durability through the accelerated test, and the commercialization in market was initiated. As part of the attempt to spread the PEFC residential cogeneration system, the energy supplier and the fuel cell system makers gave the name “ENE-FARM” to this commercialized product system. This name is a combination of energy and farm. The ENE-FARM was commercialized in May 2009, and it is spreading all over Japan as shown in Table 1.

6 Conclusion

For the authors who have been engaging in research of the fuel cells as the next-generation technology, the fact that the fuel cell, which was always called the technology of the coming generation, became commercialized as ENE-FARM was a satisfactory event. The factors that allowed the fuel cell to become commercialized were that the initial stage of the residential cogeneration market was formed as society became increasingly eco-minded, and that there was excellent generation efficiency of the fuel cell compared to the gas engine technology that has already been in this market. Since the electricity-main heat-sub tendency was increasing in the home energy consumption, the generation efficiency was highly adaptable in terms of the balance of electricity and heat with electricity being main. The fuel cell cogeneration system is clearly adaptable as a commercial product compared to the gas engine cogeneration. Also, the interest in reducing the emission of carbon dioxide, preparing against disaster and saving energy accelerated the formation of the residential cogeneration market. The technology development in the industry-academia-government collaboration was important in the commercialization of the ENE-FARM. For a product that was so close to commercialization, there was very little incentive on the part of the companies to engage in joint technological development while sharing the unique corporate information. In this case, vertical collaboration with the energy supply companies was done aiming for the new market formation for residential cogeneration. AIST managed the unique technological information, the sharing of developed information progressed, and the positive incentives such as lowered risk of R&D functioned well.

Currently, the ENE-FARM is spread widely due to government’s subsidies. For autonomic market growth, further decreased cost and increased reliability and durability are necessary. To do so, research and development must be conducted from the designing aspect of residential cogeneration system by the fuel cell system makers, and at the same time, it is necessary to engage in researches to increase the performance and durability of the PEFC as well as to decrease the cost. AIST wishes to contribute as much as possible.

Acknowledgement

The industry-academia-government collaboration project “Fundamental Research of Degradation of PEFC Stacks” was conducted from October 2004 to March 2008, under the subcontract by New Energy and Industrial Technology Development Organization (NEDO). We are thankful to the people involved. We also express our thanks to the following participants of the project: Toshiba Fuel Cell Power Systems Corporation, Sanyo Electric Co., Ltd. (now part of Panasonic Corporation), Matsushita Electric Industrial Co., Ltd. (now Panasonic Corporation), Tokyo Gas Co., Ltd., Osaka Gas Co., Ltd., Nippon Oil Corporation, Kyoto University, Yokohama National University, and Doshisha University.

Note

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Discussion with Reviewers

1 Difference between "product" and "commercial product"

Question (Kazuo Igarashi, Institute of National Colleges of Technology, Japan)

In the text, you use the two terms "product" and "commercial product." There are places where you make the distinction between the two and places where you don't. I think it is important to separate the two, so please review the use of these terms.

Answer (Kazumi Tanimoto)

In this paper, the "product" is the device that incorporates the fuel cell such as the fuel cell cogeneration system and fuel cell automobile. "Commercial product" is the product that has been commercialized such as the residential cogeneration system "ENE-FARM." When the "product" is commercialized, the cost is added to the functions such as performance and durability to be acceptable in society, and this becomes the "commercial product."

As you indicated, there were two places in "Chapter 6 Conclusion" where the terms were interchanged, and this was corrected.

2 Molten carbonate fuel cell (MCFC)

Question (Kazuo Igarashi)

In paragraph 2, chapter 2, you write "… there seemed to be opportunities for trials ... due to the characteristic of the product." What do you mean by this trial?

Answer (Kazumi Tanimoto)

This was a reference to the molten carbonate fuel cell (MCFC) that is one of the distributed fuel cell generation technology. In Japan, the Marubeni Corporation attempted to market the technology developed by FuelCell Energy of the USA as a distributed generation system. Marubeni established the Nihon Nenryo Denchi Hatsuden K.K. and conducted several demonstration tests, but the venture company was terminated in December 2011 and it was never launched in Japan. I regret this course of event, because I was involved in this technological development for 20 years. I think it has superior performance compared to other fuel cells. The demonstration trials are done in other countries as part of the investigation of the process for its commercialization. I added this description since I hope for the revival of this technology.

3 Degradation pattern of the polymer electrolyte fuel cell (PEFC)

Question (Kazuo Igarashi)

In paragraph 1, subchapter 4.1, you write, "the accelerated degradation pattern of (c) ... was determined to be most fatal for the cogeneration system." Can you describe in detail why you say so?

Answer (Kazumi Tanimoto)

This is based on the empirical data of the manufacturers and the energy companies. The individual system designs are different in terms of the flexibility and adaptability of the system control in the cogeneration units. Fatal degradation is judged on the degree of damage.

4 Scenario toward the practical use of fuel cell

Question (Norimitsu Murayama, Advanced Manufacturing Research Institute, AIST)

You write at the beginning of paragraph 2, "Chapter 2 For the practical application of fuel cell," "in the fuel cell technology… lower the hurdle of technological issues…." Specifically, what were the technological issues and how were the hurdles lowered?

Answer (Kazumi Tanimoto)

One of the technological issues for the fuel cells was to scale up when it was introduced as the distributed power source. There is the issue of cost due to scale up. Scaling up the assemblies also brings new processing development for manufacturing components and unifying systems. For the application to small sized cells, the manufacturing technology will be an extension of the laboratory level, and I used the expression "lowering the hurdle" in that sense.

5 Degradation mechanism of the polymer electrolyte fuel cell

Question(Norimitsu Murayama)

Isn't it more straightforward if you say that the "decrease of gas diffusion by enhanced flooding at the electrode" and the "decrease of CO poisoning resistance" are accelerated by the gas switching method? Assuming this statement, in paragraph 3, "Subchapter 4.1 Degradation factors of the actual cell/stack and the accelerated aging method," I think you should explain the mechanism by which the CO poisoning resistance decreases by the gas switching test.

Answer (Kazumi Tanimoto)

In the project, the two factors of degradation were selected and investigated, and as described in the text, we were unable to sufficiently control the factor that accelerated the "decrease in CO poisoning resistance." As you indicated, if the two factors are presented in this text, I should follow them logically, but I write from the perspective of showing the efforts and processes of the research method. Also, seeing the "decrease of CO poisoning resistance," we specifically considered the accelerated aging method of adjusting the CO content of the fuel to change the degree of degradation. However, we could not obtain the expected results within several thousand hours, and therefore, it is as written in the paper.

6 Standardization of the accelerated aging test of the polymer electrolyte fuel cell

Question(Norimitsu Murayama)

Is the introduced gas switching test standardized?

Answer (Kazumi Tanimoto)

To be established as the actual accelerated test protocol, I think it is necessary to calculate the acceleration coefficient by comparing the developed accelerated test protocol with the tests conducted under standard conditions. Since there are not many tests conducted in real time, it is necessary to collect sufficient data including the text conducted by the accelerated aging method.

Synthesiology Workshop at the Annual Meeting of the Japan Society for Science Policy and Research Management (JSSPRM)

Synthesiology through knowledge integration to innovation

[Translation from *Synthesiology*, Vol.5, No.1, p.62-68 (2012)]

This is a report of the synthesiology workshop "Synthesiology through knowledge integration to innovation" at the Annual Conference of the Japan Society for Science Policy and Research Management, held at the Tokiwa Campus, Yamaguchi University in October 2011.

***Synthesiology* Editorial Board**

[Opening Address]

Naoto Kobayashi (Vice Editor-in-Chief, *Synthesiology*; Waseda University)

What can we, or those of us involved in "academics" and "research," do in the face of the difficulties that stand before us including the global economic crisis, the high yen rate, the floods in Thailand, the decelerating growth of emerging countries, the recovery from the enormous earthquake, and the massive national deficit? I think we must utilize the products of R&D in society and create and accelerate innovations.

Synthesiology aims to practice the science of synthesis and accelerate innovation, by integrating the scientific findings and technologies. The Japan Society for Science Policy and Research Management studies the proposal, planning, management, intellectual property, and technology management to enable the utilization of science and technology toward innovations. However, looking at the real world, even if an excellent research result or technology is created, that alone will not lead directly to innovation or be accepted into society.

Then what must be done to promote innovation? This workshop is a place to discuss the "methodology to link synthetic knowledge to innovation," and it is held jointly by Japan Society for Science Policy and Research Management (JSSPRM) and AIST. In this workshop, the methodology of synthesis science will be discussed. We also hope to step into the innovation theory, give specific examples of methods for promoting innovation, and deepen mutual understanding.

As the keynote address, we shall hear from Dr. Ono of AIST on the "Methodology for the establishment of synthetic knowledge." Then, Prof. Ken Senoh of The University of Tokyo will give a special lecture, "Innovation and synthesiology – How knowledge creation and restructuring can be useful in converting the social value and strengthening the industrial competitiveness." Finally, Prof. Senoh, Dr. Sumikura of the National Graduate Institute for Policy Studies, and Dr. Akamatsu of AIST will join us in the panel discussion entitled "From knowledge integration to innovation creation."

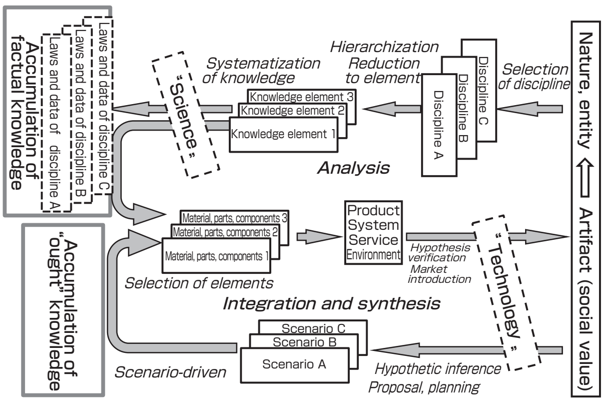
[Keynote Lecture] Methodology for the establishment of synthetic knowledge

Akira Ono (Editor-in-Chief, *Synthesiology*; AIST)

Much time is needed for the basic scientific research to get out into the real society, and many scientific results become lost in the process. How do we overcome this "valley of death" or "period of nightmare" of research? I wish to establish the methodology through *Synthesiology*.

First of all, in scientific research, one selects a discipline such as physics, biology, or electricity. Next, using the method of analysis, one classifies various phenomena into hierarchies, break them down into knowledge elements, and finally organize them systematically to understand a certain aspect of nature. Ever since the birth of science in the 17th century, science has been developed mainly by reductionism and analytic methods. On the other hand, there is the activity of creating a purposeful artifact that does not originally exist in nature. Using knowledge elements obtained in various disciplines, materials, parts, components, systems, services, and environments are created according to scenarios. Here, the processes of synthesis from and integration of knowledge

Comparison of analytic research and synthetic research



elements are important. The former may be defined as "science" and latter as "technology." When an artifact created is recognized as an "entity," that itself becomes the subject of analysis, and results of these analyses are used for technology again. I believe this is the interaction of "science" and "technology." This is what is called *kogaku* (engineering) in Japanese. However currently, there is a trend where engineering itself is also being broken down into disciplines.

Let us compare analytical research and synthetic research. In terms of methodology, the analytical research is by analysis and breakdown, while synthetic research is by synthesis and integration. The former normally is done in a single discipline, while the latter is done across multiple disciplines. The major difference between the two researches is whether there is a unique solution. Under the belief that there is a unique solution with factual knowledge, the analytical research never stops until a unique solution is attained, and the research is completed when this point is reached. In the synthetic research, there can be multiple, equivalent solutions. Although there may be varying degrees of excellence among the solutions, the nature of synthetic research is very distinct from that of analytic one in the point that there may be multiple, equivalent solutions. When evaluating the analytical research, the peer reviewing is done by experts, because in a finely specialized discipline, only the experts of that particular discipline can determine whether a conclusion is a unique solution. However, in the synthetic research, the evaluation should be done by people who use the research results or those who gain benefit from them. I think the reviewing of synthetic research may be a merit review done by non-experts.

Issues of the present society including the environmental issues are extremely complex. Although the "science of synthesis" is needed along with the "science of analysis," the "science of synthesis" has not been sufficiently formulated, and the knowledge of what ought to be done are only accumulated and enclosed within individual researchers or groups. I do not want such knowledge to be lost. It must be accumulated as social assets, and made available to the public. Also, I want the researchers who are capable of the "science of synthesis" to be highlighted more, to have their proper place in society, and to be more active in promoting innovation. One of our innovation issues is "how to form the strong link between basic research and the real world." It is necessary to establish the methodology of the "science of synthesis" and to solve the issues of the present society through its practice. To do so, it is important to develop a formulation of original research papers to describe the "science of synthesis," and that is the reason we launched the new journal *Synthesiology.*

The characteristic of *Synthesiology* is that it offers the shift from a narrow discipline to wide disciplines, from the novelty of knowledge to its usability, and from the peer review to merit review. It also highlights the researchers capable of innovation. Another characteristic of the journal is that the discussions between the authors and reviewers are placed at the end of the papers with disclosure of reviewers' names. In ordinary academic journals, reviews are done anonymously from the perspective of neutrality and fairness, but we took the stance of developing the paper formulation with the cooperation of the authors and reviewers, as well as the readers, and decided to present the dialog between the authors and reviewers. What we learned from this is that because the names are disclosed, the reviewers cannot give biased opinions and comments, and due to this autonomous feedback and the obligation to be neutral and fair, they give excellent reviews, and the discussions with the authors are now very interesting. Some readers even read the discussions between the authors and reviewers before they read the actual papers.

In the past four years, we received various positive comments from many readers. Some authors said, "I was able to write things that could not be written in conventional academic journals." Some readers said, "It is interesting because I can understand clearly researches of other fields," and some industry people commented, "This is useful information because we can understand the researches of many fields."

To solve the issues of the present society, it is important to establish the methodology of the "science of synthesis" and to practice it. I believe innovation can be accelerated through the "science of synthesis."

[Special Lecture] Innovation and synthesiology – How knowledge creation and restructuring can be useful in converting the social values and strengthening the industrial competitiveness–

Ken Senoh(The Industry Academia Collaboration Initiative NPO; Hitotsubashi University [The University of Tokyo on the day of this workshop])

First, I would like to discuss "synthesiology seen from two systems theories' view," then "synthesiology seen from innovation studies," and finally "how knowledge creation and restructuring contribute to converting social values and strengthening industrial competitiveness"

I shall review the systems theories. The systemic systems theory based on the phenomenological interpretation is, in that sense, British rather than American. When we approach a subject, there are four ways: 1) daily life approach, 2) scientific approach, 3) hard systems approach, and 4) soft systems approach. In daily life, we "wait and see" through our "preconception," or the framework based on various existing worldviews or Weltanschauungen and unexamined assumptions. To this, we add the approach based on "scientific thinking." This is represented by the three Rs: analysis based on "reductionism," adaptation to the world with "repeatability," and the factual expression of the result or, in Popper's term, to enunciate by "refutation." This can be called scientific knowledge when it is synthesized as "knowledge." The success of this methodology is apparent as evidenced from the world of science in the 19th and 20th century. However, we reached the limit of it. Why? It's because reductionism cannot get the knowledge of "wholeness" or "systemicity." The practical, managerial, or political actions is not repeatable due to human learning. Hence, the general systems theory such as of Bertalanffy appeared. The systems theory focuses on "relationships of elements," rather than looking at certain parts in a reductionistic manner. The systems theory was led by the engineering approach that assumed that the existing world was composed of "systems," and therefore it could be approached systematically. With the influence of the World War II, this hard systems concept dominated the scene. This methodology developed as system engineering (SE), operational research (OR), system analysis (SA), and management science (MS). Meanwhile, the soft systems concept developed in the 1980s mainly in England. Unlike the hard systems concept where the hypothesis verification is done assuming that the "world is composed of a set of systems," this is a paradigm that takes the approach of systemic exploratory learning assuming that "although the world can be seen as a system, the world is unknown." While the hard systems view is based on logical positivism that involves the hypothesis verification through ontological statement, the soft systems view is based on phenomenological and interpretationism centering on the exploratory learning through epistemological statement. It is characterized particularly by the social semantics and conceptualism for understanding a human action can be regarded as various systems.

What would happen when *Synthesiology* is seen from this perspective? I think there are two perspectives. First, there can be a paradigm of rationalization and emergence against the thinking of whether synthesiology engages in analysis or synthesis. Second, there are the three aspects of "logy." Does synthesiology seek statements by ontology, epistemology, or methodology? I think there are all three aspects to synthesiology.

Since we place emphasis on "emergence," the important concept is "correlation." In "correlation," the social phenomena are interpreted and recognized as emergences, but there is a need of the methodology for practice that enables the emergence of new social phenomena. I think there are the following six ways: 1) to replace the individual that composes the system that enables emergence, 2) to change the correlationship of the individual that composes the system, 3) to cause a new combination by design, 4) to cause a new combination by induction, 5) to discover and nurture new combinations through place and opportunity, and 6) to practice exploratory learning that causes emergence by directly being involved in the place and opportunity.

Next is "synthesiology seen from innovation."

When talking about innovation, I stress that "growth" and "development" should be separated. Growth is a quantitative expansion of / in the same model, while development means the non-successive transfer to a new model. What promotes growth is the improvement by polishing the current state, while innovation means the new creation of a model. I am saddened that the *Nihon Keizai Shimbun* still translates "innovation" as *gijutsu kakushin* (technological renewal), but no matter how much improvement is done, it is only a part of innovation. Innovation is a creation of social / industrial new value(s), so it does not necessary start with technology invention. Or invention needs to have further parts: conversion and diffusion. Innovation does not last long. It is impossible to win the industrial competition without ceaseless effort in innovation. In my innovation theory in terms of industrial competition, the improvement model and the new creation model must be clearly separated ideologically. In doing so, it is extremely important to combine the two models. In a company, it is essential to internalize the Christensen-style innovation dilemma within a company. In Canon's research center, they engage in research to crush Canon itself, and at Toyota's research center, they do research to beat Toyota itself. Unless they do that, the companies will be crushed by external innovation. If the companies do not want to be crushed by innovation, there is no other way but to engage in self-innovation. We have entered such a world.

Then how can synthesiology support innovation? Before going into that, I would like to check two points. First, innovation is not invention itself. I do not understand the phrase "innovation of science and technology." That is because something that just newly creates some social value is not an innovation unless it is diffused and becomes rooted in society. If something merely creates technological value, then it is an invention. That is one of the issues that I shall raise. Second, even if the current model is improved or refined, it will not become an innovation. It is necessary to separate the improvement of the existing model and the innovation that is the creation of the new model. Even if the record technology is advanced, it will not surpass the CD, and even if the CD technology is advanced as far as possible, ultimately the world of iPod will take over. In this case, how do we create, diffuse, and make the new value adhere? I think synthesizing is one of the methodologies in the sense of "integration" or "synthesis," along with creation, generation, and producing. But is this all?

Finally, I shall discuss "how knowledge creation and restructuring contribute in converting the social values and strengthening the industrial competitiveness."

The methodology of innovation includes the "technological driven innovation" type on which the JSSPRM places emphasis, but there is also the "business driven innovation" type where a business concept or a value design is the starting point and the technology is utilized by the initiative of the design or the concept. It can be concept driven or design driven. For example, "iPod" is an example that started from product planning that creates new social values. The "Asahiyama Zoo" is an example of starting from the concepts or meaning and then changing the thing and action. The popularity of the zoo increased because it shifted from the concept of "exhibit of animal form/ outlook" to the "exhibit of animal behavior," and the design of the zoo was changed entirely. Design driven includes the "smart design" where the border between the every day and the extraordinary is crossed, for example, using sundry goods as emergency items. I am currently starting that movement with business companies. I call this "the shift from 'or' relation to 'and' relation." There are also concepts of universal design and eco design, but these are also styles where the starting point is an innovative concept from which the technology is induced or exisiting technologies are gathering.

Then, there is a "business concept / design driven innovation" style. Shifting from the age when manufactured articles equaled commercial products, now is the age where software and useware come into hardware. The iPod promotes the innovative formation of new value along with the service called the iTunes store. I have stated that while Walkman is a player, iPod is a fusion of the media, player, and storage, and moreover, it is a complex value form joined with the service called the iTunes store. All the business models are moving in this direction. The value formation by the synergetic hierarchization of the product and service is innovation of the product and business model or architecture.

Up to the 20th century, something could be produced by doing a survey and studying the needs. Some people translate "needs" as "wants" or "requests," but people like me and those in marketing translate the term as "shortage," "absence," or "deficiency." It is no longer an age where the subject of the survey is to fill in the deficiency. In the age where multiple, vertically-integrated companies could work hard and succeed by independence and doing everything by themselves, technology was linked directly to innovation. However, such methodology is not valid today, in the age of "innovation by internationally inclined division of labor" through the development of business models and intellectual property management, as well as standardization in a wide sense. Like in the age when the company became a leader if it was technologically excellent, will business excel if technology excels now? In the age of G7, the market was composed of advanced countries with a billion people. In the age of G20 plus, we must face the world of over 4 billion people. In such a world, the technology changes completely according to product architecture, business model, and industrial ecosystems. This may be like picking a fight with those of you working on technological policy. In fact, I am picking a fight. I think people should turn their eyes to the new cardinal rule of industry, that once the industrial ecosystem is made, one will not be able to survive even if excellent elemental technology is developed.

Here is the conclusion. The R&D policy that assumes technological excellence equals industrial excellence is no longer valid. Or, the policy that merely assumes that all industrial competitiveness originates from technology is no longer valid. These are the basic models when the concept of intellectual property nation was established in 2002. Of course, it is the main road and so it is important, but we must see the reality that the innovations of the world are moving along the road of business domination. We must think that each wheel is important. How would synthesiology change the world in what ways? What kind of discussions should we engage in? I think those are the things we must seek. At any rate, I expect a lot from the development of synthesiology.

[Topic contribution]

Koichi Sumikura (National Graduate Institute for Policy Studies)

Inspired by the lectures, I would like to contribute some topics in relation to intellectual property.

One of the points of *Synthesiology* is to "achieve the goal through the selection and integration of the elements." The right to intellectual property has the original function of exercising the individual right while maintaining exclusivity, or in other words, the function to block and slow down other people's R&D. However the intellectual properties in the future may enter the age of synthesis. Various intellectual properties including patents and know-how are selected, integrated, pooled, and packaged to promote their distribution. This will encourage R&D, as the innovations will be promoted since people can easily access the accumulated knowledge. I would like to introduce a case study.

I considered two patterns of cooperative management of intellectual property. One is the pattern where "R&Ds are conducted individually at each institute while the management of intellectual property is done jointly."

This includes the patent pool that assumes the conclusion of a license contract with a monetary agreement, and the commons that assume the use free of charge. It is important to determine which elements to select, what package to make, and how these are diffused.

A famous example of a patent pool is MPEG-2. It is licensed as a package by creating a patent portfolio, and it is very successful as a business. In the field of agriculture, the Golden Rice contains high quantity of vitamin A and is expected to improve the nutrition of the people of developing countries. In this case, by packaging a product with over 70 patents in the United States alone and the need to sign six material transfer contracts, the time and cost of negotiating with individual right holders are avoided to promote the diffusion of the technology. Another example is GlaxoSmithKline plc. While this is a CSR activity by a company, an attempt is made to construct a patent pool for neglected topical diseases to provide it at low cost, and other companies are asked to participate. There is also a similar movement in the agricultural field for developing software by open source. The Cambia of Australia asks the BiOS licensees to allow free use of any improved inventions generated. On the other hand, for example, there is the commons that collect the data for drug toxicity with the concept of preventing dual investment on the toxicity tests, and the patents of specific fields are aggregated and packaged to be used free of charge, as in the eco patent commons.

Intellectual property rights enter the age of synthesis

・Selection and integration of element⇒Achievement of goal

・Intellectual property rights:

Maintenance of exclusive rights by execution of individual rights
(= Blocking and delay of R&D)
↓
Pooling and distribution promotion through selection /integration of intellectual knowledge
(= Promotion of R&D, promotion of access to knowledge)

Second is that the "R&D is done jointly by multiple institutes and at the same time the management of intellectual property is done under a certain rule." The SC4SM (Stem Cells for Safer Medicines) is a British government-private sector consortium that enables the use of stem cells such as iPS cells in the drug toxicity tests. The government institutes and major pharmaceutical companies participate to develop the mechanism and to manage the developed patents.

Finally, I would like to touch upon the development of new technology for "enabling both the reduction of energy consumption and economic vitalization." In the situation after the earthquake, the economic vitalization must not be stalled while it is necessary to reduce the energy consumption. To do so, it is necessary to create a mechanism for widely gathering demands, to develop the necessary elements, to conduct R&D to combine such elements, and to have this new technology spread throughout society.

As one specific plan, a bottom-up type website like Wikipedia where anyone can write can be set up to gather the demands. For the combination and development of necessary elements, the technology needed immediately is determined by committees of experts, and the R&D is promoted by preferential tax treatment or reduction/exemption of patent fees. Then, to diffuse the implemented product, the companies that use such products are given preferential tax breaks. Such mechanism can be considered. I mention these as the materials for discussion pertaining to the handling of intellectual property rights and the possibility that reduction/exemption of patent fees may help promote R&D.

Motoyuki Akamatsu (Senior Editor, *Synthesiology*; AIST)

The general process by which R&D was used in the market until now was that the company people found and used the elemental technology research results. *Synthesiology* aims to establish a methodology that allows the product realization in society from the researchers' side. We analyzed and categorized about 70 *Synthesiology* papers on how the researches entered society and what scenarios and processes were taken. I would like to present some examples.

There is the group of "cases where the demand is clarified in society." In the research where the performance of the hard disk was increased using spintronics, the companies grabbed this technology when it was shown that the performance increased greatly. Moreover, when the researcher contributed in the development of the production system, the companies were able to deploy the technology more readily. Also, there were cases where the use of technology was established as a social structure, as in the case of the traceability of measurement standard.

On the other hand, there are "cases where the social demand is not clarified." In this case, the process of (1) "trial use" is important. The researcher created a nanotube with organic material, thought that the potential for its usage is infinite, and wanted to see how it could be used by providing samples. One of the points here was to provide the sample while showing that the product could be mass-produced in the manufacturing process. Another example is Aimulet, the powerless portable information device used at the Aichi Expo to explain the exhibits. By using the product at exhibitions and events, the demands can be excavated and the technological development is conducted by taking in feedback for improvements.

There is also the method of (2) "demonstrating by making the product." The actual product is made to specifically present what kind of performance the product is capable of. The emission wavelength of the iodine stabilized He-Ne laser that is used as the national standard of lengths in many countries was determined by the mechanical length of the laser resonator. The general-use elemental technologies were integrated adeptly to create a compact standard that fit on a desk, and this was used to demonstrate the fact that "it could be made this small." Also, real time all-in-focus microscope was realized as a product by demonstrating the impact that the image could be focused for objects with varying heights.

Scenario for introducing the outcome of R&D to society

In cases the demand is clarified by industry	• Construction of traceability system for measurement standard • Development of production technology that matches the new technology
In cases the demand is not clarified by industry	Display elemental technology and provide samples • Present impact of new technology by demonstrating the function using the sample • Extract technological problem and research items through feedback obtained from sample trial
	Provision of the prototype for wide trial opportunity • Rent out prototypes to target users, and extract problems and necessary functions from open prototype • Express impact of realized function by creating the product
	Promote technological introduction to the stakeholder • Take time to obtain understanding of the value of new technology • Promote understanding by seeking problems jointly with the people on site
Establishment and expansion of industry	• Add use value of the product through sensitivity-based leading user • Collaboration with different businesses, sectors and competing companies and standardization with competing companies, construction of joint relationship

Then there is (3) "the demand is understood, but there is hesitation." There is understanding for the necessity and importance of the technology, but people are hesitant to actually work on it due to intellectual property issues. In such a case, the researcher must wait for the company's understanding, or jump right into their arms. In the case of ultraviolet protective cosmetics, the product was made but the negotiations stalled due to intellectual property issues. Therefore, it was put on hold for a while, and after two to three years of adjustment, the product was finally realized. In the group that engaged in the activity to increase the reliability of the information system, the researchers actually entered the field to have the people understand the value of the technology.

Finally, there is the group of "cases where the product is created and it must be spread in society." The contribution of diverse stakeholders will be the point here. In the process of the diffusion of the IH cooking device into homes, an important role was played by a certain cooking instructor, a sensitivity based leading user. Also, car navigation is an integration of various technologies from micro to macro, from elemental technology to the whole social system. The car navigation was spread by the coordination of the entire industrial system and the people involved considering their roles. In this case, particularly important was the fact that the people of the companies of each layer shared the dream of "spreading the car navigation."

These are summaries of some case studies, and I hope they serve as material for the following discussion.

Panel discussion: From knowledge integration to innovation creation

Kobayashi

I would like to receive questions and comments from the audience on the presentations of the methodology for linking the "synthesized knowledge" to innovation.

Audience

The 4th Science and Technology Basic Plan decided upon the direction "from science and technology policy to science, technology innovation policy," but the situation seems to be that no one knows what we are supposed to do. In this time of crisis, isn't this a chance to change the framework of concept? I would like to hear radical remarks from Prof. Senoh and Dr. Sumikura.

Senoh

I feel that the "perceived rate of innovation" is extremely slow only in Japan. The problem of valley of death exists so it must be solved. However, looking at the American and European business models, they devise a model so the valley of death will not occur. Rather than solving the problem, they try to prevent the problem from happening. I think we must learn from this. If the market grows rapidly without putting in the investment funds, the investment to R&D can be recovered very quickly. I am wondering why Japan is unable to create a model of win-win relationship with the emerging countries in this style.

Sumikura
As a method for gathering the technology needed in society, there is, for example, a map website where people with GPS cellphones walk or drive, the route taken is displayed like a map, and other people can follow the route. This indicates the possibility of truly bottom-up manufacturing, and I think this method can be utilized effectively.

Senoh
That map can be considered user-driven rather than vendor-driven. Instead of the concept that the proposal for innovation is done by the vendor, we must bring out the power of the user-driven innovation. In the crisis situation today, what is talked about is social innovation. I think the social innovation is to “do social things by social participants in a social manner.” The sense of stagnation today in the living space and social space cannot be overcome unless the value of the whole society is changed. Now, the field of social business is emerging. I would like to focus on the fact that the world in which various things are innovated by linking socially in the same space is starting to take off.

Audience
As the precursor of the JSSPRM, the 2nd Department of Basic Science was created 30 years ago in the University of Tokyo, and it was about doing synthesis and doing something practical. What do you think about the relationship between *Synthesiology* and discipline, and the mechanism for actualizing them?

Akamatsu
Synthesiology aims to seek some sort of methodology that transcends the existing disciplines, by gathering case studies. For example, the categorizations include the strategic selection, breakthrough, and *aufheben* types. The good thing about *Synthesiology* is that it regards all fields as its subjects. One can understand even if it is not one’s own field of specialty, and that is because there is a common thread in the “way of thinking of the researcher.” We can discuss and understand mutually from the perspective of synthesis. I think that will be one of the powers that enable the construction of the discipline to link the disciplines.

Senoh
In terms of disciplinary, I think there are six methods for developing a new discipline: apical / advanced knowledge, interdisciplinary knowledge, niche / interstitial knowledge, fused knowledge, cross-disciplinary knowledge, and meta level / superior knowledge. Also, I question whether the cutting-edge discipline will be of hypothesis verification, and I think it will be of exploratory learning. When looking at *Synthesiology* from the sideline and wondering where it will go, I feel that there can be developments of epistemological discipline and methodological discipline, rather than ontological discipline. If that is its orientation, I think synthesiology has huge potential to bring about a wonderful discipline, and it is exciting.

Ono
Thank you for your very encouraging comment. The term *kagaku* (science) in Japanese has the meaning of “individual branches of knowledge.” I am thinking that a definitive discipline will not be made in synthesiology, and now we emphasize the three forms of methodology that can be used commonly and cross-sectionally for each discipline, or for its fusion. Yet, I would like to investigate further the forms Prof. Senoh suggested.

Kobayashi
Pertaining to “how to discuss the policy that leads to innovation,” you talked about “innovation is done by user driven rather than vendor driven” and “Japan cannot keep up with the speed of the world.” How about “how to plan and lead to the policy?”

Akamatsu
I think one feels something only after picking up that object in one’s hand. Since the thing and system that became an entity is very powerful, one way is to set up the process of developing it by receiving feedback. Until now, the thing could not be created without the solid build-up of hardware, but I think some assumed form can be made at a very early stage by using simulations.

Sumikura
I have suggested that a bottom-up system is necessary as a mechanism to collect the demands, but of course, there are various routes. There are cases where basic research done without considering any particular demand may link to a demand. Therefore, we need a matching mechanism to pick out such researches and put them into necessary places, and it’s also necessary to train connoisseurs for their interaction.

Senoh
Everyone started to develop “a way of knowledge for how to use knowledge.” That’s the point. I talk about the “knowledge to utilize knowledge,” and what Japan is lacking is not the development of knowledge itself, but the development of knowledge to utilize knowledge. I would like to consider synthesiology as an attempt to develop the knowledge to utilize knowledge.

Akamatsu
It is not factual knowledge, but the "knowledge of what ought to be." I think that is the main target.

Senoh
I think it is great that you stepped in that direction. One is that temporal and spatial transformations are occurring in R&D. It must be global first rather than domestic leading such as in something done locally being sent out globally. Talking about the time issue, is it still okay to consider short-term as one to three years, mid-term as five years, and long-term as 10 years? Defining the short-term of innovation as the period of polishing the existing model, long-term as the period of diffusion and fixing of the next-generation model, and mid-term as the period of transition from the old to new model, there is a distinct difference temporally between the world of bio and the world of IT.

Another point is the gap between the policy and the industrial trend, and I suggest retuning this separation. I hope that the methodology of this retuning will be one of the targets developed in *Synthesiology*.

Kobayashi
We would like today's discussions to be developed further. We have gained much new insight today, and we hope the audience was able to find some new direction. I shall close the panel discussion here. Thank you very much.

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

1 Types of contributions

Research papers or editorials and manuscripts to the "Readers' Forum" should be submitted to the Editorial Board. After receiving the manuscript, if the editorial board judges it necessary, the reviewers may give an interview to the author(s) in person or by phone to clarify points in addition to the exchange of the reviewers'reports.

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. Manuscripts for "Readers' Forum" shall be comments on or impressions of articles in Synthesiology, or beneficial information for the readers, and should be written in a free style of no more than 1,200 words. Editorials and manuscripts for "Readers' Forum" will be reviewed by the Editorial Board prior to being approved for publication.
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.

3.3.2 The text should be in formal style. 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 of manuscript with a checklist attached should be submitted to the following address:

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Letter from the editor

Here we deliver *Synthesiology* Volume 5, Issue 1 containing five research papers and a report of a workshop. Topics of the research papers cover a diverse range of fields from information, life, measurement, to energy. All researches seek outlets to society and actively push technologies into society utilizing, for example, standardization of evaluation method.

I wish to draw the readers' attention to the paper "Analysis of synthetic approaches described in papers of the journal *Synthesiology* - Towards establishing synthesiological methodology for bridging the gap between scientific research results and society." This is a research paper that analyzes the "synthesis methods" found in seventy papers published in *Synthesiology* in the last three years. It highlights characteristic patterns in various technological fields on how and by what processes synthetic researches are pursued.

The editorial board asks the *Synthesiology* authors to present research objectives that are related to social values, to explain scenarios taken in achieving the objectives, and to describe processes of integration and synthesis of elemental technologies based on the scenario. It has been found that each author has a unique way of undertaking processes of integration and synthesis and the ways are diverse. However, overviewing the processes, it is interesting that several common ways become apparent.

Synthetic approaches are actually practiced in research projects. Categorizing the processes of integration and synthesis, I think, can leave a positive influence on the planning and management of research projects as well as on the follow-up evaluation.

Also, a workshop "Synthesiology through knowledge integration to innovation" was conducted jointly by AIST and the Japan Society for Science Policy and Research Management at its Annual Conference held at the Yamaguchi University in October, 2011. There we discussed the relationship between synthetic research and innovation. As it can be seen from the report of the workshop published herein, various interesting points were raised. I feel these points may influence science and technology policies of Japan in the future.

Editor in Chief
Akira Ono

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