Vol.6 No.1 June 2013

ISSN 1883-0978 (Print)
ISSN 1883-2318 (Online)

Synthesiology
English edition

Round-table talks

New research method in the age of science, technology, and innovation

Research papers

Progress towards realizing distributed power generation with highly efficient SOFC systems

Earthquake prediction research based on observation of groundwater

Estimation of legible font size for elderly people

Development of fiber optic broadband vibration-detection system

Synthesiology editorial board

2013 1

Synthesiology-English edition ❶ 2013

National Institute of Advanced Industrial Science and Technology (AIST)

MESSAGES FROM THE EDITORIAL BOARD

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

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

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

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

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

Addendum to Synthesiology-English edition,

"Synthesiology-English edition" is a translated version of "Synthesiology", which is published quarterly, ISSN 1882-6229, by AIST.

Papers or articles published in "Synthesiology-English edition" appear approximately four months after the publication of the original "Synthesiology". Those published in Japanese are translated into English, so the views expressed in translated versions are exclusively those of the Japanese authors and editors. The Japanese authors are generally consulted regarding the translation of their papers, but are not responsible for the published English version.

Papers or articles in the "Synthesiology" originally submitted in English are also reproduced just as they were published in "Synthesiology". Some papers or articles in "Synthesiology" are not translated due to the authors' or editors' judgement.

Synthesiology Editorial Board
(written in January, 2008)

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

Synthesiology – English edition Vol.6 No.1 (Jun. 2013)

Contents

Roundtable talk to commemorate the fifth anniversary of the publication of *Synthesiology*

New research method in the age of science, technology, and innovation

— On synthetic approach in basic research —

[Translation from *Synthesiology*, Vol.6, No.1, p.1-11 (2013)]

In the R&D for creating a product or business, the approach is taken where the necessary elemental technologies are integrated to achieve the goal, while many basic researches are driven by intellectual curiosity. On the other hand, in the R&D conducted using public funding, basic and fundamental researches that cannot be done by private companies are expected, as well as production of results that will benefit society and bring forth innovations to society. On the fifth anniversary since the launch of the journal *Synthesiology*, experts of the fields convened to discuss how the high expectation of basic and fundamental researches should be met, the significance and potential of the synthetic approach addressed by *Synthesiology*, and the direction of science, technology, and innovation in the future.

***Synthesiology* Editorial Board**
Translated by the editor

List of Participants

Tateo ARIMOTO	Director-General, Research Institute of Science and Technology for Society, Japan Science and Technology Agency
Yuichiro ANZAI	President, Japan Society for the Promotion of Science
Hiroshi KUWAHARA	Former Member, Council for Science and Technology Policy
Ayao TSUGE	President, The Japan Federation of Engineering Societies
Michiharu NAKAMURA	President, Japan Science and Technology Agency
Kazuo FURUKAWA	Chairman, New Energy and Industrial Technology Development Organization
Hiroyuki YOSHIKAWA	Director, Center for Research and Development Strategy, Japan Science and Technology Agency (Senior Advisor, AIST; Editor, *Synthesiology*)

Moderator: *Synthesiology* Editorial Board (Motoyuki AKAMATSU, Senior Editor)

Akamatsu

We launched *Synthesiology* in 2008, as a journal to provide knowledge for the integration of the science and technology to shape the results of R&D into a form usable in society. Five years have passed since its first publication. First, Dr. Yoshikawa, will you please talk about how *Synthesiology* was born?

Yoshikawa

In the academic societies for engineering, there have been long discussions on whether “synthesis can be written up as a thesis.” Although there were thoughts that “a paper cannot be written just by making a new machine” or “engineering cannot exist with only analysis,” we did not know what synthesis was. However, when I joined AIST in 2001, I was surprised to meet a group of 3,000 researchers who were conducting synthesis as a motto. They were engaged in research that couldn’t be shaped into papers in the traditional sense. I set a rather realistic goal of creating a journal where the researchers can submit papers on synthesis, and to have this recognized as an academic journal. Although a “thing” can be made, the methodology for making the “thing” does not remain, and historically, synthesis could not be transferred to the next generation. Making a journal was a challenge for leaving such efforts to the future, just like the so-called analytical academic journals. For the name of the journal, Dr. Akamatsu suggested “synthesiology” as a combination of “synthesis” and “logy.” The term synthesiology is gradually becoming accepted. However, there is still no conclusion on how synthesis contributes and develops in science and technology for the sake of humankind, and I think the mission of *Synthesiology* is extremely important.

Akamatsu

The issue is what must be done to bridge the gap between *Type 1 Basic Research* and *Product Realization Research*. The investment of funds into public R&D plays an important role to solve the global issues and to promote innovations through such basic researches. Since we have here today, people with experiences at the funding agencies and corporations, please discuss whether it is sufficient to go

on with the conventional methodology, or more effective to introduce synthetic research.

Do you think synthesiological thinking is useful in planning and preliminary evaluation of an R&D project?

Is synthetic approach effective?

Tsuge

Before the discussion of whether synthesis can be written as an academic paper, I will speak from the stance that an innovation leads to social and economic values, and that synthesiology is "practical." Looking at the GDP from 1995 to 2010, Japan's GDP is flat while the world has doubled, and Japan has clearly been left behind in the continuous developing world. I think there are many reasons for this, but one of them is that the national investment in science and technology has not led to innovation. At what kind of innovation are we aiming? Rather than the catch-up style of the 20th century, we are aiming for the extremely difficult front-runner type innovation. This requires individual creativity to generate the state-of-the-art science and technologies, and integration ability where these are integrated and then converted into socioeconomic value. Both of these abilities and human resources are essential, and I regard the social utilization of synthesiology as specifically the "integration ability" and "human resources."

Industry is responsible for innovation and training; national institutes for R&D, training, and education; and universities engage in education and basic research. Each part needs to create values, clarify the flow and interface of the players, and make full commitment. I think we have fallen into a mechanism where these are lacking and therefore science and technology do not lead to innovation. I think the importance of the role of synthetic approach lies there.

Akamatsu

What is your specific image of people as the interface?

Tsuge

I think there are two participants: the researcher in charge of research and the coordinator. Currently, the government is trying to build up a group of professionals called research administrators. Although coordinators and research administrators may not be able to write papers, they do contribute to social and economic values. Such professionals should be evaluated in society.

Dr. Ayao Tsuge

Kuwahara

I am confident that a "synthetic approach is effective" and I'd like to indicate two fields of its application. One is that when an R&D project involves system development, it could never be realized with a single technology, and it involves "how to combine several technologies in which order, how they should be harmonized, and how they are finally shaped into a final system structure." Therefore, synthesis thinking is mandatory as the objective and realizing processes are clarified, managed, and finalized through intermediate evaluation. Although some companies may still be inexperienced, the chances for success are higher for the projects where this process is done properly. Another field is that in the case where the R&D project is an individual science and technology development, the usefulness of synthetic approach also is high in positioning the research for the future, determining how widely it should be studied for, and clarifying the necessary human resource, even if at the time the objective is vague. The synthetic approach in these two fields will probably fuse into one eventually. I hope that by overviewing the whole in the process of reviewing the synthetic approaches in the two points, we will go in the right direction without missing out anything.

If I may add a point, I want to divide basic research into one based on intellectual curiosity and one to be a part of realizing innovation. I think a strong scenario is harmful for the former, but for the latter, a clear scenario must be made for outlining the objective and the synthesis process needed, the possible selection process in the intermediate evaluation, the prediction of other new key technologies that may be necessary, and for ways to hand them over to the people responsible for future innovation.

Akamatsu

Aren't the researches at New Energy and Industrial Technology Development Organization (NEDO) characterized by setting objectives to nurture innovation, and the necessary developments conducted to achieve the objectives?

Furukawa

I studied *Synthesiology* and thought it was a really innovative concept. Reflecting on why we were able to continue our efforts without being cognizant of *Synthesiology*, I think it was because we were trying to catch up with overseas research over the past 40 years, which overwhelmingly involved analysis rather than synthesis. Synthesis became

extremely important when we caught up and subsequently tried to overtake overseas research. At the same time, we recognized the importance of setting goals and objectives. I was somewhat shocked that such words came from basic researchers. I think basic and applied research should be done by the Japan Society for the Promotion of Science (JSPS) or Japan Science and Technology Agency (JST), and the mission of NEDO is to nurture research results into practical applications in industry. In that sense, the concept of *Synthesiology* is extremely important for NEDO, and we realized that this concept must be examined from the systems side.

Tool to join the last sentence of the paper and the goal

Nakamura

JST is positioned slightly closer to universities rather than being at the midpoint between industry and the university researchers who engage in basic research based on free, intellectual curiosity. However, it links them to social and economic values by overcoming the valley of death, and it advocates the "virtual network laboratory." This means a virtual laboratory is created by gathering the best researchers of Japan or the world for a fixed period. There, the basic research that "matches the strategic goal," as described by the government, is done, and the results generated is thrown directly to industry. When the result is brought to a company, new issues will emerge, and this is fed back to the goal-oriented basic research to form a spiral-up structure. The strategic goal is considered by the Center for Research and Development Strategy (CRDS) as a strategy proposal where the direction of science and technology innovation and the issues to be solved are considered. The strategic decision is made by the Ministry of Education, Culture, Sports, Science and Technology (MEXT). If a mistake is made at the lift-off, major problems may emerge in five or ten years.

The work of JST actually starts from allotting the strategic goal to the research disciplines. However, rather than considering "it may lead to some social and economic values if successful," the work tends to look at the world trend or at the authorities and the academic societies that say "this is important." Therefore, creating a scenario is a must. The basic research deals with results that may be highly uncertain and may only be significant in the distant future, but we must spend effort to create a scenario or vision at the starting line, and improve it as we go. I would appreciate it if *Synthesiology* becomes a usable tool as a methodology for starting up and designing a research project and for creating the scenario; or becomes a common tool that can be shared widely.

Dr. Michiharu Nakamura

Akamatsu

Does this mean "the proponent must write a scenario" when applying for a JST grant?

Nakamura

It is not that way right now. The final sentence of the paper is always, "In the future, this will become clarified and it will benefit the health of humankind." However, the statement is far distant from the actual research, and only the final sentence is written in the word of society. We are not making the effort to make the link. I think we must continuously think about the linkage to society even if one is engaged in basic research, but currently, there is no linking tool.

Funding and innovation

Akamatsu

I would like to move on to the topic of intermediate and post-facto evaluation of the R&D project. Dr. Arimoto, you have managed several projects, haven't you?

Arimoto

There are several points to be considered: In what position the funding programs and the individual projects that are run under such programs are in the innovation ecosystem of entire Japan and the world. Next, in which direction of society and market the innovation is going in the long timespan, where it is now, and whether this awareness for the position is shared by program directors (PDs), program officers (POs), and principal investigators (PIs) from the starting phase. Concerning these points, I have doubts whether they are being considered and shared.

However, there are distinct differences between evaluation and management methods for the blue-sky and mission-oriented research programs. Interference of management with the blue-sky research may be inappropriate and is often rejected, but I think it should be managed properly when the research begins to bear a mission. When I became in charge of the Research Institute of Science and Technology for Society (RISTEX), JST, funding programs were for scientific paper production, differing from the founding principle of RISTEX. I thought we should experiment, and conducted activities such as selecting POs and working on application

conditions always thinking about the shift of emphasis to social implementation. If social implementation is mentioned continuously, the applicants must think outside of the conventional style, and think about how the research team should be built, how to conduct social experiments using results, or how to bridge science and societies accordingly. I certainly think this is a form of synthesiology.

Akamatsu
You must evaluate whether the R&D conducted is appropriate within the process and interfere. However, once the project starts, isn't it difficult to interfere?

Arimoto
Yes, that is true. However, at RISTEX, the principal investigators and the research teams have been changed in several projects. Not just the individual research result and evaluation by project, but synthetic and panoramic analyses of management methods are done at the program level that is the upper level where the projects are concentrated, and this is reflected in the management improvement of the entire RISTEX. I think such interaction is extremely important.

Akamatsu
Doesn't Japan Society for the Promotion of Science (JSPS) conduct rather basic funding?

Anzai
Other than the goal-oriented research, there are sprouts of approaches that started from intellectual pursuits in various places, and I think spotting them plays an important role in innovation. Even if a topic is set by selecting a certain area, the sprout may spring up in some other field. There are infinite number of fields and the potential for science and technology is great. Nurturing the sprouts in these various fields is extremely important for a country like Japan that must work on innovation through its original efforts after it has past the "catch-up and overtake" stage. In relation to the talk today, JSPS must be a funding institute that nurtures sprouts in infinite fields and provides fertilizers so that the sprouts can grow on their own. These efforts are unspectacular because they are far from the market. Yet, the excitement of synthesis lies in the breadth of the science and technology topics and the wonders of innovations sprouting from totally different fields. To support innovation that may arise from such synthesis, I think we must till the fields, and need a stable and strong mechanism that allows sprouting.

Dr. Yuichiro Anzai

Another point I would like to mention is that "synthesis" sounds like project management for innovations, but I think innovations are generated from people. New sprouts are generated by enhancing the potential through the strong will of the developers, engineers, and researchers. To clarify why and how this is accomplished should be the direction of "science of synthesis."

Akamatsu
How should we judge what have become sprouts and what have become buds?

Anzai
I think the evaluation should depend on the objective of funding. For example, I am not for evaluating whether the results have been achieved in exactly two years with the small grants for young researchers or research encouragement offered by JSPS. I think the evaluation should be on how the person develops as a researcher over time. However, large funding cases must be evaluated strictly.

I think this may be the problem of the evaluation of government R&D funds, but the evaluation when applying tends to be strict, yet the interest shifts when evaluating the research results of the R&D to whether it can get the next grant. If the evaluation standard is unclear, the research that may sprout and the research that has an objective may be evaluated similarly. I think it is necessary to lay down a clear line, where basic research is evaluated on a long term basis and longitudinally, while the goal-oriented research should be evaluated on whether the result has been obtained in the eyes of industry and other sectors at the end of the research period.

Nakamura
I think JST must conduct different management according to the field and the phase. Particularly for the phase, quite a number of research topics are set in the beginning, and after two years, as the situation becomes clearer, JST has been cutting down about one-third of the researches. When cutting the researches, the reason is clearly delivered that "although the research is yielding excellent results, it departs from our objective." Then, we restructure the project.

Akamatsu
When you tell the researchers, "Your research departs from our objective," what kind of response do you get?

Nakamura

We receive significant response. The researchers are capable people who can do research in various places. However, we have many students and post-docs, and we have to let them go after giving them a year of a soft-landing period. We devise many ways to do so. However, we are conducting basic research for certain objectives, and within JST, we talk about emphasizing that point more.

Akamatsu

How about NEDO where the objectives are much stricter or more specific?

Furukawa

Since NEDO is an Incorporated Administrative Agency under the Ministry of Economy, Trade and Industry (METI), it takes a qualitative direction based on METI's policies. I think it is important how such a direction is incorporated into quantitative objectives and goals. We have engaged in projects of various scopes and budgets. Now, we have concentrated on national projects with greater direction, such as green innovation and life innovation. We conduct intermediate, post-project, and follow-up evaluations. Such evaluations can reveal ambiguity when initial project goals are set, and thus I feel these evaluations are extremely important.

In terms of the synthetic approach, the "four elements required for *Synthesiology*" are very important. These elements include; "R&D objective and social values," "scenarios for the introduction of research results to society," "selection and integration of the elemental technologies," and "evaluation of research results and future prospects." Although NEDO has its own evaluation frameworks, if this approach is implemented from the time of initial basic research and passed on to us, maybe we can more readily overcome periods of nightmares, valleys of death, or Darwinian seas.

In any event, rather than conducting evaluations using conventional methods, we conduct intermediate and final evaluations of issues relating to accountability and management in a strict manner to determine whether or not goals have been met or sufficiently achieved, and if the next direction is correct.

Dr. Kazuo Furukawa

Social mission of synthesiology

Yoshikawa

I think it is about how basic research projecs should be. The difficulty of research that is not curiosity driven will gradually become apparent, but beside that, there is no intention of creating a scenario for curiosity-driven research. In the *Mathematical Principles of Natural Philosophy* (Principia), Sir Isaac Newton described the hypotheses of the three laws, provided 500 pages of analysis, and proved that the hypotheses were correct. Meanwhile, *Synthesiology* is about the thesis on "why Newton proved the three laws." Setting up a hypothesis may seem to be one kind of scenario, but in general analytical research, there is no question about why a certain hypothesis is set up. When a certain interesting phenomenon occurs in nature, a hypothesis is offered about why such phenomenon occurs, and if it is proven, the thesis becomes a hit. In a research with an objective, a scenario that matches the objective must be written, and the objective is described in details. *Synthesiology* attempts to evaluate that point. However, this is not seen in other papers, and as Dr. Nakamura points out, the objective is simply written in the last sentence. In research with an objective, the last sentence should be investigated deeply, and the following question should be directed to the author, "Will your method realize the last sentence?" The paper is a presentation of the issue of what the goal-oriented research should be.

Tsuge

While this is not a direct answer to the topic raised by Dr. Yoshikawa, overlapping the issue of whether the idea of *Synthesiology* is academically valuable and the issue of the age of science, technology, and innovation, I think there is another social mission of *Synthesiology*. The birth of *Synthesiology* occurred due to curiosity-driven interest under the hypothesis that the result of the curiosity-driven basic research may be useful in fulfilling the social demands. I think the role of *Synthesiology* may be new, social-value-creating research through the fusion of disciplines and goal-oriented basic research based on original potentials. On the other hand, looking from the side of society, that itself does not lead to social value. Therefore, the entire process of bringing the research result to the market and social value must be architecturally designed, and *Synthesiology* should be the engine to propel this structure. We must work on these two issues.

Yoshikawa

In *Synthesiology*, the activities must be done so the project can be handed over to the people who will make the innovations. Unless sufficient consideration is taken for the

specific people who create the innovation and how such innovation will have an impact on society, a paper on the subject will be insufficient. Speaking rather radically, the starting point is curiosity. "Why does the heavenly body move?" "Will the earth come to an end tomorrow?" Both are curiosities. If one can explain how the heavenly body moves, that will be "good." However, if one finds out what will become of the earth tomorrow, that may be "bad," and action must be taken immediately, and this action may lead to a specific innovation. The actions that may be taken differ greatly according to the subject of curiosity. In the sense that research may lead to "then, what do we do?" situation, an action is not complete if the problem is only clarified. The application research begins from the point when the researcher finds the subject of application. Therefore, I am pointing out that everything arises from people's basic curiosity.

Akamatsu
What do you think about the question: while both curiosity-driven and scenario hypotheses are the same hypothetical investigations, aren't they subject to different thinking processes?

Anzai
This may be abstract, but it is a cause-and-effect relationship of "if this is done here, that may happen there." One will do something regardless of whether something happens or does not happen. This is a trial-and-error approach. In contrast, when one does something, and the result is considered good or bad; these are the two faces of cause-and-effect. Considering that a research is done from both ends, both contribute to synthesis.

Kuwahara
I would like to ask a question to Dr. Yoshikawa. Do you propose that *Synthesiology* itself should have individual value in a paper, or are you saying that a paper should be written synthesiologically to achieve ease of understanding and clarification of the origin of the paper?

Yoshikawa
This is a challenging point, but it is the former. While human wisdom has grown with massive scientific knowledge through the accumulation of fragmental scientific researches, manufacturing has not become gigantic knowledge. If manufacturing disappears, manufacturing will fade away socially. Science will not disappear but synthesis will. Humankind is unable to record the valuable thoughts during manufacturing, and this is a massive loss. One of the unfortunate results is making things that shouldn't be made because of lack of prior knowledge, thus destroying the environment. That is why people have to learn the basic knowledge of "this will happen when that is made." This is my basic motivation.

Kuwahara
How is *Synthesiology* useful in that learning process?

Yoshikawa
It is useful in clarifying the basic principle of how to make "things." To make some material, to make some system, or to make a social structure; these are all "making." When these are accumulated and used "to make" something new, the past experiences are utilized, and humankind will understand whether doing something will be good or bad for the earth. Currently, we are still repeating the process of making something new and finding out "it doesn't work."

Kuwahara
I think there are many "ways of thinking" about project management, where a project is started with an objective and brought to completion. Do you think that this way of thinking can be the subject of a paper?

Yoshikawa
I think a person who makes a "thing" may write a paper. It is said that a craftsman is expected to "steal the technique (from the master)," and this is the only way the craftsman can learn. This is because there is no record of how the master made a thing, the follower cannot learn how to make the product.

Kuwahara
Simply put, I think you mean synthesis should be described in all human behavior.

Yoshikawa
If the person who made the "thing" describes what went right and what went wrong in detail, the knowledge is accumulated, and humankind will become wiser. Currently, we have only the "thing" as a result. The proposal of *Synthesiology* is to objectively describe the process by which the "thing" was made.

Kuwahara
That is indeed valuable knowledge that should be left behind.

Arimoto
Dr. Naoto Kobayashi and others organized about 70 *Synthesiology* papers into three types: the aufheben, breakthrough, and strategic selection types. That was very instructive. I thought it was very useful in forming the framework of thought when setting up the mechanism for funding management or designing and realizing the scenario. I hope this effort continues.

Nakamura
In the sense of generating value in this world, I think such efforts are always taking a synthetic approach. For example, corporate research reports list the bottlenecks of the projects, but such information is rarely disclosed. If these are

accumulated and people can learn from them, I think they will be very useful.

Yoshikawa
If they are written and disclosed, that will be beneficial to humankind.

Tsuge
These reports are not disclosed not only because they are corporate assets and property, but because there is a mechanism in which such reports are not evaluated in the current academia. In that sense, the significance of starting *Synthesiology* is extremely great.

Human resource that can cause innovation

Akamatsu
I think human resource training is important. What do you think?

Tsuge
As an upper level issue of training human resources capable of the synthetic approach, there is no vision on the part of the trainers or the trainees, about which people should be trained or what kind of resource one wishes to become. This is also the greatest problem in training the science and technology human resources who bear the future of the nation based on science and technology creation. The teachers and the students or children must be able to see "who supports society" at an early stage of education. If this is done, one can study with the image of what one wishes to become.

If Japan were to survive with science and technology, I think at least four types of human resource categories are needed. First is type-D (differentiator) who carries the state-of-the-art technology. There are two of this type: one who is purely curiosity-driven and the other who has some social objective. Second is type-E (enabler technology) who generates technology that without it one may lose. Third is type-B (base) who has wide-ranging basic and fundamental technologies and skills. The fourth is type-Σ who integrates the types D, E, and B to generate socioeconomic value. I feel that the perspective of how to train the type-Σ human resource with generalization capability is lacking in the current science and technology policy and the educational policy. Therefore, this point must be made visible, and training must be done with the combination of education, research, and innovation policy. I feel that someone among the types D, E, and B who excels in one field may turn out to be an excellent type-Σ.

Akamatsu
I agree. Looking at the researchers around me, there are people with a good sense for synthesis even though they belong to type D, E, or B, and I have the impression that this ability may bloom when given the opportunity.

Kuwahara
I want to formalize this as follows. Synthesis is a field that stands alone as a discipline. Synthetic approach is totally different, but it is a method, and an extremely beneficial linkage to our society.

For innovation that is part of the whole, it is crystal clear that one must take the synthetic approach if one wishes to create an innovation. However, I feel there is vagueness of the definition of "what is an innovation." Innovation is "to achieve a totally new thing by breaking the conventional barrier." It is not remodeling or improvement of the conventional item. Also it should be understood that the word "innovation" contains in itself valuable outlet to our society. When we need to break the conventional barrier, we need creative and capable people. We must separate the education of such active people and the education for the people who passively join in innovation. I do not have much experience with the former, but we provide, in companies, opportunities of various experiences to selected prospective people, let them experience success and failure, and allow them to grow aggressive under severe world competition. This is a selective training. I think there may be another better educational method, but I cannot think of any yet. For the latter or the people who passively join in innovation, I hope they are correctly taught what an innovation is. In my understanding, innovation cannot be accomplished just by research results, but the government and/or companies that spearhead this effort must conduct necessary investments, plan so the investment return will be maximized, consider the acceptability of society, and finally realize innovation. Many people participate partially, and the project is successful only when the people who thoroughly understand innovation pour in their full effort. I think specific training for such people can be done, and I hope a certain format for their education can be laid.

Incidentally, we often hear about the necessity of making innovations happen in Japan, but there is no discussion of how many and what kind of innovations should be realized. Considering the national level including industries, several large scale innovations are necessary to solve the present

Dr. Hiroshi Kuwahara

economic difficulties. Selection is absolutely necessary for concentration, and the mechanism to study and determine such matters should be prepared by the government in collaboration with industries.

Akamatsu
What kinds of approaches are there when considering the human resource training for innovation at universities?

Anzai
At Keio University, we felt that there will be no future for Japan unless we educate innovative project manager, and started up the Department of System Design Engineering in the Faculty of Science and Technology, and created the Graduate School of System Design and Management (SDM). We are producing doctors from SDM, and the majority are students with work experience. As I mentioned earlier, to educate an innovative project manager, our objective is to provide training in system design, system management, system thinking, and communication abilities. It is essential to create a place of learning that nurtures the mind that can create innovation. We create a practical curriculum where people can learn through projects, by drawing a detailed design for educating people that are capable of producing new ideas, engage in teamwork, and can become team leaders. A team that combines people of humanities and sciences is created, and the courses are taught directly by professors that were involved in creating an innovation at companies. Considering the current state of Japan, merely discussing things is insufficient, and therefore we practice actual human resource training.

Akamatsu
I think it would be possible to train people in management at the graduate school level, but I also hear discussions about whether this capacity can be developed earlier.

Anzai
The study time of the middle layer of high school has reduced to half in the past 15 years, and in college, 70 % of the students spend five hours or less on studying per week. This is not the fault of the students but the education system. In the style of teaching en masse, the professor gives a one-way lecture from the podium, and the students earn credits if they write what they memorized for their final exam. When the students become used to this, come to graduate schools, become post-docs or go to companies, they cannot "be creative" or "be innovative." They must learn the basics of rational thinking by high school. Of course they need basic scholastic abilities, and the discussion for implementing the two is starting at the subcommittee for transition from high school to college of the Central Council for Education. This is extremely important. It is often said that the whole of Japan "is capable of doing what they are told but do not have the courage to initiate anything new," and this must be changed. There is an increased consciousness that this must be done from an early age. Whether this can be done will affect the future of Japan.

Arimoto
When I talk with the graduates and post-docs at the universities, I often get the feeling that they do not have sufficient understanding of where in a body of knowledge their researches are positioned or what relevance the researches have to society. On the other hand, at the management committee of a university, a student voiced, "Most of the professors give one-way lectures and do not tell us why the classes are important in history." I was struck by the fact that the young people are aware of the problem and have a sense of crisis.

At RISTEX, we are trying to use the keywords "researchers who move forward" and "managers who move forward," or human resources who go beyond and become the link between science and society. The antonyms are "researchers and managers who retreat inside." The dangerous ones are "researchers and managers who trample everything." Ultimately, we need to balance analysis and synthesis, and while analysis is the tradition of academics and is important, synthesis or the design and the systems are also important for innovation. During the International Year of Chemistry 2011, *Nature* did an article on "which direction chemistry should proceed in the future." They summarized: "There is analysis in chemistry, but synthesis also has been important historically. This may be the framework of thought and methodology that may allow chemistry to lead the other fields in the 21st century." I think the importance of synthesis is becoming recognized in various fields.

Another point is, when one wishes to create a major innovation, we must mobilize human resources with the knowledge of social sciences as well as of natural science and technology. There are many people who say they do not "wish to become involved in policy design" in economics, but I think that is exactly the most important point, and a mission-oriented fund should be created, so the social scientists can participate in solving the social problems. Unless such

Dr. Tateo Arimoto

structure is created, the social sciences are unable to work together despite various crises, and I fear there will be questions about whether they are of any use to society.

Furukawa

I think Japan's innovative direction may be towards the "realization of a hydrogen society." In terms of developing a hydrogen society, key points include a top-down approach for issues such as regulations and safety, as well as determining how to ultimately utilize batteries and fuel cells. Regarding fuel cells, we are conducting fundamental analysis at SPring-8 (Super Photon Ring-8 GeV) and J-PARC (Japan Proton Accelerator Research Complex), but in reality, we still do not really understand the behavior of fuel cells. The ability to carry out social synthesis at the top level and the analysis of cells at the molecular and atomic levels, I think, is the strength of Japan. There are many thoughts and ideas about hydrogen societies, and in this respect, one automobile company has committed to selling fuel cell vehicles at a price of about five million yen by 2015. I think it would be an innovative approach if our society as a whole moves in this direction, including innovations from the parts level to innovations in the structure of society.

Kuwahara

Your comment is extremely important. If the government spends maximum effort to build a hydrogen society, the focus of the research will become set. There are not too many big projects of the government, and many cannot be done. The government should raise this project as a candidate, and unless Japan shows the spirit of taking the lead in the world, even using the results from overseas if the Japanese R&D is insufficient, there will be no innovation. There are many people who think that the budget will be shifted away from them if such a decision is made. If it is stated, "This is not to exclude others. Major projects will be continued," then, we can include the "infinite number of fields" as mentioned by Dr. Anzai. Randomness will not generate anything.

Synthesiology is the stage for industry

Akamatsu

We have heard comments about how to conduct research, how to build organizations, and human resource training. Would Dr. Yoshikawa provide us with a general overview?

Yoshikawa

Recently, we are receiving submissions to *Synthesiology* from people of external universities, companies, and overseas, and I think this is a good trend. We received a difficult question from Mr. Kuwahara on what is the main concept of *Synthesiology*, but I am glad that you understand it now. Simply said, while science progressed mainly through analysis, most of human behavior has been synthesis. Although there were results of behavior and discussions on natural objects, when one tried to learn about behavior itself, an extremely academic new field called synthesis emerged. In fact, because the majority of industry is synthesis, the importance of synthesis is extremely high. I think we obtained consensus that a journal that addresses this is good.

There was a comment on what human behavior is and that it is"innovation." It was indicated that the innovation promoter must understand the receptivity of the bearing body or society, whether it will be beneficial to the body, and what the ecosystem is that makes up this innovation. These are very important, and individual activities are all synthesis. In that sense, the point of *Synthesiology* must be how to create an ecosystem where innovation can take place, rather than creating one product. This leads to the policy debate as discussed before, and it must spread further in the future. Aside from whether this journal will be able to spread it or not, I feel that it is a massive proposal of the issues including such topics. Then, the matter of funding and the evaluation of research results in terms of how synthesis is to be studied become quite important. JSPS, JST, NEDO, and RISTEX take different stances, but isn't the evaluation of the synthetic ability important for funding? Getting down to realistic issues, I really hope you provide lots of research funds to people who submit papers to *Synthesiology*.

There was a discussion about "nurturing people." Although innovation is inside people's heads, there is a lack of awareness that it must be handed over to the next generation. If humankind becomes extinct because of environmental problems, it means that humankind has failed to become smart over the ages because the transfer over generations of the knowledge of making "things" and modifying nature was extremely insufficient, despite the vast analytical accumulation. There is a deep relationship between the transfer of the processes and nurturing people, and there are many problems that must be reconsidered in education. I thought the suggestion that what kind of human resources should be nurtured is one effective approach when considering *Synthesiology* or synthesis is important.

Also, Mr. Furukawa talked about the realization of the

Dr. Hiroyuki Yoshikawa

hydrogen society as a Japanese innovation. Small innovations are of course necessary, but we would like to see one or two national level innovations. During the period of rapid economic growth when Japan was successful, there were 250 million Europeans, 200 million Americans, and about 100 million Japanese in terms of market and supplier of products. Therefore, about 100 million people out of about 550 million worked hard and rejoiced in victory. Now, the world population has reached nearly 8 billion, and they are the suppliers and market of industry. Five hundred million became 8 billion or it increased more than 10 times. As such qualitative changes occur in the competition, what is the superiority of "small" Japan. There are many. We have many excellent basic researchers, as well as nanotechnology and materials technology through basic research. These are the foundations of technology born during the period of rapid economic growth. They may be production technology, machine tools, or basic design methodology. If one wishes to do business using them, the market expands immensely. In fact, we are at the threshold of opportunity, and one should apply the *Synthesiology* way of thinking. I think it is "to carefully do analysis of the background of what the government should do," as Mr. Furukawa and Mr. Kuwahara pointed out. When the CRDS creates a research program, we say we must consider which way the research direction should go. Also, a leader is necessary. I believe the leader is industry. In other words, with *Synthesiology*, it is now the stage for industry.

Akamatsu

We were able to hear various insightful comments on the future research methods, and this talk was highly appropriate for commemorating the fifth anniversary of *Synthesiology*. Thank you very much.

This roundtable talk was held at the Annex Building, Tokyo Headquarters of the Japan Science and Technology Agency in Chiyoda-ku, Tokyo on October 3, 2012.

Dr. Motoyuki Akamatsu

Profile of Participants

Tateo ARIMOTO
Completed the master's program at the Graduate School of Science, Kyoto University in 1974. Joined the Agency of Science and Technology in 1974. After serving as the Deputy Director-General, Science and Technology Policy Bureau, was appointed as the Director-General, Science and Technology Policy Bureau, Ministry of Education, Sports, Science and Technology (MEXT) in 2004. Director-General, Research Institute of Science and Technology for Society(RISTEX),, Japan Science and Technology Agency (JST); and Deputy Director-General, Center for Research and Development Strategy, JST in 2006. Concurrently, Professor, National Graduate Institute for Policy Studies from 2012. Acts as the key figure in the policy-making for science and technology in Japan. Recently, works to develop a new funding system for problem-solving research for practicing "science for society." Books and articles include: "Science and Technology Policy" (by T. Arimoto, in *Have Japanese Firms Changed? The Lost Decade*, Palgrave Macmillan, 2011); and "Rebuilding Public Trust in Science for Policy Making" (by T. Arimoto and Y. Sato, *Science*, 337, 1176-1177, (2012)).

Yuichiro ANZAI
Born 1946 in Tokyo. Completed the doctor's program at the Graduate School, Keio University in 1974. Visiting Professor, Carnegie Mellon University; Assistant Professor, Faculty of Letters, Hokkaido University; and Professor, Faculty of Science and Technology, Keio University. Head, Faculty of Science and Technology, Keio University, 1993~2001; and President, Keio University, 2001~2009. Currently, President, Japan Society for the Promotion of Science; and Executive Advisor for Academic Affairs, Keio University. Also acting as Chairman, University Sub-Council, Central Council of Education, MEXT; Chairman, Committee for Promotion of Learning Innovation Previously worked as Chairman, Japanese Association of University Physical Education and Sports; Chairman, Japan Association of Private Universities and Colleges; Chairman, Association of Pacific Rim Universities; Chairman, Information Processing Society of Japan; Chairman, Japanese Cognitive Science Society; and others. Books include: *Kokoro To No* (Mind and Brain) (Iwanami Shinsho); *Digital No Ga Nihon O Sukuu* (Digital Brain will Save Japan) (Kodansha); *Kyoiku Ga Nihon O Hiraku* (Education will Open Japan) (Keio University Press); *Ninshiki To Gakushu* (Cognition and Learning) (Iwanami Shoten); *Mondai Kaiketsu No Shinrigaku* (Psychology of Problem Solving) (Chuo Shinsho); and others. Specialties are cognitive science and information science.

Hiroshi KUWAHARA
Graduated from the Department of Electrical Engineering, The University of Tokyo in 1960. Joined Hitachi, Ltd. and became Director, Ohmika Works; General Manager, Electric Systems Division; Managing Director; Senior Managing Director; Vice President; and Vice Chairman. Former Member, Council for Science and Technology Policy. Served as the chairman of Hitachi Maxell, Ltd., Hitachi Cable, Ltd., and Hitachi Kokusai Electric Inc. Special Advisor, Hitachi, Ltd. Also acted as Executive Chairman, Council on Competitiveness Nippon; Chairman, Japan International Science and Technology Exchange Center; Chairman, Trans-disciplinary Science and Technology Initiative;

President, Satellite Positioning Research and Application Center; President, Global Water Recycling Reuse System Association, Japan; Vice Chairman, Japan Federation of Engineering Societies; and others. Currently, Senior Corporate Advisor, Hitachi Maxell, Ltd. and Hitachi, Ltd.

Ayao TSUGE
Born 1943 in Tokyo. Graduated from the School of Engineering, The University of Tokyo in 1967, and completed the doctorate in 1973. Doctor of Engineering. Completed AMP 101, Harvard Business School in 1987. Joined the Mitsubishi Heavy Industries (MHI), Ltd. in 1969 and worked on the R&D for nuclear power generation. Chief, Nuclear Power Research Promotion Division; Director, Takasago R&D Center; Director/General Manager of Technology Headquarters; and President and Managing Director/General Manager of Technology Headquarters. Fulltime Member, Council for Science and Technology Policy, Cabinet Office in January 2005; Special Adviser, MHI Ltd. in January 2007; and President, Shibaura Institute of Technology in December 2007. Member, Science Council of Japan; Vice Chairman, Engineering Academy of Japan; Chairman, Japan Federation of Engineering Societies in April 2011; and Chairman, Japan International Science and Technology Exchange Center.

Michiharu NAKAMURA
Completed the master's program (physics) at the Graduate School of Science, The University of Tokyo in March 1967. Obtained Doctor of Science degree with dissertation "The study of distributed feedback laser diode." Joined Hitachi, Ltd. in April 1967. Worked at the Central Research Laboratory; Deputy-Director, Hitachi Research Laboratory in August 1990; Director, Central Research Laboratory in August 1992; Director and General Manager of R&D, Hitachi, Ltd. in April 2001; Executive Vice President, April 2004; Fellow in April 2007; and Director in June 2008. President, Japan Science and Technology Agency in October 2011 (to present); and Member, Council for Science and Technology (to present).

Kazuo FURUKAWA
Joined Hitachi, Ltd. in 1971. President and Executive Officer in June 2006; Appointed Vice Chairman and Chief Executive Officer in April 2009, and Special Advisor in June 2009. Chairman New Energy and Industrial Technology Development Organization in October 2011. In addition, served as Vice President, Keidanren from May 2007 to May 2009; and Chairman, Information Processing Society of Japan from May 2011.

Hiroyuki YOSHIKAWA
Born 1933. Professor, The University of Tokyo; President, The University of Tokyo; President, Open University of Japan; President, AIST; and currently, Director, Center for Research and Development Strategy, Japan Science and Technology Agency. Also acted as Chairman, Science Council of Japan; Chairman, Japan Society for the Promotion of Science; Chairman, International Council for Science; and Chairman, International Academy for Production Engineering. Doctor of Engineering. Research of general design theory and general synthesis theory. Engages in design education and intelligent manufacturing system research based on the theories. Books include: *Honkaku Kenkyu* (Full Research) (The University of Tokyo Press, 2009); *Kagakusha No Atarashii Yakuwari* (New Role of Scientists) (Iwanami, 2002); *Techno Globe* (Kogyo Chosakai, 1996); *Technology To Kyoiku No Yukue* (Direction of Technology and Education) (Iwanami Shoten, 2001); *Robot To Ningen* (Robot and Human) (NHK Publishing, 1985); and others.

Progress towards realizing distributed power generation with highly efficient SOFC systems

— Development and standardization of performance evaluation methods targeting early market entry of SOFC systems —

Yohei TANAKA *, Akihiko MOMMA, Akira NEGISHI, Ken KATO, Kiyonami TAKANO, Ken NOZAKI and Tohru KATO

[Translation from *Synthesiology*, Vol.6, No.1, p.12-23 (2013)]

Solid oxide fuel cells (SOFC) are expected to serve as the power source for highly efficient distributed power generation systems. To achieve early market entry and fair competition, it is essential that performance evaluation methods for SOFC be established and standardized. For this purpose, we have developed high-precision performance evaluation methods and test apparatuses to measure the power generation performance of SOFC cells, stacks, and systems. These methods were achieved by a combination of elemental technologies and tools, such as commercial measuring instruments, precision flowmeters and reference materials that are traceable to national standards, and catalysis technology. We evaluated the performance and usefulness of the test apparatuses developed in cooperation with SOFC manufacturers, and presented our standards activities, focusing mainly on the preparation of a Japanese Industrial Standard (JIS) for electrical efficiency test methods.

Keywords : Solid Oxide Fuel Cell, SOFC, highly efficient distributed power generation, performance evaluation methods, standardization

1 Introduction

The 3.11 Great East Japan Earthquake has prompted a debate on alternative ways to secure a stable supply of electricity and other forms of energy in Japan. One of the most urgent issues facing the nation is the need to reduce the country's overdependence on large-scale central power stations constructed in coastal areas. Among the proposals made, the Smart Community project is attracting increasing attention as a means to achieve efficient use of energy by installing small distributed generation systems near high-energy demand areas.[1][2] Renewable energy sources such as solar energy are expected to play the key role in the Smart Community; however, photovoltaic systems are not always able to provide the necessary electricity at night and in some weather conditions. While electricity storage systems are deployed to solve this issue,[3] high-efficiency distributed power generation systems using fuels are also considered an effective alternative.

Recently, a 500,000 kW-class combined-cycle system using natural gas achieved an electrical efficiency of 60 %, and its installation has begun in a coastal area near major cities where there is heavy demand.[4] For small-to-medium cities in the interior regions, transmission loss is a serious issue given their long distance from thermal power stations in the coastal areas. A high-efficiency power system of no more than a few 10,000 kW is therefore more appropriate for these regions.

Fuel cells have long been a promising candidate to provide power to high-efficiency distributed power generation systems because of their ability to convert fuel's chemical energy directly into electricity. Since the turn of the century in particular, research and development efforts have increasingly focused on the polymer electrolyte fuel cell (PEFC) operating around 80 ºC and the solid oxide fuel cell (SOFC) operating in the range of 700 to 1000 ºC. As Fig. 1 shows, no systems other than stand-alone SOFC systems and combined systems integrating an SOFC and a gas turbine can achieve an electrical efficiency of 50 % or higher when generating power in the range of 1 to 10,000 kW. Ultimately, SOFC systems are expected to achieve an electrical efficiency of 70 %.[5]

As will be discussed below, an SOFC system comprises a stack, which serves as the power generation unit and is formed by stacking multiple single cells (the smallest units) together, and the balance of plant (BOP) such as flow controllers. Hence, in conducting research and development for SOFC, it is important to accurately evaluate and improve the performance of each of the single cell, stack, and system.

In Japan, as part of the Demonstrative Research Project on Solid Oxide Fuel Cell Systems conducted by the New Energy Foundation (NEF) and the New Energy and Industrial Technology Development Organization (NEDO), a 700-W residential system using an SOFC demonstrated an electrical

Energy Technology Research Institute, AIST Tsukuba Central 2, 1-1-1 Umezono, Tsukuba 305-8568, Japan
* E-mail : tanaka-yo@aist.go.jp

Original manuscript received February 1, 2012, Revisions received June 21, 2012, Accepted July 23, 2012

efficiency of 45 %.[6] In October 2011, JX Nippon Oil & Energy Corporation became the first company in the world to market a cogeneration system using city gas or liquefied petroleum gas (LPG) with an electric output of 700 W. Recently, the development of commercial SOFC systems of 5 kW to 250 kW has begun, and there is also a plan to develop a triple combined-cycle system integrating a gas turbine and a steam turbine (targets: capacity of up to 800 MW and electrical efficiency of 60 % or higher).[5] Overseas, a 2-kW residential system has achieved an electrical efficiency of 60 %.

Incidentally, it is recently common to express the electrical efficiencies of SOFC systems and thermal power stations using the lower heating values (LHV) (i.e. the latent heat of vaporization is not included), and the efficiencies described so far in this paper are expressed using the LHV standard. The same will be used below unless it is noted that a high heating value (HHV) is used. In the cases of city gas and natural gas, efficiencies based on the LHV standard are 11 % higher than those based on the HHV standard.

With assistance from the Ministry of Economy, Trade and Industry (METI) and NEDO, our group has been engaged in the research and development of high-precision performance evaluation methods since around 2001 for all SOFC units from the smallest component to the complete product, namely the single cell, stack, and system. The objectives are to facilitate the early market entry of SOFC systems by assisting the research efforts in the private sector and to establish the standards for performance testing methods that are essential for promoting fair competition among manufacturers of SOFC systems once they become available for sale.

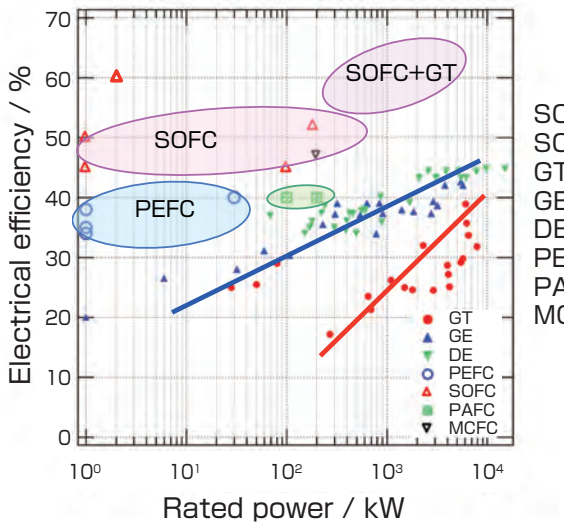
Recent IEC and ISO standards recommend that the concept of uncertainty replace error, accuracy, and other concepts as the indication of reliability of measurements.[7] Given this trend, we have collaborated with the Fluid Flow Division of the National Institute of Advanced Industrial Science and Technology (AIST), private corporations, and others to ensure that the performance measurement methods are traceable to national standards. Uncertainty measurements are estimated as the range of population means with a standard confidence level of 95 % based on the mean of observed values (measurement values) and the variability of all parameters, assuming that the true value is unknown.[8] For further details on uncertainty, see reference material [7].

This paper reports on our research and development activities for SOFC single cell/stack performance evaluation methods, which are essential for the development of SOFC systems, as well as our research/development and standardization work for the measurement methods of SOFC system electrical efficiency.

2 Research objectives and approaches aimed at early market entry of SOFC

2.1 Overview of SOFC systems and research objectives

The main components of an SOFC system, the complete SOFC product, include flow controllers, an evaporator (water vapor generator), a reformer, an SOFC stack, and an inverter, as shown in the schematic in Fig. 2. The following ingredients are supplied to the system: a raw fuel for the anode such as city gas, an oxidizing agent (water, oxygen) for the reforming of the raw fuel at the reformer, and air for the cathode. Reforming converts the raw fuel into hydrogen, carbon monoxide, methane, water vapor, and carbon dioxide, which are then distributed as anode gas to the anode of each cell forming the stack.



SOFC : Solid oxide fuel cell
SOFC+GT : SOFC-gas turbine combined
GT : Gas turbine
GE : Gas engine
DE : Diesel engine
PEFC : Polymer electrolyte fuel cell
PAFC : Phosphoric acid fuel cell
MCFC : Molten carbonate fuel cell

Fig. 1 Rated output and electrical efficiency of small power generation systems

At the anode, hydrogen and carbon monoxide react with oxygen ions (O^{2-}), which migrate from the cathode through the electrolyte. The reaction generates water vapor and carbon dioxide while electrons migrate to the external circuit to produce direct-current (DC) power (output). Generally speaking, the DC output is converted into alternating-current (AC) output using an inverter or another type of power conditioner. Some of that AC output (about 5 to 10 %) is consumed internally by the SOFC system while the remainder is available as the net AC output.

Based on this mechanism, the research and development of an SOFC system is generally conducted in the following order: the development of the materials and structure of the single cell; the development of the stack; and the design and development of the reformer and other system components. To achieve an optimal design and development of the stack, as shown in Fig. 3, it is important to first establish a good understanding of the performance of the single cell and, based on such understanding, evaluate the variability in performance among cells arising from such factors as temperature and uneven fuel distribution within the stack. For the purpose of system development, the important performance determining factors include stack performance, along with thermal design and reformer performance, while electrical efficiency is the most important performance indicator.

We believe that by developing the performance evaluation technologies for SOFC single cells, stacks, and systems, respectively, AIST is fulfilling its roles as a public institution. Such roles include not only assisting the private sector's research efforts and facilitating the early market entry of SOFC systems, but also establishing the international and national standards for the performance testing methods that are essential for promoting fair competition once SOFCs become commercially available.

The power generation performance of SOFC cells and stacks is affected substantially not only by the characteristics of the SOFC per se, but also by the testing conditions, including gas flow rate and composition, temperature, and fuel utilization (i.e. the ratio of fuel used for power generation to the supplied fuel). However, no performance evaluation methods in the past have specified the degree of accuracy required for measurements of gas flow rate/composition or other parameters. In addition, approximately 10 % of the anode gas consists of highly toxic carbon monoxide. Typically, therefore, gases such as pure carbon monoxide and pure hydrogen are sourced separately and mixed for testing. This requires stringent safety measures for the handling of pure carbon monoxide, thereby complicating the testing equipment and raising the testing cost.

As for the measurements of electrical efficiency, uncertainty of ±1 % or below (relative uncertainty of ±2.5 %) is

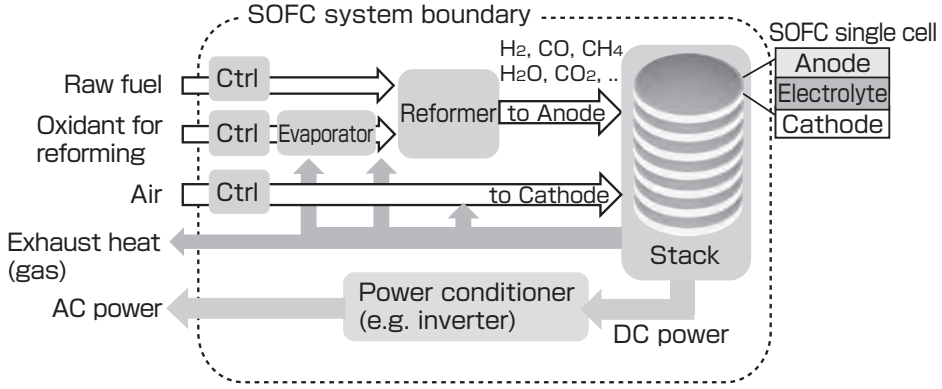


Fig. 2 Configuration of a standard SOFC system (Ctrl represents flow controller)

	Single cell	Stack	System
Principal performance indicators	V-I characteristics	Stack V-I characteristics	AC power, elec. efficiency
Performance determining factors	· Overpotentials · Gas specification · Fuel & Oxidant utilizations · Temperature	· Homogeneity of cell quality · Distribution of fuel supply & temperature · Interconnect performance	· Heat management including design · Flow-ctrl precision · Reformer performance · Inverter performance

Fig. 3 Relationships between performance indicators and performance determining factors Vand I stands for voltage and current, respectively.

considered appropriate for an electrical efficiency of 40 % (for rated, transmission-end output in HHV), the target value set for cogeneration systems in the NEDO project 2004-2007.[9] At the time, however, there were no standards that prescribed the measurement precision of the performance evaluation methods for phosphoric acid fuel cells (PAFC) or PEFC, both of which were developed earlier than SOFC. JIS B8122, the then existing standard for cogeneration units, only prescribed ±1.5 % for the wattmeter and ±3 % for the fuel gas flowmeter as the instrumental precision for the type tests.[10] As a result, the uncertainty of electrical efficiency measurements was estimated to be approximately ±5 %, which was unsatisfactory.

In addition, because it is difficult to transport an SOFC system of 10 kW or more to a well-equipped laboratory for measurement purposes, the best solution, we believed, was to perform on-site measurements at private SOFC installation locations. Hence we believed it was vital to establish a transportable method for measuring SOFC electrical efficiency.

As for the standardization of the performance testing methods, we believed that the standards for SOFC systems should be given highest priority, since cell manufacturers and system developers were working on the development of 1 to 200 kW-class SOFC systems at the time, and their market entry was imminent. Recently, however, a number of corporations in and out of Japan have begun offering SOFC cells and stacks for sale. An increase in commercial transactions involving these products is foreseeable, and the development of the relevant performance testing standards is therefore vital. We are currently proposing IEC and JIS standards for SOFC cell/stack testing methods, and the details of our activities were reported in a previous issue.[11]

Against this background, the following development objectives were established for the purpose of evaluating SOFC single cells/stacks: a measurement method for the power generation performance of SOFC cells and stacks, in which a test operator can easily simulate the operating conditions of an SOFC system and measure the voltage and other parameters as safely as possible at the relative uncertainty of ±1 %; and a stack performance evaluation method that allows for the evaluation of the variability of stack performance and the factors causing the variability.

As part of our goal to develop a high-precision measurement method for electrical efficiency, we established ±1.0 % as the target value of the relative uncertainty of on-site electrical efficiency measurements that is attributable to the measurement system. To achieve this goal, we developed various technologies, mainly focusing on the technologies for the highly accurate measurement of the flow rate and the composition of raw fuels such as city gas and liquefied natural gas (LNG). At the same time, we pursued the standardization of the testing methods for electrical efficiency.

2.2 Specific approaches to achieving research objectives

One of the goals of this study was to minimize uncertainty in measurement values. For this purpose, we worked on high-precision calibration techniques for commercially available measurement instruments with excellent repeatability and linearity, such as thermal mass flowmeters, gas chromatographs, and voltmeters, while ensuring traceability to the national standards.

Figure 4 shows a schematic of the component technologies developed and combined in this project. In the area of flow rate measurement, for example, our group worked with the

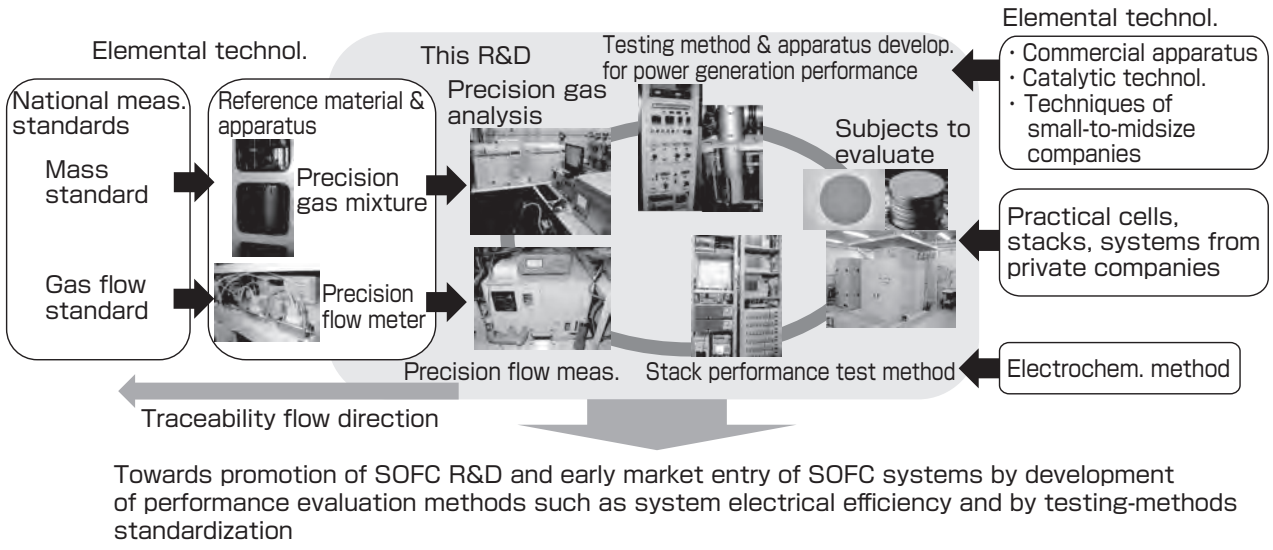


Fig. 4 Elemental technologies incorporated into the research and development project and combined results

Fluid Flow Division of the Metrology Institute of AIST, which developed the standard and the working standard used for the measurement of the flow rate of city gas and hydrogen. Our group was responsible for the development of the flow calibration method and the high-precision flow measurement method/apparatus for the measurement of electrical efficiency.

For gas composition analysis, we cooperated with a standard gas manufacturer to develop an analysis method using a standard gas mixture obtained by the gravimetric method in order to reduce the level of uncertainty. We prepared a high-precision gas composition analysis system as well in collaboration with a manufacturer of precision analysis instruments.

To establish an evaluation method for power generation performance, we developed a method that combined an existing catalytic technology and the aforementioned new high-precision flow rate measurement method, as shown in Fig. 4. In a joint effort with a instrument manufacturer, we developed a testing system capable of testing privately developed, full-size SOFC cells/stacks.

For a stack performance evaluation method, we worked with a manufacturer of electrochemical instruments to prepare a prototype of a measurement apparatus capable of making simultaneous measurements of different factors causing variability in stack performance by applying the AC impedance method, a basic electrochemical evaluation method.

Thus, in this study we developed new, high-precision SOFC performance measurement methods and systems by combining commercially available measurement instruments, high-precision flowmeters and standard gas mixtures that are traceable to measurement standards, and an existing catalytic technology. At the same time, we evaluated the performance and applicability of the systems we developed in collaboration with SOFC manufacturers and others.

3 Performance evaluation and measuring methods

3.1 Development of SOFC cell/stack performance evaluation methods

3.1.1 Development of power generation performance evaluation methods

The voltage of a single SOFC cell is obtained by subtracting the following from the electromotive force, which is determined by the partial pressure of oxygen and the temperature within the anode and cathode gases: resistance overpotentials resulting from ohmic resistance, activation overpotentials arising from electrode reactions, and concentration overpotentials caused by the low gas diffusion rate near the electrode.

The partial pressure of oxygen within the anode gas mixture (e.g. H_2-H_2O-CO-CO_2-CH_4) is dependent on factors such as the composition and pressure of the anode gas mixture and fuel utilization. It is important, therefore, to specify these parameters for the cell/stack performance test. In addition, the degree of overpotentials mentioned above varies according to the type of material and the structure of SOFC; minimizing these factors would help improve the performance of SOFC.

A variety of fuels, such as city gas and LPG, can be used for an SOFC system, and are reformed before they are fed to the anode side, as shown in Fig. 2. In other words, anode gas composition varies significantly depending on the types of feedstock fuels used and the reforming conditions.

There are a number of problems associated with the testing method of power generation performance, examples of which are: (1) The testing conditions of a simplified test using humidified hydrogen differ significantly from the actual operating conditions of an SOFC system; and (2) to supply simulated reformate gas, it is necessary to use highly poisonous pure carbon monoxide, and the difficulty of generating a stable supply of water vapor at a low flow rate increases the fluctuation of cell voltage.

Incidentally, there is very low risk arising from carbon monoxide in an SOFC system (final product), since there is no possibility that anode gas would leak in its original form; unused fuel components such as carbon monoxide within the anode exhaust gas are combusted by the oxygen within the cathode exhaust gas.

Against this background, our research efforts on SOFC power generation performance evaluation focused on the development of a method of generating and feeding simulated reformate gases that would allow SOFC developers to conduct the power generation test safely and easily while achieving reliable results.

Figure 5 shows the method of supplying reformate gases that we developed for this study. Water vapor is generated by using a catalytic combustor filled with a commercially available platinum catalyst and reacting excess hydrogen with oxygen at 200 ºC or above. This method makes it possible to generate a stable supply of water vapor even at a low flow rate and prepare an H_2-H_2O gas mixture.

In addition, to avoid the use of pure carbon monoxide, we developed an equilibrium reactor using a commercially available nickel or ruthenium catalyst for methanation. This equilibrium reactor is capable of producing carbon monoxide from carbon dioxide just before the gas mixture reaches the anode by using the reverse-shift reaction ($H_2 + CO_2 \rightarrow H_2O + CO$) while a methanation reaction ($4H_2 + CO_2 \rightarrow CH_4 +$

$2H_2O$) simultaneously proceeds to produce methane.

In sum, by using hydrogen, oxygen, carbon dioxide as gaseous ingredients and the newly developed catalytic combustor and equilibrium reactor, our method is capable of simulating reformate gases and feeding them to the anode, while maintaining their composition and flow rate identical to those generated by the reforming reaction at equilibrium.

In addition, even if carbon monoxide leaks during the test, it is possible to cut the supply of carbon dioxide and stop the production of carbon monoxide, thereby making it possible to devise safety measures for the test.

Next, we developed a test apparatus for SOFC power generation performance in collaboration with Eiwa Corporation, as shown in Fig. 5 (patent application 2008-045311), by applying the know-how we acquired from the new anode gas supply method. We successfully produced a compact catalyst combustor (10 mL) and equilibrium reactor (20 mL) for testing 100 W-class SOFC systems.

We controlled the flow rate of the simulated reformate gases using a thermal mass flow controller (MFC), and achieved an uncertainty of ±0.5 to 1.0 % by calibrating the flow rate using a high-precision flowmeter (uncertainty: ±0.2 %).[12]

An examination of the performance of this test system revealed that the precision of the composition of the simulated reform gases was ±0.5 to 1.0 mol% (Fig. 5) of the equilibrium value, while the stability of the gas composition was ±0.04 mol% of the same, demonstrating that with this apparatus it is now possible to conduct a highly accurate power generation performance test.[13]

In addition, when we tested an actual single SOFC cell developed by a private corporation, it became clear that the fuels and reform conditions can be modified easily and quickly by changing the flow ratios of the raw gases. The cell voltage stabilized within 30 seconds, significantly reducing the testing time and also keeping the fluctuation of the cell voltage at ±0.1 % or below.

In summary, the SOFC power generation evaluation method and the testing apparatus we developed in this study are capable of feeding a stable and precise supply of simulated reformate gases at a low flow rate to the anode while avoiding the use of highly poisonous pure carbon monoxide, thereby making the testing of the power generation performance of SOFC easier, safer, and more precise.

Given that several SOFC manufacturers have recently acquired this testing system, we intend to continue providing technical assistance to private testing-instrument manufacturers to contribute to the overall research and development efforts for the commercialization of SOFC. Currently, we are using the findings from this study to prepare a draft for single cell/stack performance testing methods and proceeding with the JIS and IEC standardization efforts at the same time.[11]

3.1.2 Development of stack performance evaluation methods

The performance of an SOFC system is dictated largely by the performance of its stack, which is formed by connecting multiple cells (Fig. 6). Minimizing the performance

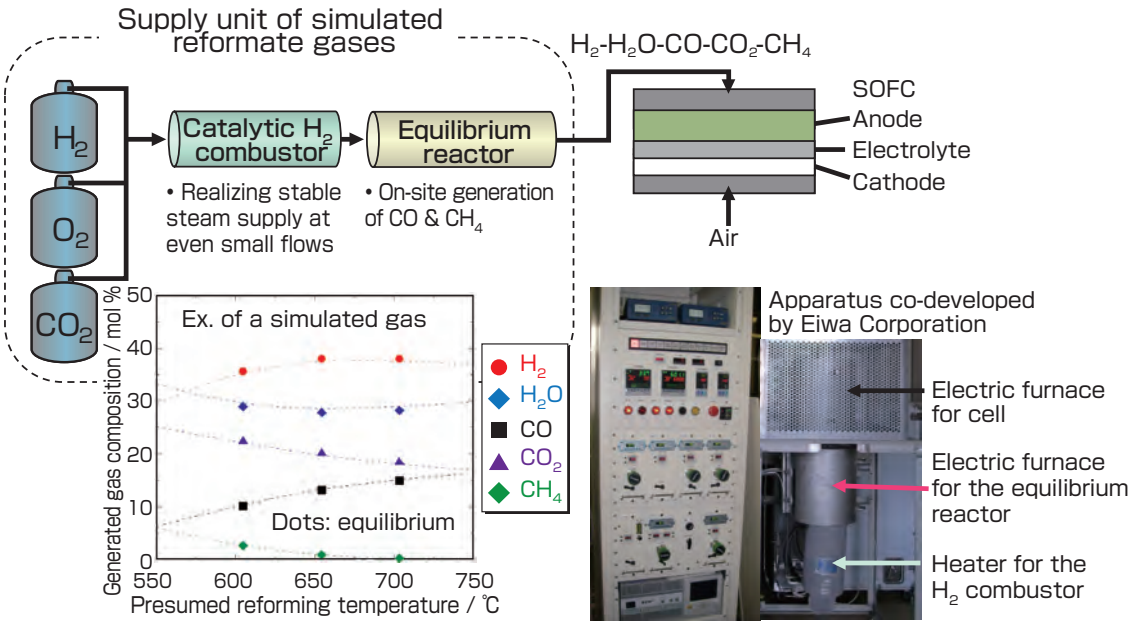


Fig. 5 SOFC power generation measurement method/apparatus developed in the project

variability among the cells in the stack makes it easier to control the performance of the system as a whole. In addition, because the cells are normally connected in series, the stack would stop functioning if any one of the cells fails or degrades significantly.

For these reasons, it is desirable to evaluate the performance of each cell within the stack as part of the research and development of the SOFC system. As shown in Fig. 6, examples of factors causing performance variability among the cells include individual variations among the cells and surrounding components, inconsistency in fuel distribution, temperature distribution in the stack, and partial degradation in performance. However, no method has been established in the past for evaluating the performance of SOFC based on different parameters such as those described above.

Applying the AC impedance method, which is commonly used for the electrochemical evaluation of single cells, we developed an evaluation method capable of making separate and simultaneous measurements of each of the factors contributing to the variability of cell performance in a stack. As shown in Fig. 6(b), we prepared a prototype of a multi-impedance analyzer capable of measuring the impedance of 47 cells simultaneously.[14]

In this test system, the AC current is superimposed on the DC current (with a frequency range of several tens of kHz to 0.01 Hz). The voltage responses of each cell are Fourier transformed to simultaneously obtain multi-impedance spectra as a function of the time constant of an electrode reaction or other parameters.

Using the prototype, we tested a 1-kW stack (46 cells in series) developed by our joint research partners, Kansai Electric Power Co., Inc. (KEPCO) and Mitsubishi Materials Corporation. Figure 6(c) exhibits an example of the impedance measurement results (cells #41 to 46) in a Cole-Cole plot.

The x-axis is the real part of impedance. As shown by the spectrum for #46, the resistance in an SOFC stack is categorized into the following: A: Ohmic resistance; B: activation overpotentials; and C: resistance corresponding to the change in gas concentration due to fuel consumption. For example, the results for cells #41 and #42 show that C is larger than for other cells, and we can conclude that the actual fuel utilization has increased due to insufficient fuel supply. Feeding back such measurement results into SOFC research efforts can help accelerate development progress.

In summary, the study demonstrated that by developing a stack performance evaluation method capable of separately measuring performance variability and each resistance

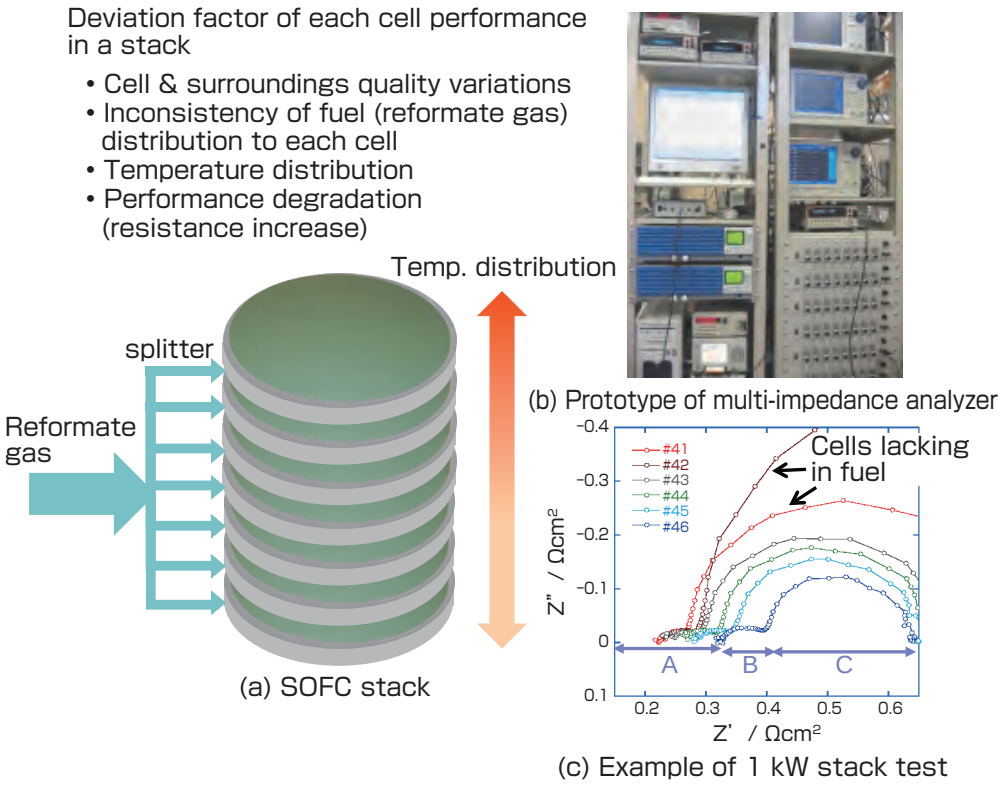


Fig. 6 Development of a stack performance evaluation method and a measurement example of a privately developed 1-kW stack

factor that causes the variability in cell performance and by applying this method to measure the performance of a privately developed 1-kW stack, it is possible to make a multifaceted evaluation of parameters such as inconsistent fuel distribution and thereby contribute to overall SOFC research efforts. In fact, the results from this study proved useful in the development of a 10-kW cogeneration system by our research partner corporations. We believe that the method also has applicability for conducting durability tests.

3.2 Development of measurement methods for electrical efficiency of SOFC systems and standardization efforts

3.2.1 Development of a high-precision measurement method for electrical efficiency

As part of the NEDO project in 2004-2007 "Research on the Technology for the Evaluation of System Efficiency Measurement," we conducted a research and development project in a joint effort with the Fluid Flow Division of the Metrology Institute of AIST, mainly focusing on the development of a high-precision measurement method for the electrical efficiency of the SOFC system. The Fluid Flow Division worked on the development of the standard and the working standard for measuring the flow rate of city gas and hydrogen.

In the meanwhile, our group developed a transportable electrical efficiency measurement method. We used this method to take an on-site measurement of the electrical efficiency of a 10-kW cogeneration system developed by Kansai Electric Power Company (KEPCO) and Mitsubishi Materials Corporation as part of the aforementioned NEDO project, and conducted uncertainty analysis. As mentioned in subchapter 2.1, the HHV standard was used to express electrical efficiency.

As shown by equation (1), the net electrical efficiency of an SOFC system, η_e, is defined by the following: heating value of city gas or other types of raw fuels supplied to the SOFC system, H; flow rate of the fuel, f; and net AC output (power to export), P.

$$\eta_e = \frac{P}{H \times f} \qquad (1)$$

In calculating an electrical efficiency, it is important to measure each of these parameters in such a manner that the target uncertainty value can be achieved. The sources of uncertainty include not only the uncertainties arising from the measurement instruments used, but also those uncertainties attributable to deviation of the parameters themselves (e.g. the composition of city gas, power output).

Hence, if the target relative uncertainty of electrical efficiency attributable to the measurement system is set at ±1.0 % and is assigned equally to H, f, and P, each parameter must be measured at the relative uncertainty of ±0.6 %.

Given the above, in this research project we established the target value of ±0.6 % for the relative uncertainty of the measurement instruments used to measure each of the heating value, flow rate, and output. In order to minimize uncertainty, we developed high-precision measurement methods, including calibration methods of measurement instruments that are traceable to standards. The measurement methods are described below.

3.2.1.1 Development of a heating value measurement method

The most commonly used method for obtaining the heating values of gaseous fuels such as city gas is to measure the gas composition using a gas chromatograph and to calculate the heating value based on the measurements, as specified by JIS K 2301 and ISO 6974 and 6976 (the ISO standards are applicable only to natural gas).

In this study, we developed measurement methods based on the method prescribed by the ISO standards that also include uncertainty calculation methods. Gas samples were taken from the SOFC system on site using a portable gas sampler (patent application 2008-045311). As illustrated in Fig. 7, the gas samples were then transported to our laboratory and measurements were taken using gas chromatographs with specifications in compliance with the aforementioned JIS or ISO standards. We also deployed a measurement method using a highly portable micro gas chromatograph with the capability of making on-site quick analysis within a few minutes (Fig. 7).

While ISO 6976 proposes an uncertainty of approximately ±0.1 % for the heating value of each city gas component, the standard does not incorporate this value into uncertainty calculations. In this study, however, this uncertainty value was taken into consideration.

For high-precision analysis of fuel gas composition, it is important to reduce the uncertainty of the standard gas mixture (i.e. a mixture that has predetermined concentration levels of gas components) to be used for the calibration of the gas chromatographs. We examined standard gas mixture products for city gas having a defined uncertainty value and commercially available in Japan. It was found that the concentration of methane, the main component, had a relative uncertainty of ±1.0 %, such as 88.47±0.89 % (k=2). This value was insufficient for this study.

With cooperation of Sumitomo Seika Chemicals Co., Ltd., we filled a 47-L gas cylinder with each component of city gas using the gravimetric method. We took three repeated measurements of the mass of each gas in the cylinder using a large balance scale that is traceable to the national standard

on mass measurements and prepared a standard gas mixture. Based on the uncertainties of the mass, the scale, and other factors, we calculated the mole fraction of each component of the standard gas mixture, and the uncertainty of each in accordance with the method described by ISO 6142. The result, in the case of methane, was 88.002±0.016 %, or a relative uncertainty of ±0.02 % (k=2), demonstrating that we were able to reduce the uncertainty of the standard gas mixture to 1/50 of the existing uncertainty value. Then, we calibrated the gas chromatographs and prepared a calibration curve using several of such high-precision standard gas mixtures.

Additionally, in collaboration with Kimoto Electric Co., Ltd., we developed a high-precision, automated heating value measurement apparatus (Fig. 7) capable of the following: repeated analyses of three types of standard gas mixtures before and after the sample measurement; automated analysis of the city gas sample in a separately developed portable gas sampler; and output of analysis data of parameters including the flow rate, gas pressure, and temperature at the time when samples are taken.

Thus, the above demonstrates that we were able to develop a system capable of measuring the heating value of city gas at an uncertainty of ±0.12 %.

3.2.1.2 Development of a measurement method of city gas flow rate

To measure the flow rate of city gas or other raw fuels supplied to the SOFC system, it is necessary to install a flowmeter designed for efficiency measurement upstream of the SOFC system. While a wet-type volumetric flowmeter designated by the Measurement Act is used as the reference instrument for the inspection of residential gas meters,[15] no industrial standard has been established for the flow rate of city gas in Japan and hence traceability has not been properly addressed in this regard. In this project, therefore, the Fluid Flow Division developed the standard and the working standard for measuring the flow rate of city gas.

Flowmeters that emit oil and water vapor such as the one mentioned above are not suitable for efficiency measurement, as they may affect the SOFC system. In contrast, thermal mass flow controllers (MFC), with easy maintenance and excellent repeatability, are often used in SOFC system prototypes. For these reasons, in this study we developed a city gas flow measurement and calibration system using a commercially available thermal mass flowmeter (MFM).

When the flow measurements of methane by commercial MFMs and MFCs were calibrated using a high-precision mass flowmeter, results showed an instrument error of up to 8 %. To achieve the target relative uncertainty of ±0.6 %, it is necessary to calibrate the flowmeter using an identical gas under efficiency measurement. Because of this, it is important to minimize the uncertainty of standard flowmeters for city gas or other fuels used for calibrating the MFM.

In addition, while gas composition has little impact on the volumetric flowmeter, the sensitivity of the MFM is influenced by the type of gas under measurement.

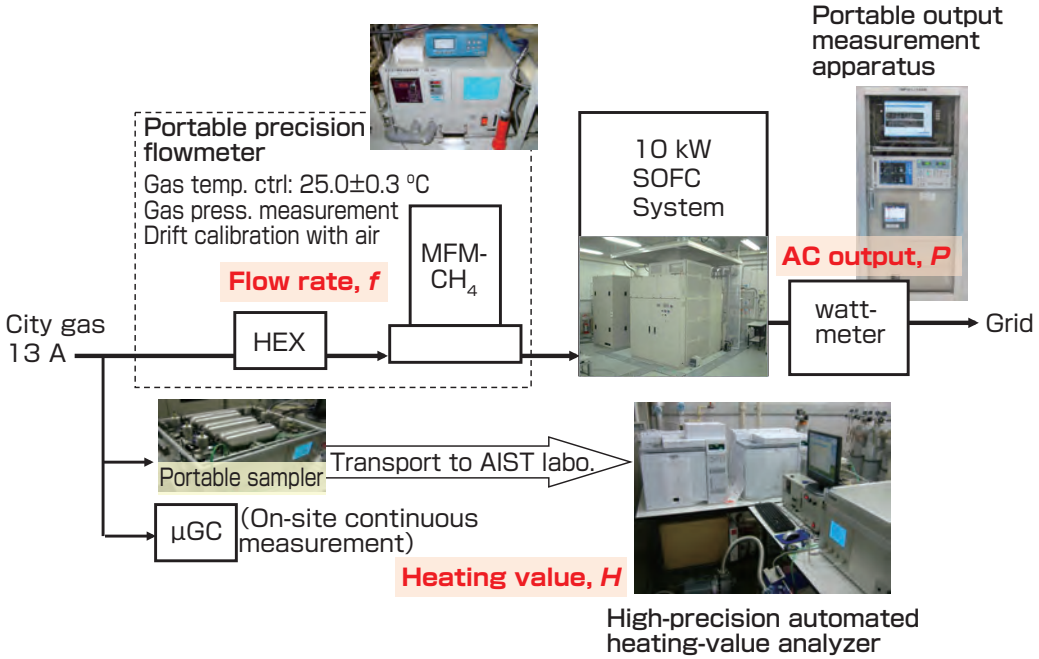


Fig. 7 Overview of transportable high-precision generation efficiency measurement system
HEX: Heat Exchanger; MFM-CH4: thermal MFM for methane; μGC: micro gas chromatograph

Therefore, corrections must be made using each gas type (mixture) under measurement. Moreover, to achieve a highly precise flow rate measurement, the impact of pressure and temperature must be taken into consideration even for measurements using the MFM.

In order to minimize the impact of temperature on the MFM, we developed a transportable flow rate measurement apparatus capable of recording data and controlling gas temperature with a fluctuation of ±0.3 ºC using a heat exchanger and others, as shown in Fig. 7. In addition, in order to prepare for the durability testing of the SOFC system, we installed on this measuring equipment a city gas bypass line, a compact air compressor, and a high-precision laminar flowmeter (molbloc from DHI), so that it is possible to calibrate the MFM and evaluate its sensitivity drift with ambient air on a regular basis (e.g. once a month) without causing any impact on the test subject.

The mass flow rate (g/min) measured by the MFM was converted into volume flow rate (l min^{-1}, m^3 s^{-1}) using the volume of the ideal gas in the standard state (0 ºC, 101.325 kPa), and is expressed in Nl min^{-1} and Nm^3 s^{-1}.

To calibrate the flow rate measurement of the MFM, an MFC was prepared for each of the main components of city gas: methane (concentration: approximately 89 %), ethane (6 %), propane (3 %), and butane (2 %). Using the MFCs, we developed a prototype of a city gas flow calibration apparatus that calibrates the flow of each component based on the mass flow rate, mixes the gas components using a static mixer, and generates simulated city gas whose temperature has been adjusted by a heat exchanger. We used this calibration apparatus to calibrate the MFM and conduct MFM characteristic tests to study the impact of city gas composition, temperature, pressure, and other factors on the MFM.

This calibration apparatus can calibrate the flow of city gas up to 70 Nl min^{-1}, which corresponds to the flow rate of a 20-kW SOFC. Details are available from a separate volume of this journal.[16]

In addition, it was confirmed that the gas component correction factor (CF_{mix}) of the MFM used for methane in this study can be calculated based on multiple linear regression analysis using the polynomial equation shown in equation (2).[16] The uncertainty of the calculated value was found to be ±0.15 %.

$$1/CF_{mix} = \sum x_i / CF_i \qquad (2)$$

where x_i is the mole fraction of component i and CF_i is the relative sensitivity of gas component i to methane in a thermal mass flowmeter. It was also confirmed that the repeatability, linearity, temperature dependence, pressure dependence, and sensitivity drift over time are approximately identical to those found in the catalogue specifications. It was determined, therefore, that catalogue specifications can be used for the analysis of uncertainties attributable to these factors.

In sum, we developed a high-precision, transportable city gas flow measurement/calibration system traceable to flow standards and supporting SOFC systems of up to 20 kW. By doing so, we achieved a relative uncertainty of ±0.44 % for the gas flow rate. We also identified the MFM properties necessary for the uncertainty analysis of the flow measurement of city gas. For example, we established a prediction equation to obtain the effect of gas compositions on the sensitivity of a thermal mass flowmeter.

Thus, it is now possible to make gas flow measurements whose traceability is ensured by calibrating the measurements using a high-precision flowmeter traceable to the standard or the working standard developed by the Fluid Division or a flowmeter certified by the Japan Calibration Service System (JCSS) that recently became available on the market.

3.2.1.3 Development of an output measurement method

For the output measurement of 10 kW-class SOFC systems, a wattmeter having an accuracy of ±0.1 % is available commercially, so that you can convert the accuracy into uncertainty with type B evaluation of uncertainty.[7] Similarly, a precision calibration method certified by the JCSS has been the established method for the measurement of electric power. In addition, the Japan Electric Meters Inspection Corporation (JEMIC) also offers general calibration services with an uncertainty of ±0.04 % (JCSS's best measurement capability is ±0.02 %). It is possible, therefore, to achieve the target relative uncertainty of ±0.6 % for output measurement.

It must be noted, however, that the AC output of the SOFC system is obtained by converting the DC output produced by the stack into the utility frequency AC power using an inverter. The AC output includes not only the fundamental wave of the utility frequency, but also different harmonics as well as the carrier of the inverter. Hence, for the purposes of this study, we defined net output, *P*, to include only the active power of the fundamental wave.

The evaluation of higher harmonic waves and other frequencies other than the fundamental is essential, as they may have a major impact on the uncertainty of the electric power measurement. Currently, however, there are no national standards that cover AC power containing higher harmonics, and general commercial wattmeters only cover

Table. 1 Measurement values and their uncertainties for the initial characteristic test for net electrical efficiency of a 10-kW cogeneration system

Parameters	Average	Relative uncertainty	(JIS regulation example[1])
Higher heating value of city gas, H (MJ Nm^{-3})	44.69	±0.12 %	No regulation
Flow rate of city gas, f (10^{-4} Nm^3 s^{-1})	5.507	±0.58 %	±3.0 %
AC output, P (kW)	10.14	±0.46 %	±1.5 %
Net electrical efficiency, η_e (%)	41.2	±0.74 %	No regulation

1) Type test in JIS-B8122 (2001) Test methods for measuring performance of cogeneration unit

AC power with higher harmonics that fall within the error range of a given accuracy class.

For these reasons, we developed a compact, transportable output measurement apparatus as shown in Fig. 7. This apparatus is based on a commercially available precision power analyzer (Yokogawa WT3000) capable of making the precision measurement of AC power, the analysis of higher harmonics, and the measurement of DC power when needed.

Other than active power, this apparatus measures various parameters, such as voltage, current, power factor, higher harmonics, and inverter carrier waves under output conditions. The apparatus is also designed to measure the environment temperature and the instrument temperature at the time of the measurement for the purpose of uncertainty analysis.

3.2.1.4 Electrical efficiency measurement of a privately developed 10 kW-class system

Using the transportable high-precision efficiency measurement system (Fig. 7) we developed as described in sections 3.2.1.1 to 3.2.1.3, we tested the initial characteristics of the net electrical efficiency of a 10 kW-class cogeneration system and took on-site measurements of its electrical efficiency during a 3000-hour durability test. As mentioned above, this power system was developed by KEPCO and Mitsubishi Materials as part of the NEDO project and had the following specifications: AC output of 60 Hz; three-phase three-wire system of 200 V; maximum current of 38 A; and power factor of 0.99.

To connect the 10-kW system to the transportable output measurement apparatus, we employed a three-phase four-wire output measurement method, whereby a virtual neutral point generated by a starpoint adapter is used for the connection, in order to minimize uncertainty.[16]

Figure 8 shows the flow rate and output measured during the initial characterization test. Because the fuel utilization (the ratio of fuel used for cell reactions) of this 10-kW system was kept constant, the city gas flow rate stayed relatively stable with a fluctuation of ±0.14 %. In contrast, the AC output fluctuated ±0.45 % due to the fluctuations of auxiliary power consumed internally by the SOFC system.

The fluctuation of the heating value of city gas was analyzed using a micro gas chromatograph at the installation location of the 10-kW system. City gas samples were also taken using the portable sampler before and after the test, and the heating value fluctuations were analyzed at the AIST laboratory. The results showed that the fluctuation range of the heating value during the initial characteristic test is sufficiently small, at ±0.02 %.

For measurement values we used the mean values of the HHV and flow rate of the city gas, and output (active power of 60 Hz), which were, respectively, 44.69 MJ Nm^{-3}, 5.507×10^{-4} Nm^3 s^{-1}, and 10.14 kW, as shown in Table 1. Using equation (1), an HHV-based net electrical efficiency of 41.2 % was obtained.

When we combined the fluctuation ranges of the parameters mentioned above, the uncertainties attributable to the measurement conditions at the time of efficiency

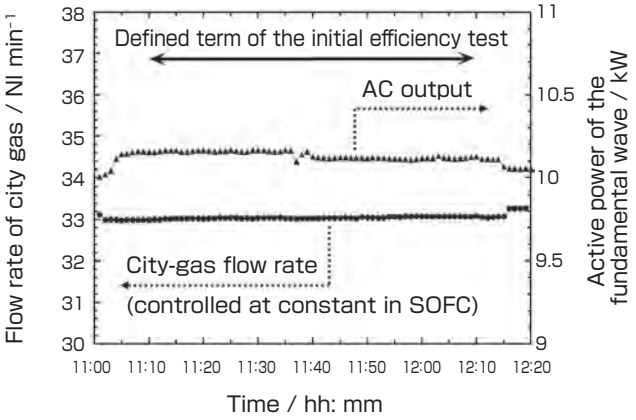


Fig. 8 City gas flow rate and AC output at the time of the initial characterization test for electrical efficiency of a 10-kW cogeneration system

measurement such as the temperature and pressure of city gas, and the uncertainties deriving from measurement instruments as described in subsections 3.2.1.1 to 3.2.1.3, we found that the relative uncertainties of the heating value, flow rate, output, and electrical efficiency were, respectively, ±0.12 %, ±0.58 %, ±0.46 %, and ±0.74 %, as shown in Table 1. The electrical efficiency is estimated to be 41.2 ±0.3 % (HHV), which meets the target uncertainty level of the NEDO project of ±1.0 % while demonstrating that this 10-kW system exceeded the electrical efficiency of 40 % (HHV), NEDO's development target value.

In sum, in this study we developed a transportable, high-precision efficiency measurement method and apparatus traceable to national measurement standards. It was shown that the apparatus was capable of measuring electrical efficiency on-site at a relative uncertainty of ±1.0 % or below.

In other words, even if net electrical efficiency improves to 50 to 70 % in the future, it will be possible to measure the efficiencies at an uncertainty of ±0.5 to ±0.7 %. In addition, this method is likely applicable not only to SOFC systems but also to efficiency measurements of systems operated by other fuel cells or other energy technologies.

3.2.2 Standardization of electrical efficiency measurement testing method

While IEC 62282-3-2 has been published as the international standard for the electrical efficiency testing methods for fuel cell systems, no JIS has been established in Japan for the electrical efficiency testing methods for SOFC systems. Furthermore, when SOFC is ready for practical and commercial applications, a testing method whose measurement uncertainty should be comparable to that of AC utility power (i.e. uncertainty of output measurement at the ±0.1 % level) is required.

Therefore, we applied the findings of the high-precision electrical efficiency measurement method described in section 3.2.1 to investigate the impact that the transportation of the measurement instrument to the SOFC installation location has on the instrument uncertainties. Based on the results, we prepared a JIS draft for electrical efficiency testing methods that achieve effective comparisons of electrical efficiency levels, the most important performance indicator of an SOFC system. With the cooperation of the Japan Electrical Manufacturers' Association (JEMA), the draft was then examined by a deliberating committee consisting of cell/stack manufacturers, system manufacturers, and neutral research institutions.

Based on the results of the committee deliberations and our surveys of existing JIS and calibration systems, we prepared a draft of a JIS Technical Specification (TS) prescribing electrical efficiency measurement methods for SOFC systems at an uncertainty level of less than ±1 % while ensuring that the methods are traceable to national measurement standards. Following the deliberation of the draft by the Japan Industrial Standards Committee (JISC), JIS TS C0054 was published in 2010 with the title of "Testing method of power generation efficiency for solid oxide fuel cell power systems fueled with gas in which methane is main component," well in advance of the release of residential SOFC systems in October 2011.

4 Summary and future prospects

We developed new SOFC performance evaluation methods for all SOFC units, cell, stack, and system (complete product), by combining commercial measurement instruments and catalyst technologies while ensuring traceability to national measurement standards. Our objectives have been to promote the early commercialization of SOFC systems and to develop domestic and international standards for performance testing methods that are essential for ensuring fair competition among makers of SOFC systems.

The establishment of performance evaluation methods for SOFC cells/stack is crucial for the research and development of SOFC systems. We devised easy, safe, and high-precision power generation performance testing methods for SOFC cells/stacks and developed a testing apparatus in collaboration with private corporations. We developed a measurement method and apparatus as well that can simultaneously measure different factors causing cell-to-cell performance variability in the stack. Through these projects we have contributed to the research and development efforts for SOFC systems in the private sector.

As for the measurement of electrical efficiency of SOFC systems, we established a transportable method capable of making high-precision measurements of electrical efficiency even at SOFC installation locations. When actual measurement was made on a 10-kW system developed by private manufacturers, the result was 41.2 ±0.3 % (HHV), which demonstrated that the NEDO project target value (net electrical efficiency of 40 % or above and uncertainty of ±1.0 %) was achieved. This method will be more than adequate even when the electrical generation efficiency of SOFC systems improves in the future. Furthermore, we prepared a JIS (TS) draft and were able to publish the final version prior to the commercial release of SOFC systems.

We will continue with our efforts to accelerate the development of JIS and IEC standards for SOFC cell/stack performance test methods. At the same time, by taking advantage of the methods developed in this study, we will make further improvements on the electrical efficiency of SOFC systems, contribute to the research and development of SOFC systems operating on novel fuels (e.g. dimethyl ether), biomass, and coal, and commit our efforts to the

development of portable SOFC systems, which have the potential to serve as a supplementary power source for automobiles and other applications. Our goals also include improving the acceptance level and applicability of high-efficiency distributed SOFC systems and the standardization of durability testing methods, which are essential for the commercialization of SOFC.

Acknowledgement

The project team would like to thank METI and NEDO for providing funding and assistance for this research and development project and the standardization of performance testing methods. We would also like to thank KEPCO, Mitsubishi Materials Corporation, Sumitomo Seika Chemicals Co., Ltd., Kimoto Electric Co., Ltd., Eiwa Corporation, and the Fluid Flow Division of the Metrology Institute of AIST and all others who have offered their generous time and cooperation for our research and development project. We would also like to thank JEMA and all SOFC cell manufacturers, SOFC system developers, and neutral research institutions that offered their collaboration for our standardization work.

References

[1] Japan Smart Community Alliance (JSCA): *Smart Community Kiyaku* (Smart Community Charter), https://www.smart-japan.org, Tokyo (2011) (in Japanese).
[2] W.W. Clark II and L. Eisenberg: Agile sustainable communities: On-site renewable energy generation, *Utilities Policy*, 16 (4), 262-274 (2008).
[3] Research Group on Technologies for Electricity Storage, the Electrochemical Society of Japan (ed.): *Daikibo Denryoku Chozoyo Chikudenchi* (Batteries for Storage of Large-scale Electric Power), 8-25, Nikkan Kogyo Shimbun, Tokyo (2011) (in Japanese).
[4] K. Kawakami, J. Kawai and M. Nagai: Design and operating experience of GTCC power plant (Kawasaki thermal power station group1 of Tokyo Electric Power Company) with gas turbine inlet temperature of 1500 ºC, *Mitsubishi Juko Giho*, 46 (2), 30-33 (2009) (in Japanese).
[5] Y. Kobayashi, Y. Ando, T. Kabata, M. Nishiura, K. Tomida and N. Matake: Extremely high efficiency power system – SOFC triple combined cycle system, *Mitsubishi Juko Giho*, 48 (3), 16-21 (2011) (in Japanese).
[6] M. Okuda: Kotaisanka bukkei nenryo denchi jissho kenkyu heisei 22 nendo seika hokoku, *Heisei 22 Nendo Kotaisanka Bukkei Nenryo Denchi Jissho Kenkyu Seika Hokokukai* (The 2010 Progress Report Meeting on the Demonstration Project for the Solid Oxide Fuel Cell), 33-62, New Energy Foundation, Tokyo (2011) (in Japanese).
[7] International Standard Organization (ISO): *Guide to the Expression of Uncertainty in Measurement (GUM)* [Kouzo Iizuka (ed.) *Keisokuni Okeru Futashikasano Hyogenno Gaido – Toitsu Sareru Shinraisei Hyogen no Kokusai Ruru*], Japanese Standards Association, Tokyo (1996).
[8] Masashi Oku: *Hyojunka Kyoiku Puroguramu* [*Kobetsu Gijutsu Bunyahen – Denki Denshi Bunya*] *Dai 15 Sho Keisokuno Shinraiseito Sokuteino Futashikasa* (Standardization Educational Program, Individual Technology Field: Electric/Electrical Field, Ch. 15, Reliability of Measurement Instruments and Uncertainty of Measurements), http://www.jsa.or.jp/stdz/edu/pdf/b4/4_15.pdf, 19 (in Japanese).
[9] New Energy and Industrial Technology Development Organization (NEDO): *Kotai Sanka Bukkei Nenryo Denchi Shisutemu Gijutsu Kaihatsu Kihon Keikaku* (SOFC System Technological Development Basic Plan), http://www.nedo.go.jp/content/100085124.pdf, Tokyo (2001) (in Japanese).
[10] Japanese Standards Association: JIS B8122: Test methods for measuring performance of cogeneration unit, 2001, 1-41, Tokyo (2001).
[11] A. Momma, K. Takano, Y. Tanaka and T. Kato: Evaluating uncertainty for the standardization of single cell/stack power generation performance tests for SOFC, *Synthesiology*, 5 (4), 251-261 (2012).
[12] Bios International Corporation: model ML-800-10, http://www.biosint.com/Products/biosmetlabseries.php, Butler NJ (2012).
[13] Y. Tanaka, A. Momma, K. Sato and T. Kato: Fuel flexibility of anode-supported planar solid oxide fuel cell evaluated with developed simulated-reformate-gas generator, *J. Fuel Cell Sci. Technol.*, 8, 061012, 1-6 (2011).
[14] A. Momma, K. Takano, Y. Kaga, K. Nozaki, A. Negishi, K. Kato, T. Kato, T. Inagaki, H. Yoshida, K. Hosoi, M. Shibata, M. Yamada, T. Akbay, J. Akikusa and N. Chitose: Simultaneous impedance measurement of 46 cells in 1 kW SOFC stack: Evaluation of the fuel flow rate distribution among the cells, *Proc. SOFC9*, 1, 554-563 (2005).
[15] Japan Measuring Instruments Federation (JMIF): *Ryuryokeino Jitsuyo Nabi* (A Practical Guide to Flowmeters), 40-41, 174-183, Tokyo (2005) (in Japanese).
[16] Y. Tanaka, A. Momma, K. Kato, A. Negishi, K. Takano, K. Nozaki and T. Kato: Development of electrical efficiency measurement techniques for 10 kW-class SOFC system: Part I. Measurement of electrical efficiency, *Energy Conversion Manage.*, 50 (3), 458-466 (2009).

Authors

Yohei TANAKA

Received his doctorate from the Department of Energy and Hydrocarbon Chemistry, Graduate School of Engineering of Kyoto University in 2005. Joined AIST in 2005. Currently works as a senior researcher at the Fuel Cell System Group of the Energy Technology Research Institute. Areas of specialization are catalytic chemistry, fuel cell performance evaluation, and energy engineering. Project responsibilities: research and development of power generation performance evaluation methods and high-precision measurement methods for city gas flow rate and heating value; coordination of efficiency measurement method activities; standardization of electrical efficiency measurement methods; and overall organization of this paper.

Akihiko MOMMA

Received his doctorate from the Metallurgical Engineering Department at the Tokyo Institute of Technology in 1985.

Worked at SRI International as a guest researcher. Joined the Electrotechnical Laboratory (the predecessor of AIST) in 1989 and conducted research and development of SOFC. Currently serves as senior researcher of the Fuel Cell System Group of AIST's Energy Technology Research Institute and specializes in electrochemical measurements and evaluations. Project responsibilities: preparation of various standards, research and development of stack performance evaluation methods, and the development of 10-kW output measurement methods.

Akira NEGISHI

Joined the Electrotechnical Laboratory of the Agency of Industrial Science and Technology of the Ministry of International Trade and Industry (MITI; the predecessor of METI) in 1968, and graduated from the Department of Chemistry, Faculty of Science Division II, Tokyo University of Science in 1972. Currently works as a technical staff member of the Fuel Cell System Group of AIST's Energy Technology Research Institute. Areas of specialization are electrochemistry and battery technology. Projects include the research and development of the conversion/storage technologies for electrochemical energy, such as fuel cell and novel batteries. Project responsibilities: research and development of high-precision measurement methods for the heating value of city gas.

Ken KATO

Joined the Electrotechnical Laboratory of the Agency of Industrial Science and Technology of the Ministry of International Trade and Industry in 1969 and graduated from the Department of Electronic Engineering, School of Engineering Evening Division, Tokyo Denki University in 1973. Was the former senior researcher of the Fuel Cell System Group of AIST's Energy Technology Research Institute. Area of specialization is electronics. Project responsibilities: the research and development of measurement methods for city gas flow rate.

Kiyonami TAKANO

Graduated from the Department of Electrical and Electronic Engineering of the Faculty of Engineering of the University of Tokushima in 1966, and joined the Electrotechnical Laboratory of the Agency of Industrial Science and Technology of MITI. Engaged in research and development relating to magnetohydrodynamic (MHD) power generation, system analysis, analysis of power generation characteristics, and power generation experiments. Currently works at the Fuel Cell System Group of the Energy Technology Research Institute through the industry-academia-government collaborative program. Awards include the Naoji Iwatani Memorial Award, the Award for the Promotion of the Moonlight Project, and the Kodaira Memorial Award. Earned a doctorate in engineering from the Tokyo Institute of Technology in 1989. After engaging in research on the simulation technology of lithium secondary batteries, began research on the power generation evaluation of SOFC in 2001. Project responsibilities: the research and development of stack performance evaluation methods and the development of 10 kW-class output measurement methods.

Ken NOZAKI

Received a Master's degree in Industrial Chemistry from The University of Tokyo in March 1968 and joined the Electrotechnical Laboratory of the Agency of Industrial Science and Technology of MITI in April 1968. Currently works as a technical staff member of the Fuel Cell System Group of AIST's Energy Technology Research Institute. Engages in the research and development of the conversion/storage technologies for electrochemical energy, such as fuel cell and novel batteries; and the research and development of global environmental technologies. Project responsibilities: the research and development of high-precision measurement methods for city gas heating value and flow rate and the draft preparation of JIS (TS) for electrical efficiency testing methods.

Tohru KATO

Completed a graduate program at Tohoku University and received his doctorate in engineering in 1991. Joined the Electrotechnical Laboratory of the Agency of Industrial Science and Technology of MITI in 1992 and conducted research on technology for high temperature electrolysis. Also worked at the Fuel Cell System Group of AIST's Energy Technology Research Institute. Currently serves as Industrial Science and Technology General Director for the Research and Development Division under the Industrial Science and Technology Policy and Environment Bureau of METI. Project responsibilities: the overall management of all research and development projects and the preparation and editing of the JIS (TS) draft on electrical efficiency testing methods.

Discussions with Reviewers

1 Clarity

Comment (Hiroshi Tateishi: AIST)

Because the paper is quite long, some parts need to be simplified. In particular, much of the chapter entitled, "1 Introduction" is about the general background/objectives of the paper, so I think it should be kept to a minimum for the benefit of the general readers. Please provide a simple description of the need to fight against global warming and adopt distributed power sources, ways in which SOFC can fulfill this need, the SOFC development progress, and the objectives and significance of the authors' R&D activities (especially in regards to the current state and importance of the evaluation methods). In addition, it is questionable how many readers can understand the description regarding '*uncertainty*' towards the end of the paper and it would be helpful to include a reference material.

Comment (Yasuo Hasegawa: AIST)

We ask the authors to write their reports in an easy-to-

understand manner so that readers from other fields can read *Synthesiology* without difficulty. For this reason, while a reference material on uncertainty is included, I think it would be even clearer if a simple explanation is included in the paper and the reader is directed to the reference material for details. Because uncertainty is a fairly common term, we need to be careful that readers are not misled into thinking that they understand the concept without actually doing so.

Answer (Yohei Tanaka)

I tried to make the introductory part simpler. I removed the detailed description of the history of SOFC development and included a brief description of the current state of system development efforts as well as the future plans. I also touched upon the characteristics of the SOFC system as a highly efficient generation system and the importance of high-precision performance evaluation technologies, our group's project.

As for the significance of SOFC, while it is an effective solution against global warming, we feel that it has an even more important role to play as a highly efficient distributed power generation system providing a stable supply of electricity and heat in the interior regions (i.e. through efficient use of energy) in the future, in contrast to centralized power stations found in coastal areas. Therefore I did not make very many corrections in this regard. Regarding uncertainty, I did add a brief explanation as suggested and added a note to refer to reference material [7].

2 Performance evaluation framework

Comment (Hiroshi Tateishi)

The paper does not provide any systematic description of the specific factors concerning each of the cell, stack, and system that need to be evaluated for the development of performance testing methods. As a result, it would be difficult for a non-expert to understand the objectives of individual R&D projects. It would be helpful to add a well-organized discussion of the specific factors that need to be measured for a comparative evaluation of fuel cell performance, the specific testing methods and the pros and cons of each, and the differences among the evaluation methods for the cell, stack, and system, etc.

Answer (Yohei Tanaka)

I discussed the importance of the performance evaluation of the single cell, stack, and system in chapter 1 and subchapter 2.1. I added Fig. 3 to explain how the evaluations of each unit level relate to one another and also included a list of the performance indicators and determining factors. I also added an explanation of evaluation parameters (performance indicators) for each unit level and their relevance.

3 Hierarchy of technology development projects

Comment (Hiroshi Tateishi)

Because there is very little analysis of the relationships between the individual technology projects described in chapter 3, they appear to be completely independent from one another. This relates to Issue 2 as well.

3.1.1 The development of performance evaluation methods for single cells

3.1.2 The development of performance evaluation methods for stacks

3.2 Development and standardization of system performance evaluation methods.

I believe it is necessary to explain the relationships between these parts and the overall flow of the projects. For example, how are the evaluation methods for the single cell useful for the evaluation methods for the stack or system?

Answer (Yohei Tanaka)

Thank you very much for the valuable comment. As I answered partly in my reply concerning Issue 2, I provided a brief description of the general flow of the performance evaluation/R&D work, from single cells to stacks to systems, along with the performance indicators and evaluation technologies for each level in chapter 1, and elaborated in subchapter 2.1.

In regards to the question of how cell performance evaluation is utilized for stacks or systems, the stack—which is formed by multiple single cells stacked together—serves as the power generation component of the SOFC system. Therefore it is important to understand the performance of single cells, evaluate the variability of cell performance due to temperature fluctuation and inconsistency of gas distribution, and establish an optimal design. For the system design, in addition to stack performance, thermal design and the design of the flow controllers and other peripherals play important roles, but stack performance especially has a direct impact on the overall performance and of the system, including its electrical efficiency.

4 Order of standard development

Question (Hiroshi Tateishi)

What are the reasons for developing the standards for system evaluation methods first before developing the standards for cell/stack performance evaluation methods? It seems to make more sense to start with the standardization of the components, and leave the systems to the end.

Answer (Yohei Tanaka)

As you suggested, the development and standardization should proceed with the cells and stacks first, before the systems. However, because cell manufacturers and system developers were working on the development of 1 to 200-kW SOFC systems at the time, and their market introduction was imminent, we determined that the standards for system testing methods took priority.

Recently, some companies in and out of Japan are starting to sell single cells and stacks, and there will likely be an increasing number of commercial translations involving these products as well as international collaborations for SOFC development. For this reason the development of standards for single cell/stack performance tests is becoming increasingly important. Currently, we are proposing IEC and JIS standards for testing methods of single cells/stacks and we reported our efforts in Vol. 5, No. 4 of *Synthesiology* (reference material [11]). I added this point in subchapter 2.1.

Earthquake prediction research based on observation of groundwater

— Earthquake forecasting based on crustal deformation estimated from groundwater level change —

Naoji KOIZUMI

[Translation from *Synthesiology*, Vol.6, No.1, p.24-33 (2013)]

We constructed a system for detecting preseismic changes in groundwater levels that uses a combination of long-term observation and analysis of groundwater, a poro-elastic theory, and the pre-slip model. This system is now in operation and is contributing to the national project for prediction of the Tokai earthquake. To apply this system to Tonankai and Nankai earthquakes, we constructed an integrated groundwater observation network in and around Shikoku and the Kii Peninsula (Japan). This network is now being used to observe and study groundwater and crustal deformation. Since 2002, we have also been carrying out international cooperative hydrological research for earthquake prediction in Taiwan to help minimize the damage caused by earthquakes in Southeast Asia. We underestimated the magnitude of the 2011 Tohoku earthquake, which was one of the factors that brought about the severe damage in and around the Tohoku area. Therefore, we should examine scientifically the reasons for the underestimation, and advance earthquake prediction research.

Keywords : Groundwater, earthquake prediction, crustal deformation, pre-slip, Tokai earthquake

1 Introduction

The earthquake prediction research is a typical *Type 2 Basic Research*. Since the basic researches of earthquakes help in estimating the earthquake occurrences, many results of *Type 1 Basic Research* that are considered useful for earthquake prediction (practical earthquake forecasting) have been reported, but it is extremely difficult to predict earthquakes simply by integrating such researches. The earthquake prediction research by groundwater observation is no exception. In Japan, the earthquake prediction research by groundwater observation started from the "Partial Review of the 3rd Earthquake Prediction Plan," a proposal of the Geodesy Council, Ministry of Education, Science, and Culture in July 1975. Initially, major participants were the University of Tokyo, Nagoya University, Kyoto University, and one public research institute, Geological Survey of Japan, Agency of Industrial Science and Technology, which is currently Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology. Both are called GSJ, AIST for short. However, it was later found that academic papers of worthy results are not always obtained although observation over a long period of time and a large expenditure is needed. Therefore the researches at the universities stagnated, and only GSJ, AIST continued to engage actively in the observation and research in the late 1990s. This was because continuous research was more acceptable at public research institutes than at universities. Also, in the Tokai Earthquake Prediction Project based on the Act on Special Measures Concerning Countermeasures for Large-Scale Earthquakes (hereinafter, Large-Scale Earthquake Act) established in 1978, GSJ, AIST was in charge of the groundwater observation, and thereinafter, the observation and research of groundwater for earthquake prediction was deemed to be the social responsibility of GSJ, AIST. Hence, GSJ, AIST survived the "period of nightmare"[1] of the *Type 2 Basic Research*.

2 Significant groundwater changes before and after the past Nankai earthquakes

From the Suruga Trough to Nankai Trough located off the coast of Tokai to Shikoku, the giant earthquakes of M8 class occurred repeatedly at intervals of about 100 to 200 years (Figs. 1, 2). Historically, the earthquakes that fractured both the Suruga Trough and the east side of the Nankai Trough, which is the area from the Kumanonada to Enshunada, have been also called the Tokai earthquakes. However, in this paper, the earthquake that occurs in the Suruga Trough is simply called the Tokai earthquake, the earthquake that occurs in the east side of the Nankai Trough is called the Tonankai earthquake, and the earthquake that occurs in the west side of the Nankai Trough is called Nankai earthquake (Figs. 1, 2).

The Nankai earthquakes or the giant earthquakes that occur off the coast of Shikoku and Kii Peninsula are recorded frequently in the ancient documents. It is probably because

Active Fault and Earthquake Research Center, Geological Survey of Japan, AIST Tsukuba Central 7, 1-1-1 Higashi, Tsukuba 305-8567, Japan E-mail: koizumi-n@aist.go.jp

Original manuscript received March 12, 2012, Revisions received June 12, 2012, Accepted July 10, 2012

there were extensive damages due to the Nankai earthquakes in and around Kyoto, the ancient capital. They are one of the groups of giant earthquakes whose history of occurrence is best recorded. Of the past eight Nankai earthquakes, the water level or discharge at Dogo Hot Spring (near N10, Fig. 1) of Matsuyama City, Ehime Prefecture dropped significant four times due to the earthquakes, and that of Yunomine Hot Spring, Hongu-cho, Wakayama Prefecture (near N5, Fig. 1) decreased four to five times (Fig. 2). However, it is not well known whether these had occurred before the earthquake or not. In the 1946 Nankai Earthquake (M8.0), the well water, which was shallow groundwater and probably unconfined groundwater, in 11 places along the Pacific coast from Kii Peninsula to Shikoku ran dry ten days before to immediately before the earthquake,[3] and it is estimated that the water level dropped several tens of centimeters or larger (Fig. 3). “Unconfined groundwater” will be explained later. In Katsuura (Fig. 3), the discharge of the hot spring decreased six hours prior to the earthquake. There were a total of 12 places where the groundwater level or hot spring discharge decreased before the earthquake, and such places were distributed widely along the Pacific coast from the Kii Peninsula to Shikoku (Fig. 3). However, there were over 160 places surveyed by the Hydrographic Bureau, Coast Guard Japan.[3] Therefore the incidence of this preseismic groundwater decrease is very low. Such decrease of groundwater level before an earthquake is also known to have occurred along the Pacific coast of Shikoku and Kii Peninsula before the 1854 Nankai Earthquake.[4]

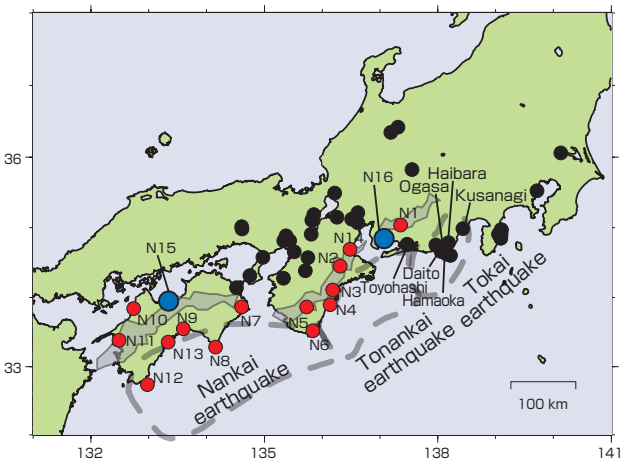


Fig. 1 Assumed focal region (dashed line) of the Tokai, Tonankai, and Nankai earthquakes, and the AIST groundwater observation network for earthquake prediction research

● (black): observation stations constructed before FY 2004. ● (red): new observation stations N1-N14 constructed after FY 2006. ● (blue): observation stations N15-N16 that are currently being constructed. The grey area in the inland area from Shikoku, Kii Peninsula, to Aichi Prefecture shows the region where the short-term slow slip events and deep low-frequency tremors occur regularly. Yunomine Hot Spring is located near the N5 observation station, and Dogo Hot Spring near the N10 observation station. As to Yunomine and Dogo hot springs, see Fig. 2.

3 Correlation between groundwater and earthquake shown by the poro-elastic theory

As mentioned above, it has been known in Japan since ancient times that the groundwater sometimes changes before earthquakes. Wakita (1978)[5] summarized the cases in a table. However, these were merely observed facts, and the theory that correlated the earthquake and groundwater was weak. Therefore the methodical research started in Japan quite late, from 1975.[6] One of the reasons for the activation of research in 1975 was the proposal of the dilatancy-diffusion model.[7][8] This model is explained as follows: the stress accumulation makes cracks increase and groundwater flows into the cracks, which reduces the strength of the region, and then earthquakes occur in the region. The dilatancy-diffusion model offered a theoretical basis for the relationship between groundwater and earthquakes. However, when the dilatancy-diffusion model lost support later,[9] the groundwater observation also lost the theoretical basis. Instead, the theoretical base was offered by the poro-elastic theory.

The elastic theory describes the relationship between the force (stress) and deformation (strain) of an elastic body, and the earthquake and crustal deformation (deformation of the ground) can be theoretically correlated by the elastic theory. The earthquake and crustal deformation can be linked by regarding the earthquake as the discrepancy of fault, which causes the deformation. The relationship between the earthquake and crustal deformation, which is observed by the GPS, strainmeter and so on, can be generally explained by the elasticity theory. Since there are only two variables, stress and strain, in the elasticity theory, there is no room for

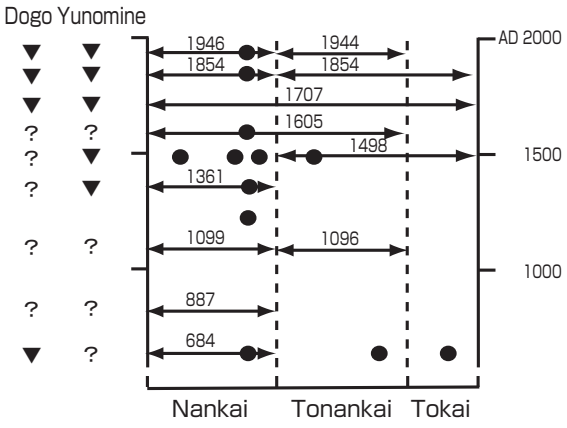


Fig. 2 History of occurrences of the Tokai, Tonankai, and Nankai earthquakes, and decrease in discharge and water level at the Dogo and Yunomine hot springs

▼ indicates decrease. ? shows that there is no record of groundwater changes in the ancient documents. ● is the mark caused by earthquake such as liquefaction. This figure is modified from Sangawa (1992).[2] Considering these results, the N5 observation station was constructed near the Yunomine hot spring, and the N10 observation station near the Dogo hot spring.

the involvement of groundwater.

On the other hand, the poro-elastic theory considers an elastic body with pores, and shows the mutual relationship among stress, strain, water pressure in pores, and amount of water in pores (hereinafter, will be called water content) under the condition that the pores are filled with water.[10]-[12] Considering water in pores = groundwater, and water pressure in pores = pore pressure = groundwater pressure = groundwater level, then the groundwater and crustal deformation can be correlated using this theory. From the standpoint of the poro-elastic theory, groundwater and crustal deformation are closely related, and it is necessary to observe the groundwater to understand crustal deformation accurately. Therefore, by applying this theory, the groundwater and earthquakes can be theoretically linked through the crustal deformation. Actually, it is difficult to grasp the water content and pore pressure in the focal region, which is located deep in the earth. In our current analysis, the elastic theory is applied to the crustal deformation due to the discrepancy of the fault in the focal region, and the poro-elastic theory is applied to the relationship between the crustal deformation and groundwater change.

To represent the relationship between the crustal deformation and groundwater change, the following proportional relationship equation is used for the change in crustal volume change (volumetric strain change ε) and the change in groundwater pressure (p), where it is assumed that crustal deformation in the event of an earthquake is sufficiently faster than the movement of groundwater, and therefore there is no change in water content:

$$p = k\varepsilon \quad (1)$$

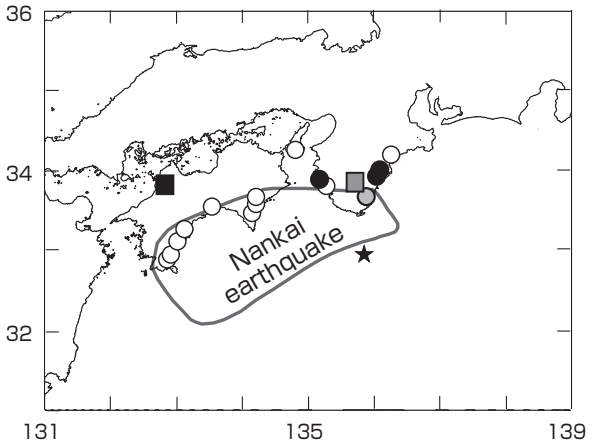


Fig. 3 Decrease in groundwater level and other groundwater changes before the 1946 Nankai Earthquake

○: 11 points where the water level of shallow wells decreased. ●: Three points where the water of shallow wells became clouded. ◎ (grey): Katsuura point where the hot spring discharge decreased. ★: Epicenter of the 1946 Nankai Earthquake. Area surrounded by solid line: Assumed focal region of the Nankai earthquake. ■: Dogo hot spring. ■ (grey): Yunomine hot spring.

The volumetric strain change is calculated from the observed groundwater pressure change, and the reverse can be done. Here, k is the so-called sensitivity of the groundwater pressure against the volumetric strain change (hereinafter, will be called the volumetric strain sensitivity).

The sensitivity k, which is needed to convert the groundwater pressure change to the volumetric strain change, is generally estimated by the change in p due to the tidal volumetric strain change (scale of about 10^{-7} in Japan), which is caused by the surface deformation from the gravity of the moon and the sun (the earth tide). The groundwater is generally divided into unconfined groundwater and confined (artesian) groundwater. The unconfined groundwater, which is located in the aquifer on the impermeable stratum or bedrock, has a free surface where the atmospheric and water pressures are balanced. The confined groundwater is located in the aquifer between the impermeable strata or bedrocks and has no free surface. In unconfined groundwater, which is shallow groundwater in general, k is quite small, and the tidal change in water level is not detected for the volumetric strain change of about 10^{-7}. On the other hand, the change is detectable in the confined groundwater, which is generally deep groundwater and hot spring. k, which varies from place to place, is around 0.1~10 (cm/10^{-7}).[13][14] Figure 4 shows the observation results for March 1~15, 2012 at N14 observation

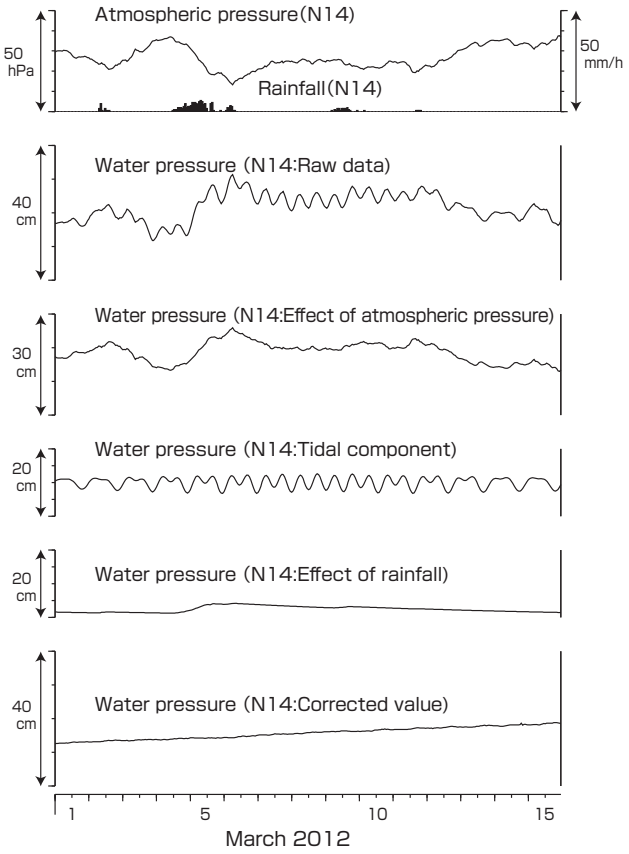


Fig. 4 Example of observation of water pressure change at N14 station (Fig. 1)

The water pressure is converted to the unit of water level.

station (Fig. 1) located in Tsu City, Mie Prefecture. At this observation station, the groundwater level appears above the ground surface, so the water pressure is measured by sealing the well. In the raw water pressure data, semidiurnal and diurnal periodical changes can be seen in addition to the changes due to atmospheric pressure and rainfall and these periodical changes are caused by the tidal changes in volumetric strain. Using the program to remove the effects of the tide, atmospheric pressure and rainfall on groundwater level (water pressure) statistically[15] and separating each component, about 6 cm tidal component is observed at peak to peak amplitudes. It can be seen that there was almost no change during this period when the effects of atmospheric pressure, rainfall and the tide were removed.

4 Forecasting the Tokai, Tonankai, and Nankai earthquakes and groundwater observation by AIST

As shown in Fig. 2, the M8 class giant earthquakes that occurred most recently in the Suruga to Nankai Trough are the 1944 Tonankai Earthquake (M7.9) and the 1946 Nankai Earthquake (M8.0). In these two earthquakes, the focal region did not reach the Suruga Trough. Therefore, a giant earthquake (Tokai earthquake) is thought to occur soon in the Suruga Trough. The government initiated the earthquake prediction project after establishing the Large-Scale Earthquake Act in 1978.

GSJ, AIST carried over the project of the Geological Survey of Japan of the Agency of Industrial Science and Technology, constructed the groundwater observation stations in the Tokai region and has been providing the observation data to the Japan Meteorological Agency (JMA). It has also been one of the expositors of the Earthquake Assessment Committee for Areas under Intensified Measures against Earthquake Disaster. Through these activities, GSJ, AIST has been a member of the governmental earthquake prediction project[16] [17] By the long-term observation of the groundwater in the Tokai region, we understood the characteristics of the groundwater changes for each observation station under normal conditions, developed the program statistically to remove the effects of atmospheric pressure and rainfall on groundwater as shown in Fig. 4,[15] and improved the S/N of groundwater observation. In addition, by applying the poro-elastic theory, we estimated the volumetric strain change through groundwater observation. As a result, we are able to evaluate the S/N of groundwater observation quantitatively in comparison with that of volumetric strain observation. In the observed groundwater level (pressure) and discharge, changes such as the long-term increase and decrease generally remain as shown in the corrected value of Fig. 4, even if the effects of atmospheric pressure, rainfall, and the tide are removed. A few mm to a few cm water level changes may also remain even in a short-term period of 24 hour or less. Such changes may be considered “noise.” When there is a change that surpasses such a noise level, it can be detected as an abnormal groundwater change. Such noise also exists in the case where the volumetric strain is directly observed. The noise level of the groundwater observation and that of volumetric strain observation cannot be compared directly. However, by using the aforementioned *k*, the groundwater data can be converted and compared to the volumetric strain data. Figure 5 compares the noise level of AIST groundwater observation to that of JMA volumetric strain observation (as of 1999). Since the estimation of noise from changes over a long term is difficult for both groundwater level and strain, the noise levels within the differences of short time spans such as 1 hour, 3 hours, and 24 hours are estimated. JMA did not remove the rainfall’s effect on the strainmeter in 1999 and calculated the noise levels for the rainy period and the normal period (without rainfall), respectively. In contrast, AIST removed rainfall’s effect on the groundwater level and therefore there is no distinction like JMA. The noise level of AIST groundwater observation is about the same to several times larger than that of JMA’s volumetric strain observation. Considering the fact that the price of the groundwater observation devices such as the water level meter is about one-tenth to one-hundredth of the price of the volumetric strainmeter, the cost performance of groundwater observation is significantly high. As it will be explained later, groundwater level is observed even in countries and regions where the expensive crustal deformation observation devices are not affordable. Therefore this groundwater observation

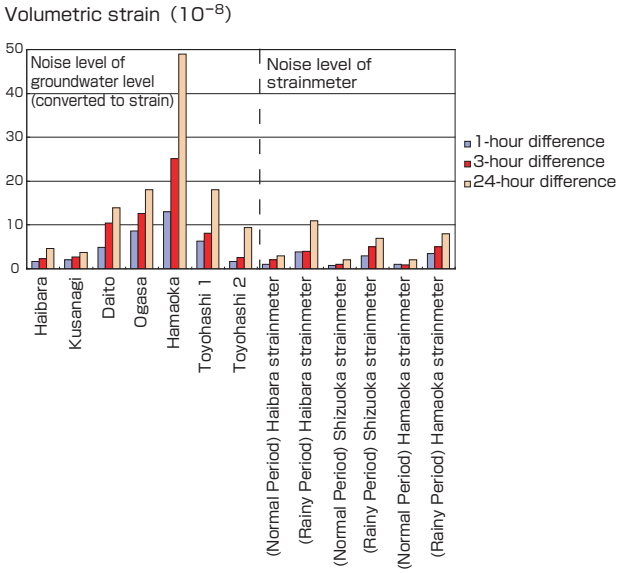


Fig. 5 Comparison of the noise levels at major AIST groundwater observation stations in the Tokai region (seven sets of graphs on left; refer to Fig. 1 for the location of observation stations) to that of JMA volumetric strainmeter[18] (six sets on right) {this figure is modified from Matsumoto and Kitagawa (2005)[19]}. There are two observation wells at Toyohashi, called Toyohashi 1 and Toyohashi 2.

and analysis can be more universally used for earthquake prediction.

As we entered the 21st century, the imminent threat of the next Tonankai and Nankai earthquakes increased,[20] and the Act on Special Measures concerning Advancement of Countermeasures against Disasters of Tonankai and Nankai Earthquakes was enforced in 2003. This law states that the countermeasures must be taken for earthquake disaster prevention in the regions such as the Shikoku and Kii Peninsula, which may be affected by the Tonankai and Nankai earthquakes. The law also encourages public institutes to prepare observation facilities and to do research of earthquakes. In such a situation, to forecast the Tonankai and Nankai earthquakes, AIST started to construct new groundwater observation facilities in and around the Shikoku and Kii Peninsula from FY 2006 and constructed 14 stations by the end of FY 2011, with two more new stations currently under construction (Fig. 1). These will be discussed in subchapter 4.3.

4.1 Detection of the pre-slip of Tokai earthquake by groundwater observation

At present, the most promising preseismic phenomenon of the Tokai earthquake is the slow slip (pre-slip) that occurs in and around the future seismogenetic area right before the earthquake. Figure 6 shows the upthrust/subsidence and expansion/contraction of the ground and the accompanying groundwater level changes when a reverse fault type slip occurs at the plate boundary. If such a slip occurs immediately before the earthquake and the accompanying crustal deformation can be detected beforehand, it may be possible to predict the earthquake.

In 2003, JMA announced the Tokai earthquake prediction scenario by detecting the crustal deformation due to the pre-slip.[21] Since we were able to evaluate the groundwater level change as volumetric strain change, we soon created a quantitative earthquake prediction method using the groundwater observation.[17] By using this method, it was possible to evaluate the groundwater level change quantitatively, in a similar way as using the crustal deformation observation devices such as the strainmeter, tiltmeter, and GPS. Figure 7 shows a simulation of the groundwater level changes at groundwater observation stations of AIST and the volumetric strain changes at observation stations of JMA when an assumed pre-slip of magnitude 6.5 occurs beneath AIST Haibara observation station. As described above, the noise level of AIST groundwater observation is the same to several times larger than that of JMA's volumetric strain observation. Therefore AIST groundwater observation detects the pre-slip at the same time or later than JMA's volumetric strain observation. If such changes actually occur, since the groundwater observation, which is independent from strain observation, can be also explained by the pre-slip, the detection of the pre-slip is considered to be more reliable. Of course, since the water level changes differ according to the place and magnitude of the pre-slip, we made it possible to compare the observed values to calculated ones in every case by conducting similar calculations by changing the magnitudes and places of pre-slips in and around the assumed focal region of the Tokai earthquake.[17] The set of these procedures from observation to analysis is called “the system for detecting preseismic changes in groundwater levels.” This system is considered to increase the accuracy of the detection of precursory phenomena by observing groundwater, and to contribute to improvement in reliability of the overall method for Tokai earthquake prediction.

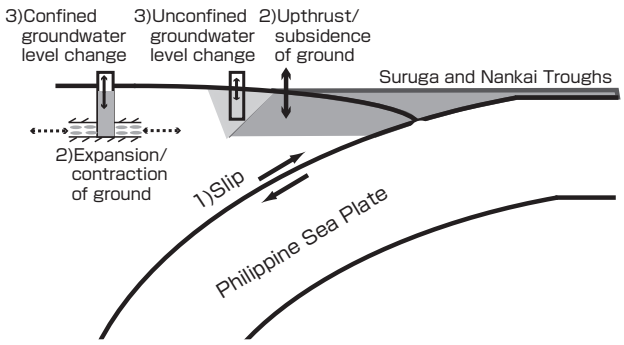


Fig. 6 Schematic figure showing the upthrust/ subsidence and expansion/contraction of the ground when reverse fault slip occurs at the plate boundary and the occurrence of groundwater level change accompanying such deformations

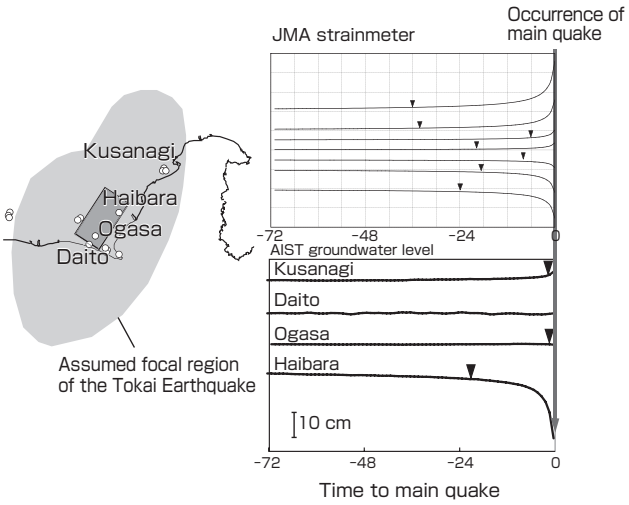


Fig. 7 Simulation of groundwater level change accompanying pre-slip[17][22]

The small open circles on the left show the positions of AIST groundwater observation stations. The grey pear-shaped zone is the projection of the assumed focal region of the Tokai earthquake onto the land area. The graph on the right is the calculation of the changes that may occur in the JMA strain data and AIST groundwater level data when a M6.5 class pre-slip occurs over 72 hours in the fault shown in the grey rectangle within the assumed focal region on the left. When the data exceed the noise level, ▼ is placed to indicate “significant change.”

The groundwater observation data in the Tokai region is sent real time to JMA via AIST, and is under 24-hour monitoring at JMA to predict the Tokai earthquake. This means that the stable groundwater observation in the Tokai region by AIST serves its role as a social outcome.

4.2 Interpretation of the past groundwater change before the Nankai earthquake based on the pre-slip model

We considered the groundwater decrease before the Nankai earthquake described in chapter 2 based on the aforementioned pre-slip model. When there is a reverse fault slow slip (pre-slip) before the Nankai earthquake at the plate boundary in the Nankai Trough, the ground is upheaved and the volumetric strain increases in wide areas from Shikoku to Kii Peninsula before the earthquake. The confined groundwater level may decrease as described above when the volumetric strain increases. Although the unconfined groundwater is insensitive to the volumetric strain, since the unconfined groundwater near the coast is in pressure equilibrium with seawater, the groundwater level will decrease in correspondence to the relatively decreased seawater level (looking from the land surface) when the ground is upheaved (Fig. 6). Therefore, the decrease of groundwater level and hot spring discharge before the past Nankai earthquake can be explained, though qualitatively, by the pre-slip model.

For the preseismic decreases of unconfined groundwater in the 1946 Nankai Earthquake, the decrease of water level over several tens of centimeters cannot be explained because the calculated upthrust is several centimeters at most according to the pre-slip model which was suggested by the Disaster Prevention Research Institute, Kyoto University in 2003.[23] In the model, the slip of about 10 % of the main quake was assumed in a part of the fault of the 1946 Nankai Earthquake. On the other hand, since the volumetric strain increase according to the model is large, the decrease of over several tens of centimeters is possible for the confined groundwater level.[16] However, the fact is that well water, which was shallow unconfined groundwater, decreased in 11 places. The discharge of the hot spring, which was possibly confined, decreased only in one place or Katsuura. Therefore, to explain the groundwater changes before the 1946 Nankai Earthquake using the model in Fig. 6, a special mechanism where the unconfined groundwater changes significantly is necessary in addition to the minute crustal deformation due to the pre-slip. One possible mechanism is as follows: firstly the confined groundwater pressure drops, and the water travels from unconfined to confined aquifer, and therefore the unconfined groundwater level also decreases. As mentioned above, the number of incidences of groundwater level decrease before the 1946 Nankai Earthquake was very low. It might be because the places where such special mechanism existed were limited.

4.3 Design and preparation of the new observation system

To apply the "system for detecting preseismic changes in groundwater levels" designed for the Tokai earthquake to the Tonankai and Nankai earthquakes, and to clarify the mechanism of groundwater level decrease that occurred in the past Nankai earthquakes, AIST made 16 integrated groundwater observation stations, including those that are under construction, from FY 2006 to FY 2012 in and around the Shikoku and Kii Peninsula (Fig. 1). We link these new stations to the observation network in the Tokai region and analyze all the data together.[22] The new observation stations were selected by considering the places where the groundwater changed before/after the past Nankai earthquakes (Fig. 3), the places close to the assumed focal region of the Tonankai and Nankai earthquakes (Fig. 1), and the places where short-term slow slip events and deep low-frequency tremors, which will be explained later, occurred (Fig. 1). Since the Tokai earthquake occurred together with the Tonankai and Nankai earthquakes historically (Fig. 2), these observations and analyses are expected to help predict the Tokai earthquake.

At the AIST new observation stations in and around Shikoku and Kii Peninsula (N1-N14 in Fig. 1), the observations of strain, tilt, and earthquake are conducted in addition to groundwater observation. In the case where there is no nearby GPS observation station of the Geospatial Information Authority of Japan (GSI), GPS is also equipped. In the past Nankai earthquake, not only the deep groundwater or hot spring, which is thought to be confined, but shallow unconfined groundwater also changed preseismically (Fig. 3). As mentioned above, since the groundwater may move vertically, three wells with different depths were drilled to observe the water level (pressure) and temperature (Fig. 8). Similar observations are scheduled for the N15 and N16 observation stations that are currently being constructed. The observation data are sent to AIST and then relayed to JMA in real time.

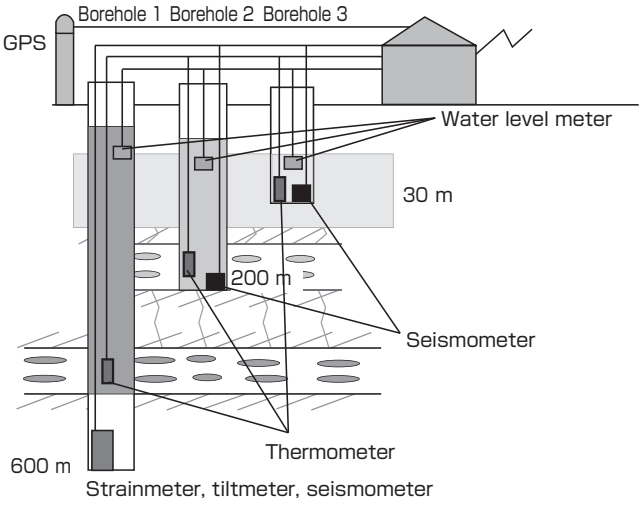


Fig. 8 Typical observation system at N1-N16 observation stations (Fig. 1)

In the deeper extension of the assumed focal region of the Tokai,Tonankai and Nankai earthquakes, the short-term slow slip event very similar to the expected pre-slip is known to occur several times a year with the deep low-frequency tremors,[24][25] which are earthquakes that occur at depth of 30−40 km near the plate boundary. The tremors emit weak lower-frequency waves than ordinary earthquakes do and have unclear beginning and end. Accurate understanding of the spatiotemporal distribution of the slow slip events is important to improve the forecast accuracy of the Tokai, Tonankai, and Nankai earthquakes.[26] If the short-term slow slip expands to the assumed focal region, it is possible to induce the main earthquake. Moreover, when the stress concentrates in the focal region and the occurrence of the main quake approaches, it is estimated by simulation that change in the stress conditions in the deep extension of the focal region will cause change in the occurrence pattern of the short-term slow slip events.[27] AIST monitors the short-term slow slip events and the tremors in cooperation with the National Research Institute for Earth Science and Disaster Prevention (NIED) and JMA. AIST has already found the spatiotemporal distribution of the short-term slow slip events[28][29] in the Kii Peninsula that was not well known before, and AIST's high-sensitive monitoring of the tremors found some interesting results.[30] AIST also investigates how groundwater changes due to the short-term slow slip events. Actually, some changes in confined groundwater pressure were already detected in association with the short-term slow slip event in some observation stations[31] although they were within the range expected from the volumetric strain changes due to the slow slip events. Any changes in the unconfined groundwater level due to the short-term slow slip event have not been detected. Therefore we have not been able to clarify the mechanism of the preseismic groundwater level decrease in the past Nankai earthquakes. The graphs of these observation data are publicized at http:/www.gsj.jp/wellweb/ and they are updated daily.

5 On the attempt overseas to apply the earthquake prediction research based on observation of groundwater

The devices for observation of crustal deformation are generally expensive, and there are many countries and regions where the crustal deformation observation is insufficient although their seismic risks are high. The Southeast Asian countries are such examples. However, groundwater is usually observed in such countries for reasons other than earthquake prediction. By selecting the observation wells under conditions that they are not affected by rainfall, not affected by artificial pumping around them, and have high volumetric strain sensitivity, a groundwater level observation network can be created for observation of crustal deformation. It means that we can create a "simple" crustal deformation (volumetric strain) observation network in a short period. This will enable the application of the "system for detecting preseismic changes in groundwater levels" to such regions. By reviewing the past groundwater level changes related to earthquakes using the volumetric strain sensitivity, it becomes possible to estimate the volumetric strain changes before and after the past earthquakes. From the above, it is thought that this method can contribute to the earthquake disaster mitigation at low cost. Based on such an idea, we started a joint research of "Hydrological and geochemical research for earthquake prediction in Taiwan" with the National Cheng Kung University, Taiwan in 2002.[32] The earthquake and active fault researches including the research for earthquake prediction have been active in Taiwan since 2001. It is because Taiwan suffered massive damage by the Chi-Chi Earthquake (moment magnitude 7.6) that occurred in western Taiwan in 1999.

In the joint research that has been continued for about 10 years, we obtained good results on the mechanism of groundwater change accompanying the 1999 Chi-Chi Earthquake,[33][34] constructed the groundwater observation network consisting of 16 stations to study the earthquake-related groundwater changes and analyzed groundwater changes during and after the earthquakes using the data from this network.[35] On the other hand, the evaluation of S/N is a major issue, since many of the wells of the network are still affected by artificial pumping. By conducting the technological transfer of the "system for detecting preseismic changes in groundwater levels" in Taiwan, the human resources can be trained, and these will contribute to the prevention of earthquake disasters in Taiwan. Besides, the seismicity is more active in Taiwan than in Japan, and annual crustal deformation in some places in Taiwan is more than 10 times larger than in Japan. Therefore, the observation data for groundwater changes related to earthquakes and crustal deformation can be accumulated at a shorter time than in Japan. Therefore if the observations and researches of groundwater changes in relation to earthquakes and crustal deformation are continued, research results can be obtained efficiently. This joint research, which may yield benefit for both Japan and Taiwan, should be continued. In the future, we would like to contribute to the earthquake disaster mitigation in many of Southeast Asian countries.

6 Thinking about the earthquake prediction research after the 2011 Off the Pacific Coast of Tohoku Earthquake

In the research in which the place, magnitude, and time of an earthquake are estimated beforehand to mitigate earthquake disaster, our forerunners used the strong word "prediction" rather than "forecast" (e.g. Imamura (1929)[36]). This was because they aimed at "forecasting with high accuracy" that leads directly to disaster preventing actions before the earthquake. Yet, in fact, the researchers involved in earthquake prediction have been researching "earthquake forecasting"

and have struggled to increase its accuracy.[37] As one of the results, long-term earthquake forecasting is now in operation in Japan.[38] However, the magnitude of the 2011 Off the Pacific Coast of Tohoku Earthquake became 9 that surpassed the magnitude ever assumed for this area by earthquake researchers, and about 20 thousand people were dead or missing mainly by the tsunami. It showed that our level of forecasting was still far from prediction.[39] In the region off the coast of middle Sanriku, data were scarce and evaluation could not be done, and in the region off the coast of Fukushima Prefecture, the possibility of occurrence within 30 years of a M7.4 earthquake was estimated to be 7 % . However, in the region off the coast of northern Sanriku, Miyagi Prefecture, and Ibaragi Prefecture, the possibility of occurrence within 30 years of a M7-7.5 class earthquake was estimated to be 80 % or greater.[40][41] Therefore it can be said that the place and time in the long-term earthquake forecasting was approximately correct. Particularly in the region off the coast of Miyagi Prefecture, the possibility of occurrence within 30 years of a M7.5 class earthquake was kept at 99 % in 2011 for alert although a M7.2 earthquake occurred in this region in 2005. It was because the GPS observation results[42] were considered to show that the energy had not been completely dissipated in the assumed focal regions. The figure of 99 % was the maximum figure of all the long-term forecasts by the Headquarters for Earthquake Research Promotion. Therefore, some factors could be positively evaluated from the perspective of science and disaster prevention in forecasting this earthquake, and the criticism that “the research for earthquake prediction (forecasting) is useless” is not valid. We should thoroughly conduct scientific evaluation and review of the forecasting of the 2011 Off the Pacific Coast of Tohoku Earthquake, and continue the earthquake prediction research.[43]

7 Conclusion

As a *Type 2 Basic Research*, we constructed a system for detecting preseismic changes in groundwater levels that uses a combination of long-term observation and analysis of groundwater, a poro-elastic theory, and the Tokai earthquake prediction model suggested by JMA. The outcome is our contribution to the national project for prediction of the Tokai earthquake. To apply the system to Tonankai and Nankai earthquakes, we constructed an integrated groundwater observation network in and around the Shikoku and the Kii Peninsula. This network is now being used to observe and study groundwater and crustal deformation. Since 2002, we have also been carrying out international cooperative hydrological research for earthquake prediction in Taiwan to help minimize the damage caused by earthquakes in Southeast Asia. Since seismic activities are higher and crustal deformation is larger in Taiwan than in Japan, we can learn about the relationship between earthquakes and groundwater more efficiently. This cooperative research is also expected to improve the system. We underestimated the magnitude of the 2011 Off the Pacific Coast of Tohoku Earthquake, which was one of the factors that brought the severe damage in and around the Tohoku area. However the long-term forecast of the place and time of the earthquake can be considered to be fairly accurate. Therefore, we should examine scientifically the reasons for the underestimation, and advance earthquake prediction research.

References

[1] H. Yoshikawa and K. Naito: *Dainishu Kiso Kenkyu – Jitsuyoka Ni Tsunagaru Kaihatsu Kenkyu No Atarashii Kangaekata* (Type 2 Basic Research – New Way of Thinking about Development Research that Leads to Practical Use), Nikkei BP (2003) (in Japanese).

[2] A. Sangawa: *Jishin Kokogaku* (Earthquake Archaeology), Chuokoronsha (1992) (in Japanese).

[3] Hydrographic Department, Japan Coast Guard: *Showa 21-nen Nankai Daijishin Chosa Hokoku – Chihen Oyobi Higai Hen* (Survey Report of the Great Nankai Earthquake in 1946 – Disaster and Damage), *The Hydrographic Bulletin Extra Ed*., 201 (1948) (in Japanese).

[4] K. Shigetomi, Y. Umeda, K. Onoue, T. Asada, Y. Hoso, K. Kondo and K. Tatsumi: Well water decrease and ocean tide abnormality before Nankai Earthquake found out by the literature and hearing investigation, *Bulletin of Disaster Prevention Research Institute, Kyoto University*, 48-B, 191-195 (2005) (in Japanese).

[5] H. Wakita: Chikasui no suii, kagakusosei henka (Changes in water level and chemical composition of groundwater) in *Jishin Yochi No Hoho* (Earthquake Prediction Method) (T. Asada ed.), The University of Tokyo Press, 146-166 (1978) (in Japanese).

[6] N. Koizumi: Review of geochemical research for earthquake prediction, *J. Natural Disaster Science*, 16, 41-60 (1997) (in Japanese).

[7] A. Nur: Dilatancy, pore fluids, and premonitory variation of *tp/ts* travel times, *Bull. Seismo. Soc. Am*., 62, 1217-1222 (1972).

[8] C. H. Scholz, L. R. Sykes and Y. P. Aggarwal: Earthquake prediction: a physical basis, *Science*, 181, 803-810 (1973).

[9] K. Mogi: *Nihon No Jishin Yochi* (Earthquake Prediction in Japan), Saiensu-sha (1982) (in Japanese).

[10] M. A. Biot: General theory of three-dimensional consolidation, *J. Appl. Phys*., 12, 155-164 (1941).

[11] E. A. Roeloffs: Poroelastic techniques in the study of earthquake-related hydrologic phenomena, *Adv. Geophys*., 37, 135-195 (1996).

[12] H. F. Wang: *Theory of Linear Poroelasticity with Applications to Geomechanics and Hydrogeology*, Princeton Univ. Press, Princeton (2000).

[13] E. A. Roeloffs: Hydrologic precursors to earthquakes: a review, *Pure Appli. Geophys*., 126, 177-209 (1988).

[14] S. Itaba, N. Koizumi, T. Toyoshima, M. Kaneko, K. Sekiya, and K. Ozawa: Groundwater changes associated with the 2004 Niigata-Chuetsu and 2007 Chuetsu-oki earthquakes, *Earth Planets Space*, 60, 1161-1168 (2008).

[15] N. Matsumoto: Regression analysis for anomalous changes of groundwater level due to earthquakes, *Geophys. Res. Lett*., 19, 1193-1196 (1992).

[16] N. Koizumi, M. Takahashi, N. Matsumoto, T. Sato, R. Ohtani and Y. Kitagawa: Hydrological research for earthquake prediction - Trial for detection of preseismic crustal deformation from groundwater changes -, *Jishin 2*,

58, 247-258 (2005) (in Japanese).
[17] N. Matsumoto, Y. Kitagawa and N. Koizumi: Groundwater-level anomalies associated with a hypothetical preslip prior to the anticipated Tokai earthquake: Detectability using the groundwater observation network of the Geological Survey of Japan, AIST, *Pure Appli. Geophys.*, 164, 2377-2396 (2007).
[18] A. Kobayashi and T. Matsumori: An investigation of noise levels for the data of bore-hole type volumetric strain-meters and process for detecting abnormal changes, *Kenshin Jiho*, 62, 17-41 (1999) (in Japanese).
[19] N. Matsumoto and Y. Kitagawa: Strain sensitivities and noise levels in groundwater levels at observation wells in and around the rupture zone of the future Tokai Earthquake, *J. Geodetic Society of Japan*, 51, 131-145 (2005) (in Japanese).
[20] Headquarters for Earthquake Research Promotion: Nankai torafu no jishin no choki hyoka (Long-term evaluation of earthquakes in the Nankai Trough), http://www.jishin.go.jp/main/chousa/01sep_nankai/nankai.pdf (2001) (in Japanese).
[21] Japan Meteorological Agency: Tokai jishin ni kansuru atarashii joho happyo ni tsuite (On new information release for the Tokai Earthquake), http://www.jma.go.jp/jma/press/0307/28a/20030728tokai.pdf (2003) (in Japanese).
[22] N. Koizumi, M. Takahashi, N. Matsumoto, T. Sato, R. Ohtani, Y. Kitagawa, S. Itaba, Y. Umeda and N.Takeda: Integrated groundwater observation for forecasting the Tokai, Tonankai and Nankai earthquakes, *Chishitsu News*, 663, 29-34 (2009) (in Japanese).
[23] Disaster Prevention Research Institute, Kyoto University: A fault model for the precursory slip that might have induced groundwater changes, *Report of the Coordinating Committee for Earthquake Prediction*, 70, 402-403 (2003) (in Japanese).
[24] K. Obara: Nonvolcanic deep tremor associated with subduction in southwest Japan, *Science*, 296, 1679-1681 (2002).
[25] K. Obara, H. Hirose, F. Yamamizu and K. Kasahara: Episodic slow slip events accompanied with non-volcanic tremors in southwest Japan subduction zone, *Geophys. Res. Lett.*, 31, L23602, doi: 10.1029/2004GL020848 (2004)
[26] K. Obara: Suro jishin monitaringu wa kyodai jishin yosoku ni yuko ka (Is slow earthquake monitoring effective for giant earthquake prediction?), *Abstracts of the 2011 Fall Meeting of the Seismological Society of Japan*, 104 (2011) (in Japanese).
[27] T. Matsuzawa, H. Hirose, B. Shibazaki and K. Obara: Modeling short- and long-term slow slip events in the seismic cycles of large subduction earthquakes, *J. Geophys. Res.*, 115, B12301, doi: 10.1029/2010JB007566 (2010).
[28] S. Itaba, N. Koizumi, N. Matsumoto and R. Ohtani: Continuous observation of groundwater and crustal deformation for forecasting Tonankai and Nankai earthquakes in Japan, *Pure Appli. Geophys.*, 167, 1105-1114 (2010).
[29] S. Itaba and R. Ando: A slow slip event triggered by teleseismic surface waves, *Geophys. Res. Lett.*, 38, L21306, doi:10.1029/2011GL049593 (2011).
[30] K. Imanishi, N. Takeda, Y. Kuwahara and N. Koizumi: Enhanced detection capability of non-volcanic tremor using a 3-level vertical seismic array network, VA-net, in southwest Japan, *Geophys. Res. Lett.*, 38, L20305, doi:10.1029/2011GL049071 (2011).
[31] Y. Kitagawa, N. Matsumoto and N. Koizumi: Tsuano kansokuten no chikasuiatsu henka ni yoru Mie-ken hokubu oyobi chubu deno tankiteki SSE no kenshutsu (Detection of short-term SSE in northern and middle Mie Prefecture by groundwater pressure change at Tsuanou observation station), *Abstracts of the 2011 Fall Meeting of the Seismological Society of Japan*, 148 (2011) (in Japanese).
[32] N. Koizumi, N. Matsumoto and WC. Lai: Cooperative research entitled “Hydrological and geochemical research for earthquake prediction in Taiwan “ between National Cheng-Kung University, Taiwan and National Institute of Advanced Industrial Science and Technology, Japan. *Bull. Geol. Surv. Japan*, 62, 185-190 (2011) (in Japanese).
[33] WC. Lai, N. Koizumi, N. Matsumoto, Y. Kitagawa, CW. Lin, CL. Shieh and YP. Lee: Effects of seismic ground motion and geological setting on the coseismic groundwater level changes caused by the 1999 Chi-Chi Earthquake, Taiwan, *Earth Planets Space*, 56, 873-880 (2004).
[34] N. Koizumi, WC. Lai, Y. Kitagawa and N. Matsumoto: Comments on “Coseismic hydrological changes associated with dislocation of the September 21, 1999 Chichi earthquake, Taiwan” by Min Lee *et al*., *Geophys. Res. Lett.*, 31, L13603, doi: 10.1029/2004GL019897 (2004).
[35] WC. Lai, KC. Hsu, CL. Shieh, YP. Lee, KC. Chung, N. Koizumi and N. Matsumoto: Evaluation of the effects of ground shaking and static volumetric strain change on earthquake-related groundwater level changes in Taiwan, *Earth Planets Space*, 62, 391-400 (2010).
[36] A. Imamura: Kanto narabini Kinki chiho ni okeru jishin katsudo no junkan to daishinmae no shogensho tonitsuite (On the cycle of earthquake activities in the Kanto and Kinki regions and the various phenomena before large earthquakes), *Jishin 1*, 1, 4-16 (1929) (in Japanese).
[37] Committee for Examining Earthquake Prediction, Seismological Society of Japan: *Jishin Yochi No Kagaku* (Science of Earthquake Prediction), The University of Tokyo Press (2007) (in Japanese).
[38] Headquarters for Earthquake Research Promotion: Jishin ni kansuru hyoka (Evaluation of earthquake), http://www.jishin.go.jp/main/p_hyoka.htm (2011) (in Japanese).
[39] T. Matsuzawa: Naze Tohoku Nihon shizumitai de M9 no jishin ga hassei shietanoka? Wareware wa doko de machigaetanoka? (Why could the M9 earthquake occur in the northeastern Japan subduction zone? Why did we believe it would not occur there?), *Kagaku*, 81, 1020-1026 (2011) (in Japanese).
[40] Headquarters for Earthquake Research Promotion: Miyagiken-oki jishin no choki hyoka (Long-term evaluation of earthquake off the coast of Miyagi Prefecture), http://www.jishin.go.jp/main/chousa/00nov4/miyagi.htm (2000) (in Japanese)
[41] Headquarters for Earthquake Research Promotion: Sanriku-oki kara bouso-oki ni kakete no jishin katsudo no chokihyoka no ichibu kaitei ni tsuite (On the partial revision of the long-term evaluation of the earthquake activities off the coasts of Sanriku to Boso), http://www.jishin.go.jp/main/chousa/09mar_sanriku/index.htm (2009) (in Japanese).
[42] Headquarters for Earthquake Research Promotion: Ima made ni kohyo shita katsudanso oyobi kaikogata jishin no choki hyoka kekka ichiran (List of the past long-term evaluations of active faults andsubduction-zone earthquakes), http://www.jishin.go.jp/main/choukihyoka/ichiran_past/ichiran20110111.pdf (2011) (in Japanese).
[43] N. Koizumi: 2011 nen Tohoku Chiho Taiheiyo-oki Jishingo ni okeru jishin no yochi yosoku kenkyu heno hihan ni tsuite (On the criticisms against research for earthquake prediction and forecasting after the 2011 Off the Pacific

Coast of Tohoku Earthquake), *Jishingaku No Ima O Tou – Tohoku Chiho Taiheiyooki Jishin Taio Rinji Iinkai Hokoku* (Questioning Current Seismology – Report of the Extraordinary Committee for Off the Pacific Coast of Tohoku Earthquake), *Monograph of the Seismological Society of Japan*, 58-61 (2012) (in Japanese).

Postscript

After this paper was written and accepted, the Seismological Society of Japan (SSJ), of which the author is a member, released the action plan for the various issues that were raised by the 2011 Off the Pacific Coast of Tohoku Earthquake (http://www.zisin.jp/pdf/SSJplan2012.pdf). In this document, the use of the terms "earthquake prediction" and "earthquake forecasting" are strictly defined. Conventionally, the term "earthquake prediction" had been also used widely for "forecasting beforehand the specific place, magnitude, and time of the earthquake that may occur." However this was sometimes confused with the earthquake prediction in the narrow sense that leads to warning and it generated the excessive expectation of society for preseismic "warning." As a reaction, the earthquake researchers were criticized heavily after the 2011 Off the Pacific Coast of Tohoku Earthquake. Therefore, the SSJ decided to distinguish the terminologies by defining earthquake forecasting as "forecasting beforehand the specific place, magnitude, and time of the earthquake that may occur," and earthquake prediction as the accurate earthquake forecasting that actually leads to warning. The SSJ also re-emphasized that earthquake prediction is extremely difficult at present. However, as mentioned in chapter 6, if the accuracy of earthquake forecasting is raised, it will become earthquake prediction in the narrow sense, and therefore it seems difficult to differentiate the earthquake prediction and forecasting clearly at the research level. Since the "strict definition of earthquake prediction and earthquake forecasting" has been discussed in the SSJ, I consciously tried to distinguish the usage of the terms in this paper: those that lead immediately to warning (earthquake prediction) and those that do not (earthquake forecasting). However, there is no clear-cut distinction.

In the earthquake at L'Aquila, Italy (occurred April 6, 2009; M6.3; over 300 people dead), seven people including six scientists were charged for issuing the "statement of safety" prior to the earthquake. This was an incident that illustrated the difficulty of earthquake prediction. However there are research topics that must be tackled even if they seem insurmountable. The author thinks that earthquake prediction is one of those topics in earthquake-prone Japan.

Author

Naoji KOIZUMI

Completed the courses but withdrew from the doctorate program at the Department of Geophysics, Graduate School of Science, Kyoto University in 1988. Assistant professor at the Disaster Prevention Research Institute, Kyoto University in 1989. Obtained doctorate (Doctor of Science, Kyoto University) in 1989. Transferred to the Geological Survey of Japan, Agency of Industrial Science and Technology, Ministry of International Trade and Industry in 1996. Leader of Tectono-Hydrology Research Group, GSJ, AIST in 2001; leader of Tectono-Hydrology Research Team, Active Fault and Earthquake Research Center, AIST in 2009; and principal research scientist of the Active Fault and Earthquake Research Center, AIST in 2011. Has been engaging in earthquake prediction research using groundwater observation since being a student. Believes the most important factor in disaster mitigation is to publicize the research results.

Discussions with Reviewers

1 Overall comment

Comment (Eikichi Tsukuda, AIST and Hideto Taya, AIST)

This is an excellent research paper that describes the development of the relationship between earthquake occurrence and groundwater level accompanying crustal deformation with theoretical foundation (poro-elastic theory) in the background, and long-term groundwater level observation and analysis at the core. It addresses the processes of the construction of groundwater observation system and the prediction of the Tokai, Tonankai, and Nankai earthquakes through the organization of such an observation network. As the imminent threat increases for the Tokai, Tonankai, and Nankai earthquakes and with the experience of the Great East Japan Earthquake or the 2011 off the Pacific coast of Tohoku Earthquake, the social interest in this field is increasing. Since human damage can be effectively mitigated if the earthquake prediction information is released, the progress of this research draws high expectations. On the other hand, long-term observation must be continued before any results can be obtained, and it is apparent that this responsibility must be borne by the public research institute. I think this is a difficult challenge as a *Full Research*.

2 Volumetric strain caused by tides

Question (Hideto Taya)

I have a question about the "volumetric strain" caused by tides. You mention that "the scale is about 10^{-7}" in Japan, but is this determined by latitude of the earth?

Answer (Naoji Koizumi)

The maximum amplitude of ground deformation by the earth tides is determined approximately by latitude.

3 Earthquake prediction by groundwater level observation

Question (Hideto Taya)

Earthquakes occur throughout Japan, but I think their mechanisms differ for each occurrence. With this understanding, which earthquakes are predictable by groundwater level

observation?

Answer (Naoji Koizumi)

At the moment, the predicable earthquakes are the subduction-zone types where the pre-slip scenario can be applied. In the future, if a quantitative, preseismic crustal deformation scenario is presented for the other types based on a reliable model, earthquake prediction by the groundwater level observation can be used for them as well.

4 Assumption of the new mega-earthquake and the observation system for it

Question (Eikichi Tsukuda)

The government has already forecasted damage due to the assumed earthquake of magnitude 9. Can you comment in relation to your observation system? This is much greater than the previously assumed magnitude. Is there any effect on the current observation based on the new assumed model?

Answer (Naoji Koizumi)

For the M9 class mega-earthquake that is newly assumed to occur in the Nankai Trough, the focal region expanded west (to Hyuganada), and new observation stations may be needed in Kyushu. The focal region expanded far off the coast cannot be monitored by land observation. Therefore cooperation with the ocean floor observations by the Japan Agency for Marine-Earth Science and Technology, JMA and others will be necessary. Also, since the assumed model changed greatly, it will be difficult to interpret the observation data and to forecast the earthquake based on those data.

5 Observation and international joint research for prediction research of infrequent giant earthquakes

Question (Eikichi Tsukuda)

The interval of earthquake occurrence in a certain region is at least 100 years, and this is significant longer than the lifespan of the researcher. I think this inhibits the dramatic scientific advancement in seismology through hypothesis and proof. International joint research may be one method to overcome this. I think there can be efforts to gather overseas case studies other than those of Taiwan. What do you think? Can you also comment on the recent overseas case studies on the earthquake occurrence process (preparatory process)?

Answer (Naoji Koizumi)

For the observation and research of the earthquake-related groundwater changes, we have also been working with the U.S. Geological Survey. It is true that more international cooperation will be necessary in the future and I would like to continue the effort.

The overseas cases where the pre-slips were possibly detected in the postseismic analysis are: the 1960 Great Chilean (Valdivia) Earthquake (M9.5), the 1997 Kamchatka Earthquake (M7.8), and the largest aftershock (M7.6) of the 2001 Peru Earthquake (M8.4). Japanese cases are: the 1944 Tonankai Earthquake (M7.9), the 1946 Nankai Earthquake (M8.0), the 1964 Niigata Earthquake (M7.5), and the 1983 Sea of Japan Earthquake (M7.7). For the 2011 Off the Pacific Coast of Tohoku Earthquake, the possibility that pre-slips might have occurred was indicated from the observation of the ocean floor tsunami meter and the movement of seismic activities immediately before the earthquake. However, there was probably no acceleration of the slip that is expected in the pre-slip of Tokai earthquake. From these results I think the conventional model will be revised or new models may be proposed for the earthquake occurrence process. There is a close relationship between the improvement and creation of models and accurate observation data. We would like to keep accurate observation and analysis to provide appropriate restraint conditions for the models. We would also like to continue gathering the research results on the earthquake occurrence process in Japan and overseas.

6 JMA's volumetric strainmeter and groundwater observation

Comment (Eikichi Tsukuda)

It can be read that groundwater observation is not necessary if we have the JMA's strainmeter. I think you should carefully explain the characteristic of the groundwater data and its complementarity to the other data.

Answer (Naoji Koizumi)

As was explained in this paper, the strain detection accuracy of the groundwater observation estimated from the noise level is about the same or slightly inferior compared to the strainmeter. However, considering that the price of the groundwater observation devices such as the water level meter is about one-tenth to one-hundredth compared to the strainmeter, I think groundwater observation is superior in terms of cost performance. Even in countries and regions where the expensive crustal deformation observation devices such as the strainmeter are not affordable, there are many places where groundwater level is observed. Therefore the groundwater observation can be used universally as a method of earthquake prediction. In addition, since the strain observation and groundwater observation are independent, if both data can be explained by a single physical model such as the pre-slip model, then that will increase the reliability of the physical model and the forecasting based on that physical model.

7 Social risk of earthquake prediction research by groundwater observation

Comment (Eikichi Tsukuda)

As stated in the paper, the groundwater is relatively easily observed and closely related to everyday life. Therefore, there have been many reports of preseismic groundwater anomalies by the general public, and there is danger that the circulation of civilian information with poor accuracy or incorrect information may arouse social unrest. In such cases, the scientific observation data over a long term are important. Therefore the social responsibility of AIST groundwater observation is heavy. I think cooperation with JMA is necessary. Can you comment on AIST's expected response?

Answer (Naoji Koizumi)

As you indicate, I think the circulation of incorrect information on earthquake prediction can be prevented by showing the properly managed, accurate groundwater observation data. Therefore, we publicize the graph of the observation data. For the research results on earthquake-related groundwater changes, we conduct active outreach activities using programs of Open Houses of AIST and dispatch lectures of AIST. We not only provide JMA the observation data and analysis results but share various information and analysis methods on earthquakes with JMA. When we receive inquiries from JMA about abnormal groundwater changes, we provide information on how to interpret them appropriately.

It is important that the disaster prevention personnel of the local government are able to correctly interpret the various data and models about earthquakes from various sources and make proper decisions to prevent social confusion. From this perspective, we offer the "training program on earthquake and tsunami for local government personnel" for the people in charge of disaster prevention in the local governments of the places where our groundwater observation stations are located.

Estimation of legible font size for elderly people

— Accessible design of characters in signs and displays and its standardization —

Ken SAGAWA * and Kenji KURAKATA

[Translation from *Synthesiology*, Vol.6, No.1, p.24-33 (2013)]

Concept, methodology, and dissemination of outcomes for accessible design research are described in this paper, using vision research as an example. Characteristics of accessible design whose standpoint is different from that of assistive technology are explained in terms of methods for problem solving, objects of design, and public usefulness, and the role of standardization is emphasized from the point of public usefulness. As an example, the process of vision research for estimating minimum legible font size for elderly people is described. To develop a general estimation method for minimum legible font size, we collected fundamental data on visual acuity which changes with age and visual distance. Then, we compiled data on legibility of letters used in actual Japanese, derived a general estimating equation of legible font size, and confirmed the practical utility of the method. We have developed this method as a domestic and international standard. In addition, we have also applied this method to international comparative testing and have confirmed the validity of the results of this research. Finally, the entire process has been clarified by separating it into two procedural cycles: one for basic research and the other for application, and the concept of "*Full Research*" has been addressed in the process.

Keywords : Accessible design, visual acuity, age-related change, minimum legible font size, standardization

1 Introduction

Care for older people and people with disabilities has widely spread in our society due to the rapid aging of society and the adoption of UN Convention of Human Rights on Persons with Disabilities.[1] The issue on older people and people with disabilities encompasses very wide fields of politics, economics as well as society. From a viewpoint of ergonomics which directly concerns with human beings, development and promotion of human-life technology are urgent as the solution to inconveniences that older people and people with disabilities have in their daily lives since such study has been progressing behind other fields.

The inconveniences of older people and people with disabilities have a large variety even in the ergonomic field only. A large variety of problems are found in the reports of surveys conducted by the Cabinet Office, Government of Japan, or the Accessible Design Foundation of Japan.[2] These are classified into (1) physical problems such as body size or movements, (2) perceptual problems such as vision and hearing, and (3) cognitive problems such as attention and memory. These various problems of older people and people with disabilities should be resolved in each of these categories.[3] We reported previously in this journal the technical problem concerning auditory signals together with the concept and design guidelines for older people and people with disabilities.[4]

In this paper, focusing on the age-related change of visual acuity and the legibility problem, our concept and methodology will be described. The problem of legibility is one of the common inconveniences found in the surveys. People pick up information from letters appearing in instructions or warnings attached to household appliances, packages, product-tags, guide pamphlets, and so on. Many difficulties exist here for older people and people with visual disabilities such as low vision. It is vitally important, therefore, to provide easy-to-read letters to those people that would lead to increasing safety and comfort in our social life.

In addition, in this paper, standardization will be picked up as a tool to disseminate the developed method for designing letters and human data. The standardization is regarded particularly important in this study, and the way of thinking and usefulness of it will also be addressed in this paper together with a technical standpoint and a specific feature of standards-related study.

2 Two approaches for solving the problems

There are so many aspects to investigate for solving the problems that older people and people with disabilities have. Two approaches may be addressed as follows from the ergonomic point of view.

One is based on the concept of assistive products or assistive technology. In this approach, the weakened or deteriorated human abilities by aging or disabilities should be compensated by providing special tools or devices that are

Human Technology Research Institute, AIST Tsukuba Central 6, 1-1-1 Higashi, Tsukuba 305-8566, Japan
* E-mail: sagawa-k@aist.go.jp

Original manuscript received March 28, 2012, Revisions received July 9, 2012, Accepted July 10, 2012

attached or worn on the human body to gain the lost abilities. No change or no modification is required for products, services, and environments for their being used directly as they are. This is the design concept actually employed in the field of "assistive devices" in which human abilities are attempted to be enhanced artificially.

The other one, on the contrary, is to change or modify products, services and environments so that they can be used by those who have weakened or deteriorated human abilities. This is the concept that things should be used without any special tools even if the loss of human abilities exists. This design concept is called "accessible design" and underlies the present study. A similar concept applies to universal design, barrier free, inclusive design etc. Slight differences may exist among exact methods in these designs but the same consideration is shared that products etc. should be designed to fit human abilities without supplying any assistive device.

The difference between the two is elaborated with an example of visibility problem which is illustrated in Fig. 1. On the left side of the figure, which is for the case of assistive devices, it is thought that visibility problem is caused by the weakened visual acuity and improving visual acuity technically is considered. This instantly leads to the development of spectacles or a magnifying lens. Developing suitable spectacles or a magnifying lens enables an older person who has low visual acuity to read small letters on a label of a pharmaceutical bottle. This is the idea to fit human ability of vision to invisible small letters. In this case, spectacles or a lens can be developed to fit one particular person and is of no use to others. This is personal fit, and the basic purpose is to solve the problem of one intended user by providing spectacles or a lens that fits him/her.

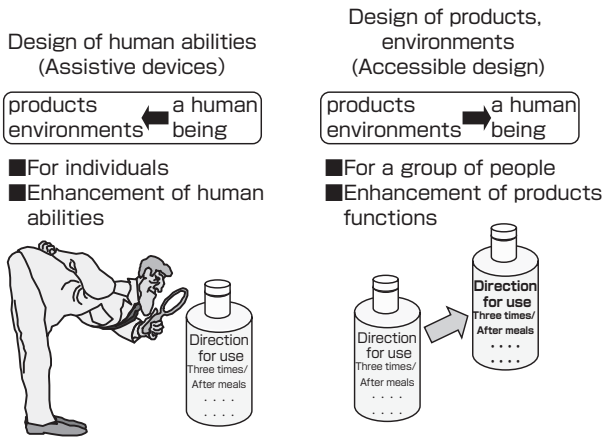


Fig. 1 Basic concept and characteristics for accessible design and assistive devices.
A solution for the legibility problem is shown as an example for each design concept. The left is the concept of assistive devices where design method for an individual like spectacles is shown. On the right, accessible design is shown where the problem is solved by product design like enlarging the letter size.

On the other hand, in accessible design, the problem is regarded as on the side of letters that are designed too small to read. Therefore, enlarging the letters to appropriate size is required. In this case, there is no prerequisite for using spectacles, and designing letters solves the problem. The idea is to fit products to weakened visual acuity. This is not the personal design as previously mentioned but the design for many other people who have similar low visual acuity. It is required to know here prior to designing that what distribution of (the low) visual acuity is found for that group of people. This process highlights the importance of feature extraction of the distribution and also of standardization.

3 Scenario of development and dissemination of the research

In this paper, a concept for the development of an accessible design method and its dissemination through standardization is described with a method for estimating minimum legible font size that takes account of age-related change of visual acuity as an example. As previously mentioned, when we seek for a solution of a problem on the bases of the concept of accessible design, the focus should not be an individual but a group of people. A number of people will see letters in printings or displays once they are designed, and how many or what type of people can see the letters depends surely on the quality of the designing. In the present study, focusing on people in older generation we tried to develop a method that provides legible letters for as wider range of older people as possible. That is, the concept of the widest range of users targeted by accessible design was put in the basics of the present study. It is anticipated that the best fit solution may not be fulfilled, but the publicness by targeting much wider users takes higher priority.

It becomes important here to create the most suitably fitted design to the user group by knowing the characteristics that specify the group, as the accessible design applies to a number of people who have a variety of characteristics individually. It is necessary to know the distribution or a specific feature of the group to obtain a maximum number of users. This idea is shared with standardization. For the standards, it is expected to get as much convenience, efficiency, and effectiveness as possible, and the extent of the commonality of the standards depends on the appropriateness of the design. The same thing is exactly true for the concept of accessible design. The aim is to solve the problems of older people and people with disabilities by design methods that are developed being based on their characteristics. The methods developed like this are intended to disseminate through standardization. To design Braille or display of lifts, for instance, it only becomes useful after a normalized location and indication method is set and the knowledge is shared among people with visual disabilities. The principles of commonality and consistency that standardization has are

of particular importance for people with disabilities. This is the most critical reason why the concept and benefit of standardization is adopted in the accessible design.

Figure 2 shows the scenario of the technical development actually taken. Design elements are classified into two parts, viewing conditions and attributes of the letter design, and the former is classified into three design factors (size factor, luminance, and age) and the latter into two such as font type and kind of font. The necessary data are to be collected along with this scheme. The data are then used for the development of an estimation method for minimum legible font size, and this proceeds finally to the goal of standards on the legible font design. This level of development can be addressed as composition and synthesis. Furthermore, it should be noted that, aiming at international standardization as a final goal, the necessary data in oversea countries are to be collected. Based on these data, an international standard on minimum legible font size is to be developed in the end.

The present study was carried out under this scenario and the development process which are based on the concepts of accessible design and standardization.

4 Estimation of minimum legible font size

4.1 Fundamental data collection

The technical point of the present study is to clarify the general relationship between the legibility of letters and visual acuity for a wider range of people including older people. In visual science, visual acuity is defined by a reciprocal of a quantity ($1/\Theta$) of the minimum gap (Θ) expressed in minutes

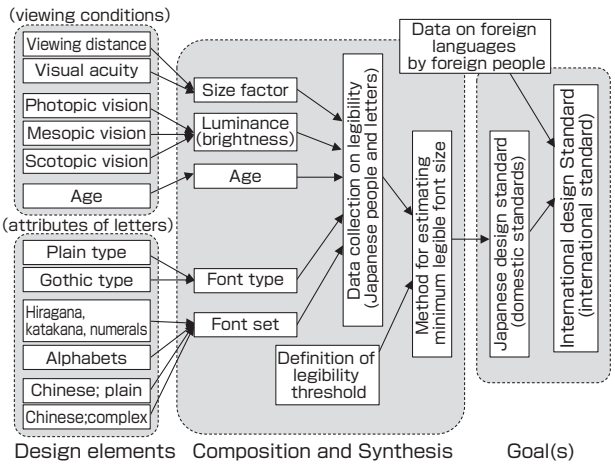


Fig. 2 Scenario of technical development of the present study

Breaking down the legibility problem into design elements and combination of factors and collecting data on legibility, a method for estimating legible font size is to be developed. The method is to be standardized as a national or an international standard. Data on foreign languages are to be collected in their countries for the international standard.

that human eye resolves spatially. Visual acuity 1.0 means to resolve the gap of 1.0 minutes of arc. Although it is well known that the extent of visual acuity affects the size of a legible letter, the quantitative relationship between the two has not been well known. In particular, the feature of age-related change in visual acuity or that of a particular aged group has not been well known. One of the purposes of the present study is to draw the relationship statistically by collecting data that serves to develop a method for estimating minimum legible font size. This relationship could be established in a general form that takes into account the major affecting factors of the viewing condition.

It is well known from the fundamental characteristics of vision that visual acuity changes with various viewing conditions.[5] Three factors such as (1) age, (2) viewing distance, (3) luminance level can be addressed as major ones, and it is required to describe the change of visual acuity as a function of these factors. As previously mentioned, visual acuity is defined by visual angle regardless of viewing distance, but as the accommodation of eye lens depends on age and viewing distance, it becomes important to investigate the effects of age in relation to viewing distance. The effect of each component has been found independently in previous studies but the interactive effects of them have not been clarified yet, and a synthesized study concerning these has been needed.[6]

It is possible to measure in detail visual acuity by means of psychophysical methods. In this study the subject, who served as a monitor of the experiment, was asked whether he/she was able to see and recognize a small cut or open space on a ring pattern or the so called Landolt Ring, which was presented on a display. If the pattern is large enough, the cut is recognized with a probability of 100 %. If it is too small, the cut is hardly recognized and the probability goes down almost to 0 % in which case some chance level of recognition exists as false response and the probability correction is done according to the method adopted by general psychophysical measurement. After deriving a curve with this procedure which is called a probability of correct response curve, a criterion was set on the probability axis (in this study 80 % of correct response) and the corresponding size of a cut on the ring was obtained as a threshold which was regarded as visual acuity of the subject in that viewing condition.

The subjects who participated were a total of 111 people ranging in age from 10s to 70s. The age distribution was as follows: 11 people in the age of 10s, 28 people in 20s, 11 people in 30s, 10 people in 40s, 10 people in 50s, 22 people in 60s, and 19 people in 70s. The subjects dominated in number for the age groups of 20s and for 60s to 70s than others. In this study, the younger and older people mean the ones in ages of 20s and over 60 respectively, but it should be noted that different definitions may exist. The older people in

this study have also a limited meaning as people who have no medical disorders in the eyes.

These subjects, from younger to older, were equipped with spectacles to correct their visual acuity so as to get the best acuity at a far point of 5 m. This is called "far point correction." This correction is of particular importance to obtain basic data at an arranged condition as there is an uncertainty in correctness of spectacles actually used by the subjects.

Five sampling points were selected for viewing distance which were 0.3, 0.5, 1.0, 2.0, and 5.0 m. Considering that visual acuity of older people becomes worse at near distance and the near point of the accommodation of the eye is at about 30 cm, the 30cm distance was set as the nearest measuring point in the present study. On the other hand, the characteristics of the optical lens are described by using dioptre (1/m). Then, accommodative characteristics of human lens at far point can be described at 5 m by regarding this point as a representative. It is reasonably considered that these 5 points from 0.3 to 5 m can be used to describe the overall feature of accommodative ability of the human eye.

As for the luminance level, a wide range from photopic[Term 1] to mesopic[Term 2] vision was covered taking account of the fact that the human eye adapts to such a wide range of luminance. Nine sampling points were actually selected from 0.05 cd/m^2 to 1000 cd/m^2 with almost even steps in logarithmic scale.

Figures 3(a) and 3(b) show the averaged results of the measurement. Figure 3(a) is for the effect of viewing distance on visual acuity and Fig. 3(b) for the effect of luminance. As shown in Fig. 3(a) viewing distance has a remarkable effect on subjects aged over 40 indicating that their visual acuity rapidly decreases as viewing distance becomes shorter. This means we should provide a font larger for older people when it is given in short viewing distance. As for the luminance effect, it can be seen for all the age groups that visual acuity decreases similarly as the luminance level decreases. Although some absolute differences exist, the manner of the relative change of visual acuity is almost the same for any of the age groups and it can be concluded that there is no age effect for the visual acuity change relative to luminance.

While the effects of factors in viewing conditions were figured out, the visual acuity data does not directly relate to the legible letter size. Therefore, the measurement on how much font size is actually needed to read the letters, which appear in Japanese sentences ("Japanese letters" hereafter), was carried out in the same viewing condition as in the visual acuity measurement. The 80 % of correct response was adopted also as the level of legibility which was the same in the case of visual acuity. This makes it possible to directly connect the data on visual acuity to the data on legibility.

Figure 4 shows the data on minimum legible font size in average for three kinds of letters such as hiragana/katakana/numerals, kanji with 5 to 10 strokes, kanji with 11 to 15 strokes. The measurement was carried out under the 8 conditions in combination of two age groups (in 20s and 60-70s), two viewing distances (0.5 and 2 m), and two luminance levels (0.5 and 100 cd/m^2).

The results of the younger 48 subjects (in average) show they were able to read a 4-point-size letter at the most preferred condition, but older people needed at least 12 points of size to read it. This corresponds to the results of visual acuity. It is a priori that longer viewing distance requires larger font size from geometrical reasons, but the need of a larger font at the low luminance level is a requirement from visual characteristics.

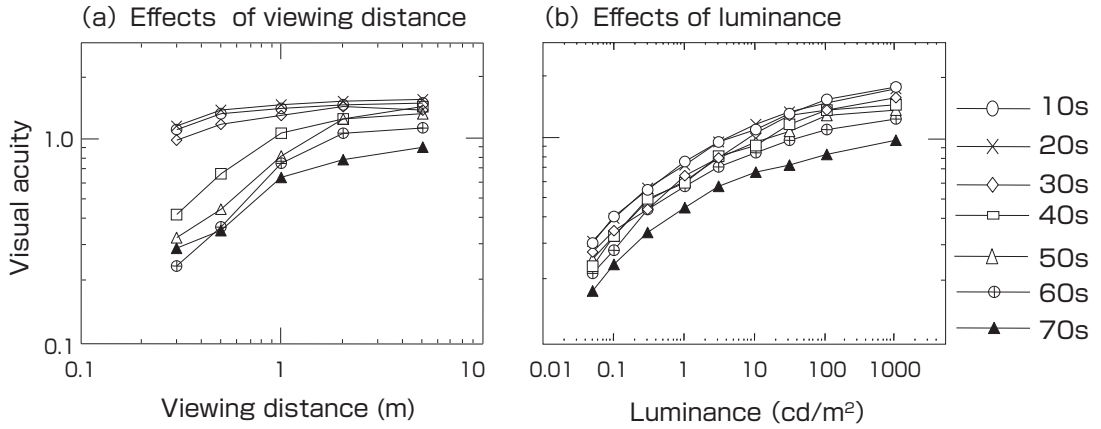


Fig. 3 Effects of viewing distance and luminance on visual acuity
(a) Effect of viewing distance. Visual acuity change for 0.3 to 5 m of viewing distance when the luminance level is fixed at a constant level of 100 cd/m^2. (b) Effect of luminance. Visual acuity change for 0.05 to 1000 cd/m^2 of luminance when viewing distance is fixed at a constant of 5 m. In both (a) and (b) data were taken from 111 subjects and averaged over each age group.

4.2 Estimation of minimum legible font size

Results shown in Fig. 4 are the data only for limited conditions and it is required to generalize these results into other conditions of age, viewing distance, and luminance level. Analysing the data in Fig. 4 we found that a newly introduced quantity namely "a size factor" enables us to describe the whole data in a more simple form. The size factor is a quantity of viewing distance divided by visual acuity as shown in Equation (1).

$$S = D/V \qquad (1)$$

Here, S means the size factor, D viewing distance in meter, and V visual acuity. The size factor implies the visual spatial resolution in a real scale. The visual acuity is defined by the minimum visual angle Θ that the eye resolves, and in the definition it does not depend on the viewing distance. However, for older people who have a limit in accommodative power, visual acuity depends largely on viewing distance in particular for short distance (less than 1 m). Although visual acuity can be known from the data on viewing distance versus visual acuity shown in Fig. 3(a), visual acuity, which only means the resolution of angle but not of actual length, cannot readily be related to font size. Introducing the size factor enables us to know the real length of resolution at the viewing distance which directly relates to font size. That is, minimum legible font size is regarded to be proportional to the actual resolution. Here, some small discrepancy between visual angle Θ and actual distance exists in the conversion from angle to distance ($\tan \Theta = \Theta$) but it is regarded negligible.

In Fig. 5, minimum legible font size experimentally obtained is plotted as a function of the size factor newly introduced here. While some discrepancies are seen, it is found that the whole data on minimum legible font size seem to be expressed well as a function of the size factor. Then, as a most simple case, the following linear equation was applied between the size factor and the minimum legible font size.

$$P = aS + b \qquad (2)$$

Here, P means the minimum legible font size (in point), a and b mean coefficients that depend on the kind and type of letters such as plain, Gothic, kanji, etc, the values of which are derived from Fig. 4 and summarized in Table 1.

When we consider that font size changes in proportion to the size factor, Equation (2) should be a line that runs through the origin point of the size factor versus the font size plane. However, looking at the experimental data in Fig. 5, it seems appropriate to use the power function that runs from the origin, or to use a linear function with a constant b like Equation (2) to make a fit to the whole range of data. Due to

Table 1. Coefficients of the equation to estimate minimum legible font size

Kind of letter		*a*	*b*
plain	hiragana, katakana, numerals	8.2	2.6
	kanji 5-10 strokes	9.6	2.8
	kanji 11-15 strokes	9.6	3.6
Gothic	hiragana, katakana, numerals	6.4	3.0
	kanji 5-10 strokes	8.1	3.4
	kanji 11-15 strokes	8.6	4.1

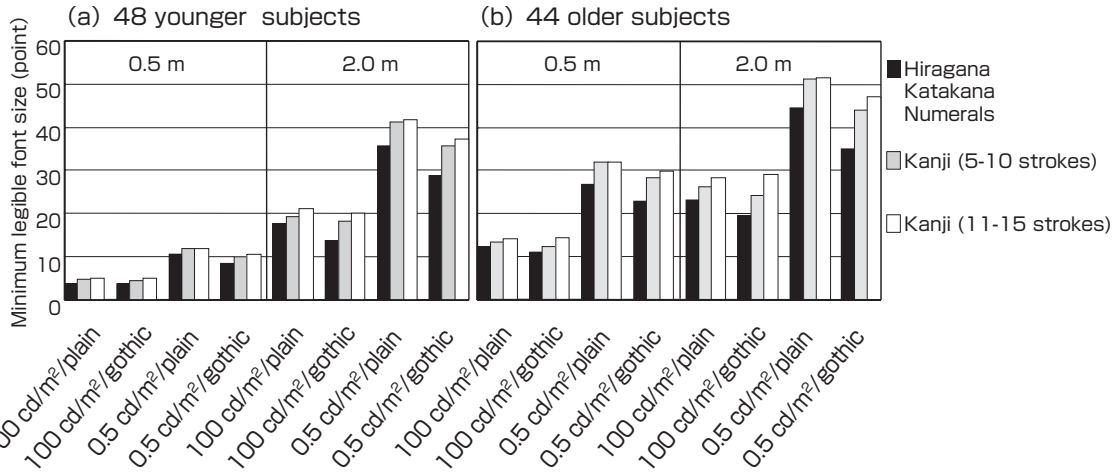


Fig. 4 Font size required to read a Japanese single letter

(a) Minimum font size required to read a Japanese single letter (hiragana/katakana/numerals, kanji 5-10 strokes, kanji 11-15 strokes) at viewing distance of 0.5 and 2 m and at luminance level of 100 and 0.5 cd/m². Results of 48 younger subjects. (b) Same as 4(a) but for 44 older subjects.

the requirement for application of standardization in this study, preference for general easy use rather than high accuracy was emphasized, and a simple linear function and not the power function was selected. Furthermore, it should be realized that Equation (2) should be applied only for the range where the eye can accommodate (from the near point to the infinite far distance) but not for the extreme case that the viewing distance is nearly zero where visual acuity has no actual meaning. This near range is out of scope of Equation (2). It is anticipated that at zero viewing distance Equation (2) gives us $P = b$, meaning that a letter of a certain small size is legible, which is unreasonable, but this situation is regarded as out of range of using Equation (2) and no convergence to $P = 0$ is required.

4.3 An example of calculation

An example of calculating minimum legible font size by using Equation (2) is shown here. Let us assume the viewing condition of a 70 year old, 50 cm of distance, and 100 cd/m^2 of luminance, minimum legible font size calculable for the case of a kanji letter with 5 to 10 strokes of the Gothic font, for example. First, visual acuity at the condition of viewing distance of 50 cm and luminance of 100 cd/m^2 is known as 0.4 from Fig. 3(a), and from this visual acuity the size factor of S (= distance (m)/visual acuity) is obtained as 1.25 (= 0.5/0.4). Then, taking proper coefficients a and b for that condition from Table 1 enables us to calculate the minimum legible font size as follows:

$$P = 8.1 \times 1.25 + 3.4 = 13.5 \text{ (point)}$$

If we do a similar calculation only for a plain font, a larger font size of 14.8 point will be obtained, which is larger than for a Gothic one. That means the plain font is less legible than the Gothic font. Furthermore, if the luminance condition becomes darker than 100 cd/m^2, the legible font size will be larger because visual acuity will become lower as shown in Fig. 3(b).

It should be noted that the minimum legible font size is a quantity that gives us a basic scale of legibility. It is convenient to have such a common scale by incorporating the affecting factors of age, viewing distance and luminance. It should also be noted that the present minimum legible font size is defined by 80 % of the probability of legibility, that is, a near threshold level, and this size does not necessarily mean “easily legible”. A new scale of legibility extent should be established by conducting relevant studies to obtain the preferable legible font size.[7]

5 Dissemination of the technical outcome through standardization

As previously mentioned, accessible design focuses on the group characteristics of many people rather than on those of an individual person. Being based on the specific feature of the group, the importance is to standardize the technical outcome of the study and to disseminate it into a whole society. As the present study is on the method for estimating minimum legible font size, it is expected to provide easily legible letters to a wider range of people through standardization of the method.

5.1 Establishment of a JIS (Japanese Industrial Standards)

The present study was based on the data collected for Japanese letters and the outcome of it was first established as a Japanese standard. It is generally important in standardization to define the scope clearly. The following items were defined as the scope of the method for estimating minimum legible font size.

(1) A single Japanese letter is applied.
(2) Minimum legible font size is designed as a function of age, viewing distance, and luminance.

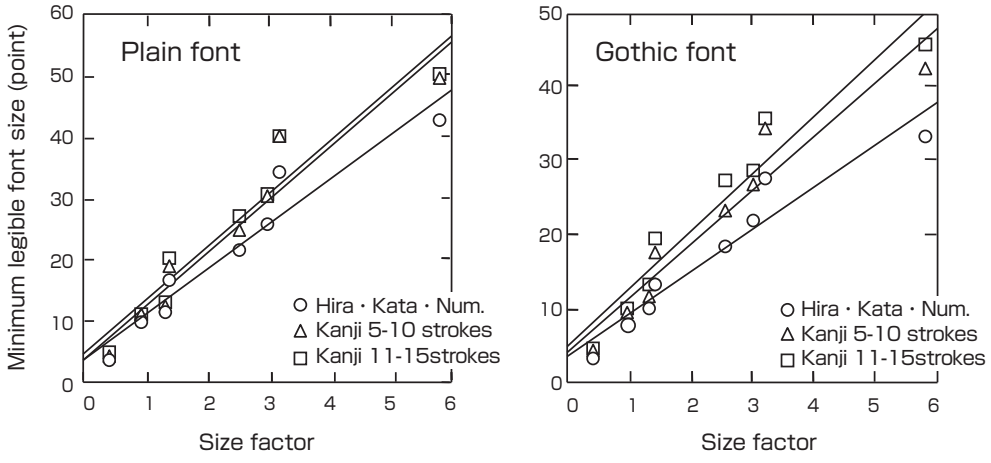


Fig. 5 Relation between minimum legible font size and the size factor
Left: Minimum legible font size as a function of the size factor for three kinds of letters (hiragana/katakana/numerals, kanji 5-10 strokes, kanji 11-15 strokes) of a plain font. Right: Same as the left but for a Gothic font.

(3) It is applicable to a person at any age from 10s to 70s, but not people with visual disabilities like low vision.
(4) Letters with high contrast such as black letters on a white background is considered.

From the viewpoint of accessible design, the design method of the present study is applicable to almost all people at any age. However, it is not applicable to those who have extremely low visual acuity such as low vision and a separate study will be needed for that.

While our actual environment for reading letters is so complicated, main factors such as age, viewing distance, and luminance are considered in the present study. Although another important factor of contrast should be investigated more, the present design method can apply to high contrast letters such as black letters printed on a white background. Care should be taken, however, when applying the present design method to electric displays which have reducing effects of contrast due to the reflection of surrounding light.

Another important point in the present study from a viewpoint of standards is that visual acuity of subjects was corrected by lenses. In the experiment, all the subjects, younger or older, had their visual acuity corrected at the far distance (5 m viewing distance) and then participated in the experiment, which is not the actual situation as visual acuity of older persons are usually corrected by their special lenses to the near point. In such a case they can read letters of much smaller size than those estimated by the present study. Therefore, it should be regarded that the present method is to estimate legible font size at the condition where no special glasses or magnifiers are used.

Under these considerations, the outcome of the present study was standardized as JIS S 0032 "Method for estimating minimum legible font size for a Japanese single character."[8] With this standard it can be said that a scale for legible font size for older people was established. This means it is possible to derive minimum legible font size by taking into account environmental factors (age, viewing distance, and luminance). Taking this size as a criterion, it would be possible to define not only "minimum" but also "legible" letter size.

5.2 Standardization at ISO (International Organization for Standardization)

It is possible to standardize the present design method not only as a domestic standard but also as an international one. As Equation (2) expresses fundamental properties of vision, this may apply to letters of any other language. In particular, legibility of numerals and alphabets should be the same in any other language because of its similar structure as long as human vision is the same. To confirm this, investigation on legibility for different languages and letters was carried out.

In the experiment, test samples of letters printed in high contrast and high resolution on the same plates were sent to 5 research institutes in Korea, China, Germany, Thailand and United States of America and the legibility was compared among them. Hangeul letters in Korea, Chinese letters in China, Thai letters in Thailand, and English in other countries were used respectively both in plain and Gothic fonts. The plain and Gothic fonts are being used in every language as serif and sans serif font respectively. In general, the difference between both types of fonts is whether decorated short lines are attached to the edges of strokes or not. The subjects were about 20 younger and 20 older people in each country. Some differences in the distribution of visual acuity of subjects or illuminance level may exist among countries, but correction using Equation (2) will be possible from the visual acuity data of the subjects measured at the same time for the same experimental condition.

Figures 6(a) and 6(b) show an example for data of percent correct for a plain font and a Gothic font respectively. Due to some differences in viewing conditions such as illuminance or kinds of letters, some deviations were observed for the data in Korea and Thailand but the overall data are almost consistent with each other. This makes it reasonable to assume that there is no basic difference in the human ability for reading and Equation (2) can be applied for estimating minimum legible font size.

Applying Equation (2) to obtain estimated font size, Figure 6(c) was drawn in which the estimated font size is compared with that of experimentally measured. In applying Equation (2), visual acuity measured in the experimental condition in each country was used to know the size factor, and by knowing coefficients from Table 1 the minimum legible font size was estimated. Coefficients for kanji 11-15 strokes and those for hiragana etc. were applied to Hangeul, Chinese, and Thai letters and to alphabets respectively. Although some discrepancies are found for Japanese and Thai data, the estimated font size does fit the one measured (80 % correct legibility). However, it can be said the predictability is not perfect. For example, the coefficients for Hangeul or Thai letters should be different from Table 1 and proper coefficients, if derived correctly, will improve the estimation much.

For the method for estimating minimum legible font size confirmed by the international comparison, discussions for an international standard in ISO have started. It seems reasonable internationally to establish first the use of Equation (2) to alphanumeric letters with appropriate estimation of coefficients because alphabetical letters are frequently used internationally. Coefficients for Chinese, Thai and Korean (Hangeul) letters should also be defined appropriately and may be provided as Annex. If all kinds of letters used in the world are considered, some classification

method concerning the visual complexity of the structure of letters will be required. Further studies should be promoted on this point.

Font design is not the only target that should be standardized in accessible design in ISO. Standardization on design methods based on human data of older people and people with disabilities is now being progressed under the initiative of Human Technology Research Institute at AIST for wider ergonomic fields concerning physical, sensory, and cognitive abilities.

Accessible design is a new field in ISO and there were no existing relevant working groups before. There was one Technical Committee (TC) named TC 159 "Ergonomics" which was closely related, and a working group (WG) was established under the TC. Figure 7 shows the structure of TC 159. The fields colored gray in the structure are all WGs established for accessible design, which are WG 2 directly under the TC, WG 10 under SC 4, WG 5 under SC 5, and Advisory Group for Accessible Design (AGAD) which is a coordinating committee for these activities. Establishing such a scheme for standardization was necessary work for disseminating the research outcomes. In accessible design, the concept is running far ahead and the technology is still in the developing stage. Much time and work is needed to form a firm basis for development and promotion such as collection of human data and this is difficult to be done only by industry. Particular knowledge and data on ergonomics will be actually needed to solve the problems with older people and people with disabilities. Studies on accessible design should be carried out with basic research outputs and dissemination of them through standardization being closely coordinated.

6 Summary: *Full research* and standardization

Figure 8 shows the flow of the whole process of the present study. The study is started from the left-bottom of the figure and after it reaches the goal at bottom right, a new research cycle is started to solve a new problem. Normally identifying problems, collection of basic data, and establishing methods for solving problems are done within the first cycle of research shown in the figure, and academic papers are published then. In accessible design, the same steps should be taken in this first cycle but it would be difficult to disseminate the outcome to society if it ends there. This is because research results of a smaller scale based on limited number of

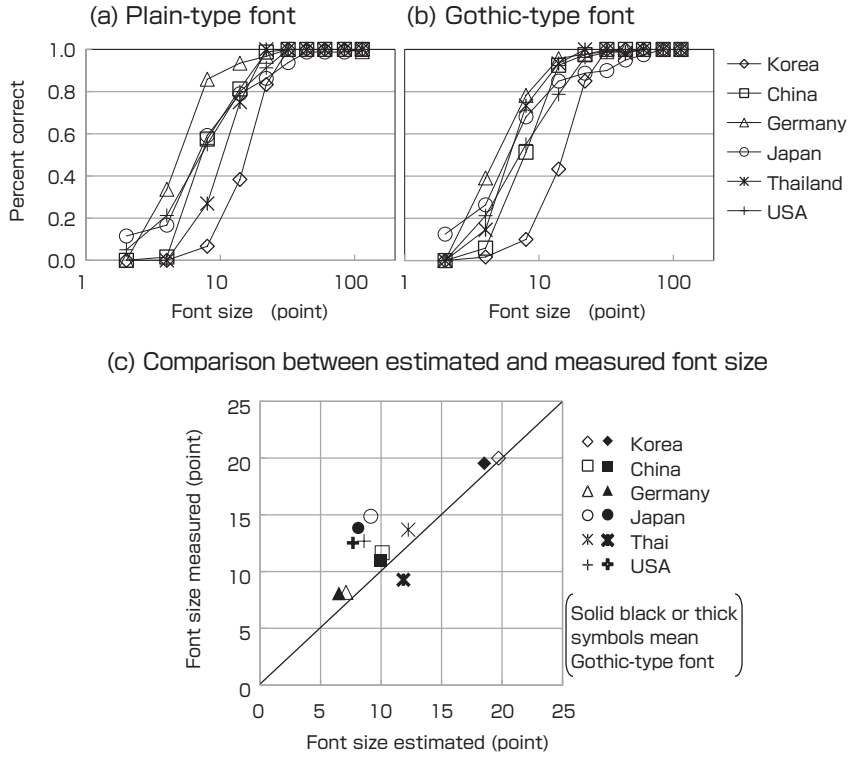


Fig. 6 Minimum legible font size for 6 countries of Korea, China, Germany, Japan, Thailand and USA.

Hangeul for Korea, Chinese for China, Thai letter for Thailand, and lowercase of the alphabet were used for other countries, all in plain and Gothic fonts. Charts (a) and (b) mean the legibility data as percent correct for a single letter with variable size from 2 to 114 point. Data are averaged over 20 older people in each country. Illuminance was from 300 to 500 lx. Chart (c) is the correlation between the data theoretically obtained and the measured ones derived from charts (a) and (b).

samples cannot make it applicable to many people including older people and people with disabilities. Another cycle of research is therefore needed for the study to disseminate the outcome.

In the second cycle, along with the concept of accessible design previously mentioned, data collection is carried out to know the characteristics of older people and people with disabilities. Through analysis of the data as well as investigation on the applicability to products and environments, the technologies developed are elaborated. Those technologies established are finally proposed to international standards for dissemination to society and industry. The whole research process is thus accomplished from identification of needs in the first cycle to developing and disseminating the accessible design methods in the 2nd cycle. When new needs or problems are raised which are not completed in this process, a new second cycle will take place where new methods of development and standards are reconsidered.

The study of minimum legible font size introduced here is now still in the process of standardization; the use and promotion of the method will probably be facilitated through this research cycle together with the experience of domestic standardization.

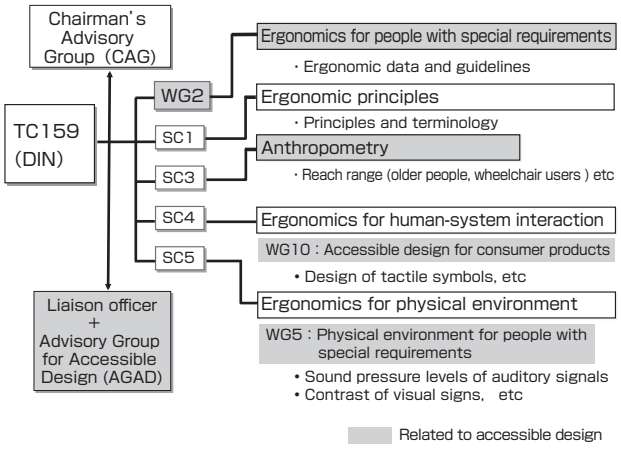


Fig. 7 Structure of TC 159 and working groups related to accessible design.
The boxes colored gray (AGAD, WG 2, SC 4/WG 10, SC 5/WG 5) are new working groups established for the development of accessible design standards. Convenors and secretaries of them are research scientists from AIST.

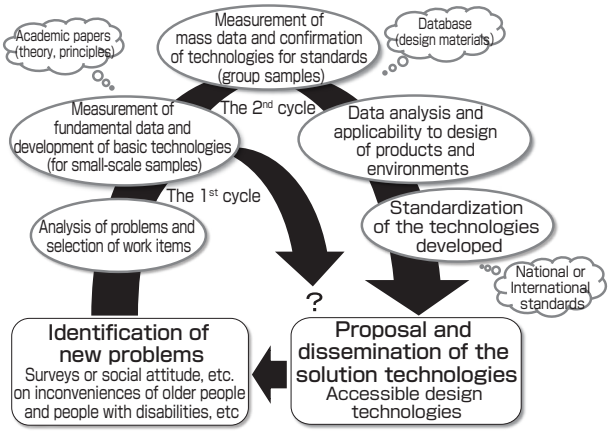


Fig. 8 The flow of the present study from identification of new problems to standardization of outcome.
From identification of new problems to fundamental data and development of basic technologies is addressed as the 1st cycle and results are published as academic papers. Starting from that stage, the 2nd cycle is for collection of mass data and confirmation of technologies to be standardized where database and standards are developed and disseminated.

Terminology

Term 1. Photopic vision; vision in which the eye is adapted to the light over 10 lx of illuminance or a few cd/m^2 of luminance at least. An adaptation state where cone photoreceptors are active in principle.

Term 2. Mesopic vision; Intermediate dim adaptation level of illuminance or luminance between photopic and scotopic vision (below about 10^{-2} lx of illuminance or 10^{-3} lx of illuminance or 10^{-3} cd/m^2 of luminance). An adaptation state where both cone and rod photoreptors are active.

References

[1] United Nations: Convention on the Rights of Persons with Disabilities, http://www.un.org/disabilities/convention/conventionfull.shtml (2006).
[2] Accessible Design Foundation of Japan: Inconveniences of people with disabilities and older people (2010).
[3] K. Sagawa, K. Kurakata and T. Yokoi: Accessible design and its international standardization, *Oukan*, 5 (1), 24-29 (2011).
[4] K. Kurakata and K. Sagawa: Development and standardization of accessible design technologies that address the needs of senior citizens – Product-design methodology based on measurements of domestic sounds and hearing characteristics –, *Synthesiology*, 1(1), 15-23 (2008).
[5] L.A. Riggs: Visual Acuity, *Vision and Visual Perception*, 321-349, John Wiley & Sons, New York (1965).
[6] K. Sagawa, H. Ujike and T. Sasaki: Legibility of Japanese characters and sentences as a function of age, *Proceedings of the IEA 2003*, 7, 496-499 (2003).
[7] K. Sagawa and N. Itoh: Legible font size of a Japanese single character for older people, *Proceedings of the IEA 2006*, CD-ROM (2006).
[8] Japan Industrial Standard Committee: JIS S 0032 Guidelines for the elderly and people with disabilities – Visual signs and displays – Estimation of minimum legible size for a Japanese single character (2003).

Authors

Ken SAGAWA

Completed the master's course of the Graduate School of Physical Information Engineering, Tokyo Institute of Technology. Doctor of Engineering. Retired from National Institute of Advanced Science and Technology, AIST, and now a professor in Department of Human Science and Design, Japan Women's University. Emeritus Researcher of AIST. Involved in research fields of visual engineering, photometry and colorimetry, evaluation on visual environments, etc., and studies on visual comfort of environment, evaluation of visual environment for older people, accessible design methods, and worked on standardization, national and international. In the present study, responsible for theoretical framework of accessible design and in experiments on legibility of letters.

Kenji KURAKATA

Completed the doctor's course of the Graduate School of Human Sciences, Osaka University in 1994. Ph.D. (Doctor of Human Sciences). Leader of Accessible Design Research Group, Human Technology Research Institute of AIST. Involved in user-interface design, hearing research of older people, and domestic and international standardization of acoustics and audiology. In the present study, responsible for theoretical framework of accessible design, analysis of the experimental data, and standardization.

Discussions with Reviewers

1 General

Comment (Akira Ono, AIST)

This is an excellent study of *Type 2 Basic Research* where it first clearly selects elemental technologies, synthesizes them, develops a method for estimating minimum legible font size, and finally standardizes the outcome. It was pointed out in chapter 3 that the standardization was useful in disseminating the outcome. However, in addition to that, it seems that setting the standardization as a goal and keeping this always in mind throughout the processes such as the selection of elemental technologies, synthesis, and integration helped to keep the whole study in appropriate control. I would be interested to hear comments from the authors on this point.

Answer (Ken Sagawa, Kenji Kurakata)

As pointed out by the comment, the present research had been carried out keeping the intention and from the viewpoint of standardization. As a matter of fact, this study was conducted with an AIST grant of "Program for Fundamental Research on Standardization." Applying for the grant was a strong requirement itself for us to realize the standardization and to develop standards or something like that as a goal.

A social need to be fulfilled by the standards is set as a goal in the planning stage of the research. In the case of the present study, legible font design for older people was a social need and the study proceeded for standardization as a final goal taking into account the public nature of the study and the difficulty of it being carried out by industry.

2 Reference value for legibility

Question (Akira Ono)

Probability of 80 % was selected as a criterion for legibility to derive minimum legible font size and its standardization. What is the reason for this? Is there any other possibility besides 80 %?

Answer (Ken Sagawa, Kenji Kurakata)

While the 50 % level is usually taken as a threshold, a higher level of probability was selected since with the 50 % level half of the population are able to read but the other half are not, which actually means it is a level which is quite difficult to read. There was an idea to take one standard deviation level (σ) which is the 84.1 % level, but as there was no strong recommendation on this point, the 80 % level was adopted as a rounded value.

The 80 % level still yields one failure of 5 trials and this is also regarded as a difficult level to read, but by using this level as a unit, a scale of legibility could be constructed by multiplying the unit.

Actually in a later study, a scale of legibility was developed with the minimum legible font size as one unit in which "very illegible" for below 0.9, "illegible" for between 0.9 to 1.2, "normal" for between 1.2 to 1.7, "legible" for between 1.7 to 2.2 and "very legible" for over 2.2 were assigned. This scaling is planned to be proposed in the next academic presentation or in the review of the standard.

3 Formula between legible font size and the size factor.

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

Considering that resolution in absolute value correlates to the minimum actual gap between strokes that is needed to be recognized as a letter, the resolution should be in a linear relationship to the font size. The most simple linear equation to fit is $P = aS$ that is a line that goes through the origin. But there may be some discrepancy which occurs with this fit at the higher value of the size factor. Looking at the data in Fig. 5, a better fit could be obtained with a power function if it is applied. I presume that in the standard document, a linear function with a cross-point of y-axis was used though a power function is known to be better if accuracy is required.

If there is a similar consideration underlying this research, it is worthwhile to clarify it to the readers because it is important to present an easy-to-use equation for the standardization even if it means reducing the accuracy.

Answer (Ken Sagawa, Kenji Kurakata)

There are several ways of thinking and methods for the curve fitting; we finally selected the simplest equation possible. As pointed out in the comment, we have come to the conclusion taking into consideration that dissemination of the research outcome is also an important point.

It is true that detailed and case-separated analysis will give us a better fit. However, keeping in mind the large variability of the data and the no need to go through the origin point, we thought pursuing the accuracy only will give us an unrealistic prediction. Having investigated all possibilities of functions such as a power function or a linear function (with or without a constant), we decided to take a linear function with a constant as the best one. We hope you understand that the conclusion was derived by paying constant respect for the application to standards.

Based on this consideration, the text was revised.

4 Font type and legibility

Question (Akira Ono)

Plain and Gothic fonts were used in this study, both in proper

shape and not deformed. Kanji letters used in traffic signs on highways, on the other hand, have missing parts or strokes or are simplified considerably. This seems to mean that deformed Kanji letters are more legible. Is there any relation between this and the present study of legibility?

Answer (Ken Sagawa, Kenji Kurakata)

There exit now several hundreds of font types and a number of fonts that aim for aesthetic appeal more than conspicuity. These are classified into serif (font with decorated short lines at ends of strokes) and sans serif (font without decorated short lines). There are many variations of fonts even in serif and sans serif fonts. In the present study the most frequently used fonts of MS-Mincho and MS-Gothic were used as representatives of the font.

Legibility of fonts can be determined by the distribution of spatial frequency (density or scarceness of lines) of components and visual sensitivity to spatial frequency. Width of strokes is strongly related to the legibility in this sense. The Mincho-font has generally narrower lines and high frequency components, and the Gothic font wider lines and low frequency components. To clarify the difference, it is efficient to study with representative Mincho and Gothic fonts. The relationship between spatial frequency and legibility is one of the fundamental issues, though not studied in detail in this study, and the way and viewpoint of the idea was taken into consideration in setting up the experimental scheme.

As a result, the Gothic font was found to be much easier to read, and this is considered due to the width of strokes. Furthermore, it was found that the minimum legible font size was increased with the change from katakana, kanji (5-10 strokes) to kanji (11-15 strokes) meaning that they are harder to read in this order. Generally speaking, as deformed letters are changed to the simpler, it is regarded that these deformed letters are being used in visual signs.

5 Legibility of letters of foreign languages and Japanese letters.

Question (Motoyuki Akamatsu)

Concerning the results in Fig. 6 where application of the present method to letters of other languages is shown, the worst fit is found to be for Japanese. Although the method was drawn by using Japanese data, the application results for Japanese were the worst. Is there any particular reason?

Furthermore, it was pointed out that using coefficients derived from Japanese data was one problem in applying to other language. Are there any other problems in the application, for example, with the different definitions of the "points" of letters (definition of letter height)? If so, please note these.

Answer (Ken Sagawa, Kenji Kurakata)

There is no essential reason for the worst fit for Japanese letters. The Japanese results were obtained from the new data in the international comparison that was carried out with different subjects and viewing conditions from the ones that yielded the equation. We first thought the bad fit was due to the difference between hiragana (for which coefficients were defined) and the alphabet, but a good fit found in Germany tells us it was not the estimated problem with the alphabet.

Applicability of coefficients derived from Japanese letters is a future problem. It is ideal to draw coefficients suitable to each letter of language, but it may be more feasible to classify according to the complexity of letters and define the appropriate coefficients for each class.

As for the expression of the "points" of letters, it is internationally defined and using the definition is reasonable. For other problems, it should be noted again as previously mentioned that the classification of the complexity of letters will be effectively used in the application of the method.

6 Normative items in standardization.

Question (Akira Ono)

JIS S 0032 "Estimation of minimum legible size for a Japanese single character" was issued as an output of the present research. Please show us what normative items (rules to follow) are defined and what informative items (information to refer) are decided in this standard, and the considerations underlying those decisions as well.

Answer (Ken Sagawa, Kenji Kurakata)

JIS S 0032 standardized the "method" but not the legible font size itself. That is, the method for estimating minimum legible font size is only the normative item [Equation (2) and Table (1)]. The use of the font size derived by the present method is solely dependent on the user of this standard. Informative items include evaluation methods for the sentence readability based on the minimum legible font size etc. which are in the Annex.

7 Strategy for dissemination of research outcome

Question (Motoyuki Akamatsu)

It is well understood that standards documentation is suitable for promotion of accessible design, but the design would not spread widely if designers do not use the standards documents. If there is any action being taken for a wider use of them, please introduce it.

Answer (Kurakata Kenji, Ken Sagawa)

We definitely understand it is important to disseminate the standards documents. At the earlier stage we took things lightly and thought that the design technology would be distributed when it was standardized, but we have clearly found that the dissemination is not so easy. Therefore, in order to let people know widely the idea of accessible design we took some actions such as developing pamphlets or holding symposiums regularly for designers or engineers in industry for the promotion in collaboration with the Ministry of Economy, Trade and Industry or ADFJ (an organization to promote accessible design).

In the future, we think some mechanism to clearly show to consumers the products that incorporate accessible design is needed. One example is a social mechanism concerning conformity assessment of the accessible design standards. With this mechanism, not only consumers are able to easily choose products but also industry will realize the impact of accessible design and the dissemination of the products will be accelerated.

8 Limitations of the methodology using standardization

Question (Motoyuki Akamatsu)

It seems the position of the present study is that a scenario of standardization was adopted to promote accessible design. Please show us the limitations of the methodology using standardization.

Answer (Kenji Kurakata, Ken Sagawa)

1) Leading or innovative research that aims for the "only one" or "number one" does not seem to be suitable for standardization, but the research that is matured and needs one more step for application (*Type 2 Basic Research*) suits standardization. On the other hand, research that needs competitive speed or that aims to develop a new field will be limited by standardization and seems to require a strategic procedure.
2) Standardization of technologies may mean, at the same time, to limit flexibility. The legibility studied in this paper is an estimation of a font size for limited conditions and a type of letters for people in a certain age group, which is something like GCD (greatest common divisor). It might be possible to estimate more accurately the legible size for a person in that condition, taking into account the visual properties of the person and specifying the conditions in more detail. It is one of the characteristics of the standardization research

and a limitation at the same time that it prioritizes speedy promotion of the technologies emphasizing simplification and generalization rather than refinement and the best suitability. There is a large stock of data, however, behind the development with this simplification and generalization. It would be effective to utilize those data for the need of making a best fit for each individual case. To meet the needs of engineers or designers of industry, the authors have started to publicly open the data behind the standardized technologies through the research information database (RIO-DB) at AIST.

3) Concerning the research system, it can be said that a systematic promotion for the standardization research is required. One of the authors (Sagawa) has been involved in international standardization of the light and lighting field in the international organization called Commission Internationale de l'Eclairage (CIE). At first he felt some limitations in conducting research, committee works, and international communication, as he worked completely alone. After reorganizing the institutes to AIST, the industrial standards division was established and the organizational environment for carrying out the program for standardization research was well prepared. With this development, many researchers joined the research intended for standardization and the group studies had been made possible. The situation remarkably progressed. It would be very difficult, on the contrary, to carry out standardization research without such a support system.
4) In relation to answer 3) there is a limitation in bringing research to standardization with projects of short timespan. The standardization work needs at least three years after the proposal (in the case of ISO). If we include the work time for the preliminary stage, it takes 6 to 7 years even if the work proceeds ideally. The projects of about three years is now becoming major, and we are required to do research by connecting these projects. If the connection is terminated, a plan for standardization itself will disappear. Standardization research can never proceed by connecting too short-term projects or new projects.

Development of fiber optic broadband vibration-detection system

— Simultaneous measurement of both strain and acoustic emission using a fiber Bragg grating sensor —

Hiroshi TSUDA *, Eiichi SATO, Tomio NAKAJIMA and Akiyoshi SATO

[Translation from *Synthesiology*, Vol.6, No.1, p.45-54 (2013)]

Structural integrity can be examined using methods that evaluate response to vibration, such as hammering tests and ultrasonic inspections. Fiber optic sensors are expected to allow structural health monitoring in harsh environments where conventional electric sensors cannot be used. Recently, detection of vibration with a fiber Bragg grating (FBG) has been intensively investigated, because FBGs have many advantages such as multifunction abilities, multiplexing, and electromagnetic immunity. In using previously proposed systems incorporating FBGs, however, there was a technical difficulty in detecting ultrasound under varying temperatures and strain conditions. We developed a novel system that overcomes this technical barrier. Our system is also capable of detecting vibrations across a broad frequency band from several Hz to around 2 MHz. This paper presents how our compact and economical vibration-detection system with an FBG sensor was developed.

Keywords : Ultrasound, vibration, acoustic emission, non-destructive testing, fiber-optic sensor

1 Introduction

The presence of defects in structures can be inspected with a test utilizing vibrations, such as a hammering test or an ultrasonic test. Acoustic emission (AE) measurements can monitor the integrity of materials and structures because the initiation of a crack generates AEs whose frequencies range from tens of kHz to hundreds of kHz. In rotating machines, it is known that the misalignment of a rotary shaft and the failure in a ball bearing give arise to anomalies in vibrations in which high intensity components appear in a frequency range different than the rotary frequency.[1] Thus, vibration measurement plays an important role in monitoring the health of structures and machinery.

Electric sensors such as resistive strain gauges and piezoelectric sensors are conventionally used in vibration measurement. Strain gauges are used to measure vibrations up to a frequency of several kHz, and piezoelectric sensors are used to measure vibrations at higher frequency. Piezoelectric sensors are selectively used to cover the frequency range to be monitored because of their resonant characteristics, i.e., narrowband frequency response characteristics. In other words, there is no electric sensor capable of detecting vibration in a wide frequency range from mechanical vibration to ultrasound. Therefore, the development of a broadband sensor and its measurement system can enhance the convenience of a non-destructive inspection test utilizing vibrations.

There are a growing number of structures to which the application of electric sensors is unsuitable. Carbon fiber-reinforced plastics (CFRPs) are widely applied to structural members of cars, airplanes and turbine blades of wind power generation because CFRPs have the advantages of high specific strength and rigidity, and a great amount of flexibility when used in structural design. Electrically conductive CFRP structures, however, are prone to being hit by lightning. The application of electric sensors to CFRP structures is inappropriate because lightning would damage the installed electric sensors. In addition, electric sensors decay in a long term application. No electric sensor can withstand the application of structural health monitoring over decades, such as those at a radioactive waste storage facility.

A fiber optic sensor can solve these challenges of electric sensors. Among the variety of fiber optic sensors, a fiber Bragg grating (FBG), which is a wavelength-modulation fiber optic sensor, is a promising candidate for sensors in structural health monitoring because of its multifunctionality and multiplexibility. Thus far, many FBGs have been used as sensors for measuring strain and temperature. There have been extensive studies on the detection of ultrasound and AE using an FBG recently.[2] There is a large technical barrier, however, to detect AE using an FBG, as mentioned below. Table 1 shows the features of sensors for detecting vibrations.

This paper reports the development of an FBG sensor system that is capable of measuring strain and detecting

Research Institute of Instrumentation Frontier, AIST Tsukuba Central 2, 1-1-1 Umezono, Tsukuba 305-8568, Japan
* E-mail: hiroshi-tsuda@aist.go.jp

Original manuscript received June 18, 2012, Revisions received August 30, 2012, Accepted September 10, 20102

Table 1. Features of vibration sensors

	Strain gauge	Piezoelectric sensor	FBG sensor
Response frequency range	up to a few kHz	tens of kHz ~ tens of MHz	a few Hz ~ 2 MHz
Strain measurement	○	×	○
ultrasound・AE measurement	×	○(*1)	○(*2)
Simultaneous measurement of both strain and AE	×	×	○
Durability	×	×	○(*3)
Electromagnetic interference	×	×	○
Unit price (JPY)	300 ~ 600	3,000 ~ 300,000	10,000 ~ 30,000

(*1) An appropriate piezoelectric sensor should be chosen in accordance with the frequency range to be measured.
(*2) There is a large technical barrier in existing technology for measuring AE with an FBG sensor.
(*3) There are time limitations in the application of an FBG sensor at a high temperature of more than 400 degrees C or in strongly radioactive environments where the FBG is eliminated.

AE simultaneously. The system was developed through collaborative research among the Japan Aerospace Exploration Agency (JAXA), two private companies and the National Institute of Advanced Industrial Science and Technology (AIST).

2 Expectations of an FBG sensor system for structural health monitoring

Recently, parts of airplanes have been manufactured based on a damage-tolerant design that predicts the structural lifetime on the assumption that crack propagation until the point of an allowable crack length can be tolerated. Such structures based on a damage-tolerant design concept require an inspection that detects a crack before reaching the allowable length. The structural reliability can be remarkably improved if the occurrence and propagation of cracks are monitored during use.[3] Thus, a smart structure including a self-diagnosing system, e.g., a function to measure strain and AE, has been given much attention in aerospace research. The development of a structural health monitoring system incorporating a simple and durable sensor network is essential for realizing smart structures.

Strain and AE are conventionally measured with a strain gauge and a piezoelectric sensor, respectively, which are electric sensors. The electric sensor network for a large-scale structure would be complex and cumbersome because electric cables are required for these sensors. In contrast, FBGs are suitable sensors for a smart structure because FBGs are lightweight and can offer a simple sensor network in which several FBGs are installed on a single optical fiber through a wavelength-division multiplexing (WDM) technique. Thus, an FBG sensor system capable of measuring both strain and AE is considered a core technology for smart structures.[4]

3 Fiber Bragg gratings

3.1 Ultrasonic detection using an FBG

An FBG consists of periodical refractive index modulation in the core of an optical fiber. When light passes through an FBG, the FBG reflects narrowband light whose central wavelength is called the Bragg wavelength.[5] The Bragg wavelength shifts with the strain and temperature applied to the FBG. An FBG whose Bragg wavelength is 1550 nm has sensitivities to strain and temperature of 1.2 pm/με and 14 pm/K, respectively. An FBG is employed as a strain or temperature sensor by measuring the Bragg wavelength with an optical instrument such as an optical spectrum analyzer or a wavelength-meter. FBGs have excellent durability except under high temperatures, exceeding 400 degrees C, or in strong radioactive environments. The application of FBG sensors in such harsh environments is subject to a time limitation because the refractive index modulation of an FBG disappears upon exposure. The time limitation in usage must be considered when using FBG sensors in harsh environment, such as a radioactive waste storage facility.

A dynamic Bragg wavelength shift induced by impact vibration cannot be detected from a reading of the Bragg wavelength using an optical measurement instrument such as a wavelength-meter because the sampling rate is a few Hz at most. A fast Bragg wavelength shift arising from ultrasonic vibration can be detected using the following two systems.[6][7] One is an optical filter demodulation system. The light reflected from a broadband light-illuminated FBG is sent to an optical filter whose optical characteristics vary with wavelength. The intensity of light transmitted through or reflected from the optical filter varies with the vibration of ultrasound impinging on the FBG sensor. The other is a laser demodulation system in which a laser is tuned to a wavelength where the gradient of the FBG reflection spectrum is steep. Usually, the laser wavelength is set to 50 % of the reflectivity. A laser demodulation system allows highly sensitive ultrasonic detection by measuring the intensity of light reflected from the FBG.

3.2 Technical barrier of AE detection with an FBG

AEs accompanied by a microscopic failure occur when a material is exposed to strain or a change in temperature. Therefore, an AE measurement system must be capable of detecting ultrasound under varying strain and temperature conditions. AE exerted on an FBG shifts the Bragg wavelength a few picometers because AE causes a strain oscillation of a few με at most.[8] Such a subtle and fast Bragg wavelength shift can be detected sensitively with a laser demodulation system. However, as shown in Fig. 1, the Bragg wavelength shifts by 0.1 nm when the FBG is subjected to a strain of 0.008 % or temperature change of 7 K. The lasing wavelength deviates from the operating range by such a small change in strain and temperature. Thus, it is difficult for a

laser demodulation system to detect AE continuously under varying strain and temperature conditions. An optical filter demodulation system is unlikely to detect AE sensitively due to its poor ultrasonic sensitivity. As mentioned above, the technique for detecting AE with an FBG is not well established. The development of a FBG sensor system capable of detecting ultrasound under varying strain and temperature conditions is awaited.

4 Development of an AE measurement system employing an FBG

The authors had joined a JAXA Space Open Lab project named "R&D of technology for monitoring the health of large-scale structures" from the autumn of 2008 until the spring of 2011. There were two goals for this research project. The first is to develop an FBG sensor AE measurement system that can be installed on space structures such as a rocket. The second is to construct an FBG sensor system featuring simultaneous multi-point measurements of both strain and AE. In the research project, AIST was in charge of developing the measurement technique. Two companies were in charge of designing and manufacturing the measurement systems and conducting experiments. JAXA was in charge of providing verification tests and administering the research project.

In 2008, when the research project commenced, an optical filter demodulation system incorporating an optical filter with periodical optical characteristics such as an arrayed waveguide grating (AWG) and a Fabry-Perot filter seemed to show potential for detecting AE.[9][10] The AE detectability of an FBG was unknown because there had been no reports on AE measurements with an FBG sensor. In the first year of the project, we concentrated on the following two tasks. One is to evaluate the AE detectability of an FBG sensor. The other is to confirm the possibility of AE measurement using an optical filter demodulation system.

4.1 AE measurement by a laser demodulation technique

AEs of a CFRP pressure vessel used for a rocket motor case during a pressure proof test are detected with a strain-insensitive FBG sensor incorporated in a laser demodulation system. The AE detectability of an FBG is compared with that of a piezoelectric sensor conventionally used in AE detection. In the previously reported ultrasonic measurement using a laser demodulation system, an FBG was glued on or embedded in the structure to be tested, as shown in Fig. 2(a). The reflection spectrum of the FBG installed in such a manner shifts with the strain applied to the test structure. AE that occurs continuously under varying strain conditions might be detected by tuning the lasing wavelength in accordance with the reflection spectrum shift. However, the tuning of the lasing wavelength cannot follow a sudden discontinuous strain change arising from a substantial failure in the test structure.

In this study, part of an FBG inscribed-optical fiber other than the grating section is bonded to the test structure to isolate the FBG from the strain applied to the test structure, as shown in Fig. 2(b). AEs occurring in the test structure travel through the optical fiber via the point of contact between the structure and the optical fiber and eventually impinge on the grating. The change in temperature can be negligible in an indoor experiment. This sensor arrangement permits a continuous AE measurement under varying strain conditions.

Figure 3 shows the cumulative AE hit curves detected from an FBG and a piezoelectric sensor, with the pressure-time curve. Both sensors begin to detect AE from a pressure exceeding 1 MPa. The AE curves of both sensors show similar behavior throughout the test. The experiment demonstrated that an FBG had ability to detect AE comparable to a piezoelectric sensor.[11]

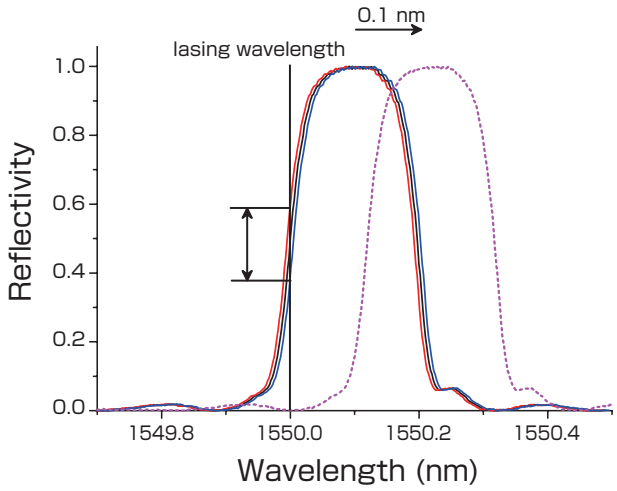


Fig. 1 Ultrasonic detection based on a laser demodulation
The reflective spectrum shifts by 0.1 nm when an FBG is exposed to a strain of 0.008 % or a change in temperature of 7 K.

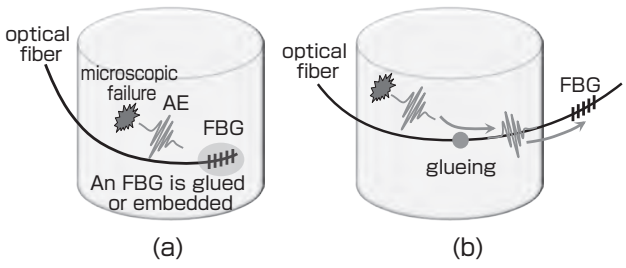


Fig. 2 FBG sensor installation onto a structure to be monitored
(a) conventional installation, (b) strain-insensitive installation.

4.2 AE measurement by an optical filter demodulation technique

There are limitations in size, weight and power consumption in a system installed in a space structure. JAXA presented the following specifications of an AE measurement system for a space structure: smaller than 200 × 300 × 150 mm^3 in size, less than 4 kg in weight and less than 14 W in power consumption. A laser demodulation system cannot meet the specifications mentioned-above because it consists of large and heavy measurement instruments such as a tunable laser and an optical spectrum analyzer.

An optical filter demodulation system can meet the specifications in spite of the lower AE sensitivity. According to a previous study on ultrasonic detection using an optical filter demodulation system, ultrasound sensitivity can be maximized by using an optical filter whose free spectral range (FSR) corresponds to the spectral width of an FBG reflection spectrum.[10] Two types of an optical filter for the demodulation are available: an AWG and a Fabry-Perot filter. A commercially available Fabry-Perot filter provides a variety of FSR, although there is little choice of FSR in AWG. Thus, an optical filter demodulation system including a Fabry-Perot filter was constructed and applied to the AE measurement of CFRP.

Although the optical filter demodulation system met the specifications for installation into a rocket, it was difficult to distinguish between AE and background noise due to the low AE sensitivity. The intensity of light reflected from an FBG incorporated in the optical filter demodulation system was as feeble as 0.01 % of that obtained from a laser demodulation system. The improvement in the AE sensitivity of the optical filter demodulation system that utilizes such feeble light seemed to be difficult. There was no prospect to develop an AE measurement system for a space structure at the end of the first year of the research project.

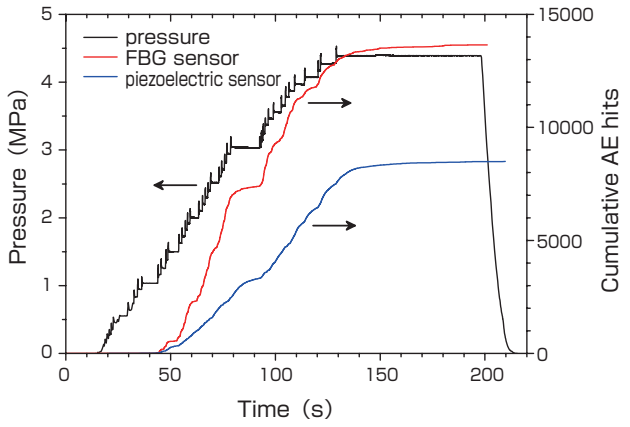


Fig. 3 Pressure and cumulative number of AE hits plotted with respect to time during the pressure test of a CFRP vessel

4.3 Development of a novel AE measurement system using a fiber ring laser

The influence of a grating length of an FBG sensor on the ultrasonic sensitivity was investigated at the end of the first year of the research project. The setup of a laser demodulation system used in the experiment is shown in Fig. 4. The laser wavelength appropriate for ultrasonic detection always fluctuates because a tiny change in strain and temperature shifts the reflection spectrum. In the experiment, ultrasound was detected in the following procedure. First, set the optical switch of the system to Port 1 and measure the reflection spectrum of a broadband light-illuminated FBG with an optical spectrum analyzer. Second, turn the optical switch to Port 2 and tune the lasing wavelength at 50 % of the reflectivity of the FBG sensor. Then, the ultrasound is detected as the photodetector output.

In some cases, the ultrasound was barely detected by averaging the ultrasonic responses in spite of using a laser demodulation system featuring a high sensitivity to ultrasound. The reduction in ultrasonic sensitivity was found to result from an operational error, where the optical switch was not turned to Port 2 when detecting the ultrasound. This operational error, however, demonstrated that ultrasound could be detected from a broadband light-illuminated FBG without an optical filter for demodulation. Ultrasound oscillates the reflection spectrum of an FBG within a range of a few picometers. This ultrasound detection must utilize a slight wavelength dependence of optical power emitted from the light source because a tiny oscillation of the reflection spectrum is detected as a change in the intensity of the light.[12] The utilization of the wavelength dependence of optical power was a new idea in demodulating ultrasounds. The authors expected that this demodulation could lead to a breakthrough in the development of a novel compact FBG sensor system because it did not need a demodulating optical filter.

Let us consider the improvement in ultrasonic sensitivity using the wavelength dependence of the optical power. The optical power spectrum of the broadband light source used in the experiment is shown in Fig. 5(a). The optical power tends to decrease slightly with wavelength at approximately 1550 nm, at which the FBG used in the experiment has the Bragg wavelength. The optical power spectrum at approximately

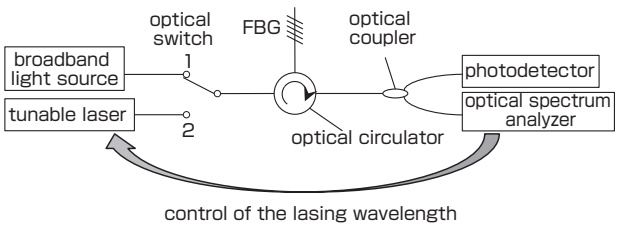


Fig. 4 A setup of a laser demodulation system

1550 nm is schematically shown in Fig. 5(b). The optical power is assumed to vary from 0.5 to 1 by ultrasonic vibration. If the intensity of light reflected from FBG is 10, ultrasound vibration causes a variation in the optical power ranging from 5 to 10. If the intensity of light reflected from an FBG increases to 100, the identical ultrasonic vibration gives rise to a change in the optical power of 50. Thus, ultrasound sensitivity can be improved by intensifying the power of light reflected from the FBG. The usage of a high power broadband light source or a fiber ring laser can intensify the light reflected from the FBG. However, a system employing a high power broadband light source is inefficient because it only utilizes a fraction of power emitted from the light source. Consequently, a system including a fiber ring laser was constructed.[13]

A setup of a fiber ring laser is shown in Fig. 6. A fiber ring laser consists of an optical amplifier, an optical circulator, an optical coupler, an FBG, a photodetector and optical fibers connecting these optical components. An optical amplifier both emits weak broadband light and amplifies wavelength components with relatively high intensity. The weak broadband light emitted from the optical amplifier reaches an FBG through an optical circulator. The narrowband light at the Bragg wavelength is reflected from the FBG and is propagated along the looped optical fiber. The light is separated into two directions at the optical coupler. Part of the light goes to a photodetector, where the intensity of light is converted into a voltage signal. The remaining light goes back to the optical amplifier, where the Bragg wavelength light is boosted. This system emits a laser at the Bragg wavelength of the FBG because the light at the Bragg wavelength is repeatedly amplified by being circulated through the looped optical fiber. If the ring cavity of the system consists of a 10-meter-long optical fiber, the time required for the light reflected from the FBG to circulate the ring cavity is approximately 33 ns, which corresponds to 30 MHz in frequency. The fiber ring laser emits a laser at the Bragg wavelength corresponding to strain and temperature applied to the FBG at a sufficient response speed. The intensity of the laser is modulated by the Bragg wavelength of the FBG by utilizing the wavelength dependence of the gain of the optical amplifier incorporated in the fiber ring laser. Although the Bragg wavelength shift induced by the ultrasound is only a few picometers at most, the fiber ring laser system converts such a subtle shift to a measurable change in the laser intensity because of the high intensity of the laser.

A technique to measure the wavelength of a laser emitted from a fiber ring laser using an optical instrument is commonly used to evaluate strain and temperature. However, the technique to detect vibration impinging on an FBG by utilizing a wavelength dependence of optical gain of an optical amplifier incorporated in a fiber ring laser is a unique invention of the present study.

An example of ultrasound detection using a fiber ring laser system is shown here. Figure 7 shows the wavelength shift in a reflection spectrum of an FBG glued on a CFRP plate that undergoes a strain change of ±0.06 %. In the case of a laser demodulation, the laser wavelength must be tuned in accordance with the shift of the reflection spectrum. In contrast, a fiber ring laser spontaneously emits a laser at the Bragg wavelength of the FBG sensor regardless of the shift in the reflection spectrum. A fiber ring laser system could detect ultrasound irrespective of considerable shift in the Bragg wavelength, as shown in Fig. 8.[14]

A fiber ring laser system was found to respond to vibration in a broadband range from a few Hz to 2 MHz. As shown in Fig. 9, a fiber ring laser-based AE measurement system that met the specification for the installation into a rocket structure and had sufficient AE sensitivity to monitor the microscopic fracture of CFRP was assembled in the spring of 2010.

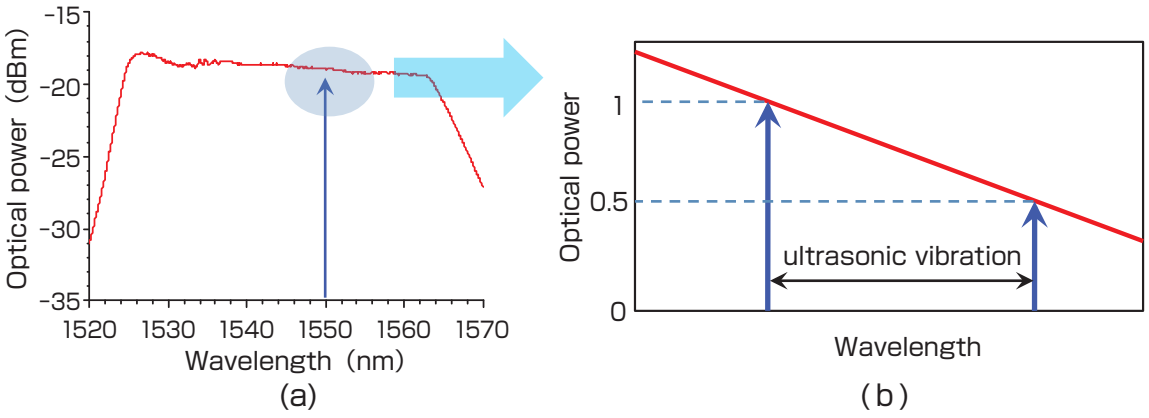


Fig. 5 (a) Optical power spectrum of the broadband light source employed, (b) a schematic illustrating the optical power distribution at approximately 1550 nm

5 Development of a simultaneous multi-point measuring system of both strain and AE

The final target of our research project was to develop a system that can simultaneously measure strain up to 1 % and AE using four FBG sensors. To measure strain and AE simultaneously, the output of the photodetector included in a fiber ring laser system was divided into two lines for measuring strain and AE individually. An optical filter demodulation technique was applied to measure the strain in the system.[6]

There are the following technical limitations in the system development.

1. It is difficult to emit a multi-wavelength laser stably using a fiber ring laser including a single optical amplifier.
2. A wavelength band more than 12 nm must be allocated to the respective FBG sensors to avoid signal interference in strain measurements because the reflective spectrum shifts by 12 nm when an FBG is subjected to a strain of 1 %.

A WDM component is available economically because a WDM technique in which a number of optical carrier signals are multiplexed onto a single optical fiber by using different wavelengths of laser light is widely used in the optical communication field. An optical filter for a coarse wavelength-division multiplex (CWDM) in which optical signals are separated by 20 nm in wavelength was used in the system to divide optical signals of four FBG sensors. The block diagram of the system is shown in Fig. 10.

The working mechanism of this system is the same as that of the system incorporating a single optical amplifier, as shown in Fig. 6. The lights reflected from four FBGs whose Bragg wavelengths are separated by 20 nm are divided into four lines according to the wavelength at the CWDM filter in the looped fiber. These divided lights at respective Bragg wavelengths are intensified by an individual optical amplifier and then are combined into a single optical fiber via an optical coupler. The lights are repeatedly amplified by being circulated through the looped fiber and eventually emit laser light at the respective Bragg wavelengths. Part of multi-wavelength laser light generated by the fiber ring laser is sent to another CWDM filter through the optical coupler in the looped optical fiber and is divided into four optical fibers with respect to the wavelength. Each laser at the Bragg wavelength of the respective FBG sensors is separated into two lines for measuring strain and AE through an optical coupler. The strain measurement line is connected to an

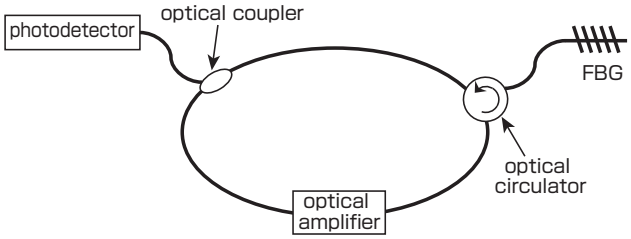


Fig. 6 A setup of a fiber ring laser system

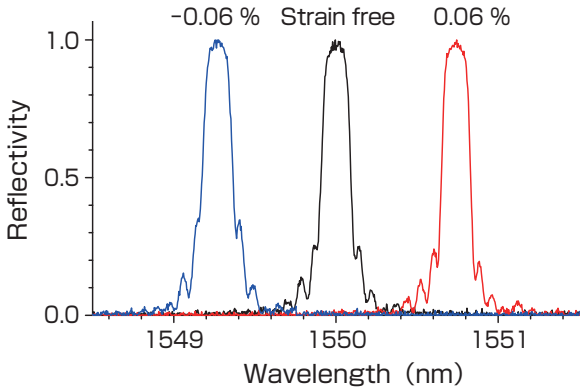


Fig. 7 FBG reflection spectrum shift when an FBG is strained by ±0.06 %

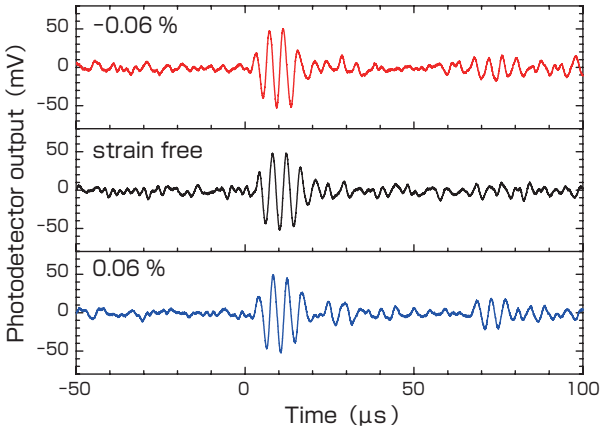


Fig. 8 An example of ultrasound detection using a fiber ring laser system in which the FBG is subjected to different strain levels

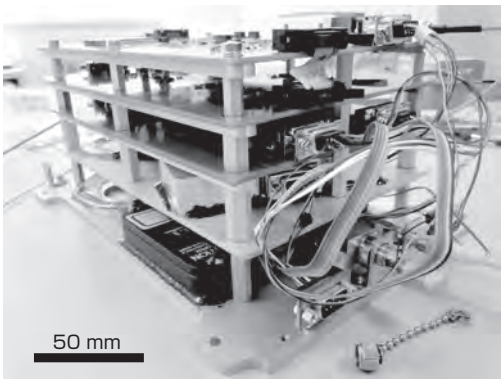


Fig. 9 A fiber-ring laser-based AE measurement system capable of installation on a rocket structure

optical filter for evaluating the strain. The strain applied to the FBG can be estimated from both the intensities of lights reflected from and transmitted through the optical filter. The AE measurement line is directly connected to a photodetector. A signal exceeding a threshold level that is predetermined to eliminate background noise is recorded as an AE signal. In Fig. 10, the two lines for measuring strain and AE are depicted only for an FBG with a Bragg wavelength of λ_1 for simplicity. In the actual system, the other three outputs have two lines for measuring strain and AE.[15]

Both strain and AE measurements of a solid rocket motor case and a vibration measurement of a liquid rocket engine in a liquid hydrogen atmosphere were performed using the 4-ch FBG sensor system. The vibration of the structure in a liquid hydrogen atmosphere was remotely measured via a waveguide rod with a piezoelectric sensor because piezoelectric sensors could not be installed in such an extremely low temperature atmosphere. An FBG could be installed onto a structure in a liquid hydrogen atmosphere, and the system could detect weak vibration components that conventional piezoelectric sensors had never detected. Furthermore, this system demonstrated that the simultaneous measurement of both strain and AE from four FBG sensors is possible.

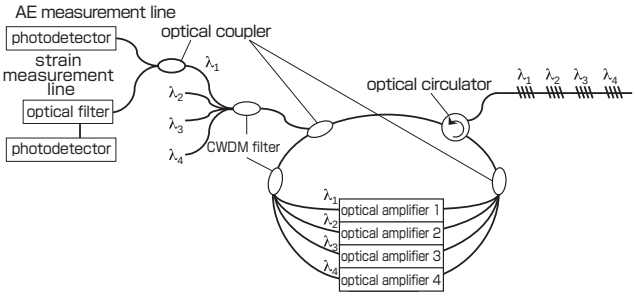


Fig. 10 A block diagram of a simultaneous multi-point system for measuring strain and AE
The lines for measuring strain and AE are depicted only for the output of the FBG whose Bragg wavelength is λ_1 for simplicity. In the actual system, each output of the respective FBG sensors has two lines for measuring strain and AE.

6 Conclusions

This research aimed to develop a multiplexed FBG sensor system featuring the simultaneous multi-point measurement of both strain and AE. The system development process is shown in Fig. 11. When the research project began, the technology of AE measurement with an FBG sensor was undeveloped, and AE detection using an FBG sensor had never been demonstrated. In the beginning of the project, we attempted to evaluate the AE detectability of an FBG sensor and to detect AE using an optical filter demodulation system that met the specification for installation on a rocket. Although an FBG itself possessed an excellent AE detectability, an FBG incorporated in an optical filter demodulation system lacked AE sensitivity. An operational

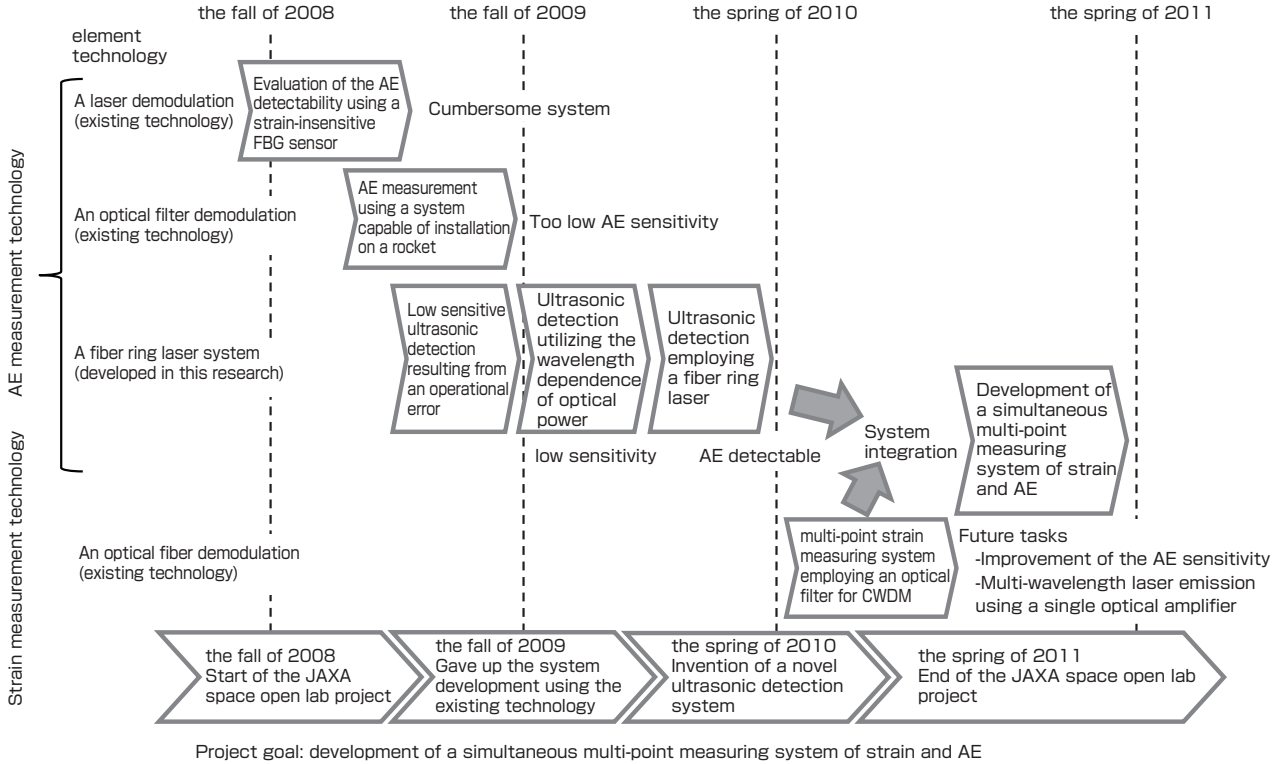


Fig. 11 The system development process

Table 2. Features of the AE measurement technology adopted in the present research

	Laser demodulation (existing technology)	Optical filter demodulation (existing technology)	Fiber ring laser system (developed in this study)
AE detectability	○(see Fig. 3)	×(cannot distinguish between AE and background noise)	○(see Fig. 8)
Installation to a space structure	×	○	○
Simultaneous measurement of strain and AE	×(*1)	○(*2)	○(*2)
System price (JPY) (*3)	6,000,000	1,000,000	500,000

(*1) It is necessary to add a broadband light source to measure strain.
(*2) Both strain and AE can be measured using a system including a single light source.
(*3) The price is for a 1-ch AE measurement system, excluding a function for evaluating strain.

error in an ultrasonic detection test brought a chance to conceive of a new AE measurement system using a fiber ring laser. A fiber ring laser system can detect vibration in a broadband range from mechanical vibration to ultrasound. The intensity of laser generated from a fiber ring laser is modulated by vibration impinging on an FBG sensor by utilizing the wavelength dependence of gain of the optical amplifier incorporated in the fiber ring laser. A simultaneous multi-point measuring system of both strain and AE was constructed by integrating a strain measurement system based on an optical filter demodulation technique into a fiber ring laser system. The features of the element technologies adopted in the present study are listed in Table 2.

A fiber ring laser system developed in the project can detect ultrasound up to 2 MHz, compared to commercially available FBG sensor systems which cannot detect ultrasound because the sampling rate is 1 kHz at most. In addition, a fiber ring laser system featuring a simple configuration, is small in size and lightweight and can be constructed inexpensively compared to conventional FBG sensor systems. However, the following technical tasks remain unsolved. A stable multi-wavelength laser oscillation cannot be realized by a fiber ring laser system including a single optical amplifier. Optical amplifiers are required for each FBG sensor for emitting multi-wavelength lasers at present. AE sensitivity of an FBG sensor incorporated in a fiber ring laser system is lower than that of piezoelectric sensors. We would like to solve these problems and expand the application of the fiber ring laser system not only to space structures but also to industrial machinery in the future.

References

[1] H. Jinyama: *Kaiten kikai no shindo shindan no saishin gijutsu to doko* (The latest technology and trends for vibrational diagnostics of rotary machinery), *Kensa gijutsu (Inspection Engineering)*, 17, No. 3, 29-35 (2012) (in Japanese).

[2] G. Wild and S. Hinckley: Acousto-ultrasonic optical fiber sensors: Overview and state-of-the-art, *IEEE Sensors Journal*, 8, 1184-1193 (2008).

[3] W.J. Staszewski, C. Boller and G.R. Tomlinson: *Health Monitoring of Aerospace Structures :Smart Sensor Technologies and Signal Processing*, 29-73, Wiley, West Sussex (2004).

[4] M. Majumder, T.K. Gangopadhyay, A.K. Chakraborty, K. Dasgupta and D.K. Bhattacharya: Fibre Bragg gratings in structural health monitoring - Present status and applications, *Sensors and Actuators A-Physical*, 147, 150-164 (2008).

[5] A. Othonos: Fiber Bragg gratings, *Review of Scientific Instruments*, 68, 4309-4341 (1997).

[6] M.A. Davis and A.D. Kersey: All-fiber Bragg grating strain-sensor demodulation technique using a wavelength-division coupler, *Electronics Letters*, 30, 75-77 (1994).

[7] N. Takahashi, K. Yoshimura, S. Takahashi and K. Imamura: Development of an optical fiber hydrophone with fiber Bragg grating, *Ultrasonics*, 38, 581-585 (2000).

[8] H. Tsuda, K. Kumakura and S. Ogihara: Ultrasonic sensitivity of strain-insensitive fiber Bragg grating sensors and evaluation of ultrasound-induced strain, *Sensors*, 10, 11248-11258 (2010).

[9] S. Kojima, A. Hongo, S. Komatsuzaki and N. Takeda: High-speed optical wavelength interrogator using a PLC-type optical filter for fiber Bragg grating sensors, *Smart Structures and Materials 2004: Smart Sensor Technology and Measurement Systems*, 5384, 241-249 (2004).

[10] J.R. Lee, H. Tsuda and Y. Akimune: Apodized fibre Bragg grating acousto-ultrasonic sensor under arbitrary strain using dual Fabry-Perot filters, *Journal of Optics A-Pure and Applied Optics*, 9, 95-100 (2007).

[11] H. Tsuda, E. Sato, T. Nakajima, H. Nakamura, T. Arakawa, H. Shiono, M. Minato, H. Kurabayashi and A. Sato: Acoustic emission measurement using a strain-insensitive fiber Bragg grating sensor under varying load conditions, *Optics Letters*, 34, 2942-2944 (2009).

[12] H. Tsuda: A Bragg wavelength-insensitive fiber Bragg grating ultrasound sensing system that uses a broadband light and no optical filter, *Sensors*, 11, 6954-6966 (2011).

[13] FBG Vibration Detection System, Apparatus and Vibration Detection Method Using the System (FBG shindo kenshutsu shisutemu, gai shisutemu o mochiita sochi oyobi shindo kenshutsu hoho), JPO Patent Publication 2011-196744 (in Japanese).

[14] H. Tsuda: Fiber Bragg grating vibration-sensing system, insensitive to Bragg wavelength and employing fiber ring laser, *Optics Letters*, 35, 2349-2351 (2010).

[15] [15] T. Nakajima, E. Sato, H. Tsuda, A. Sato and N. Kawai: Development of simultaneous measurement system for strain and AE using FBG sensors (for structural health monitoring of solid rocket motor composite chambers), *Transactions of the Japan Society of Mechanical Engineers - Part A*, 78, 728-741 (2012) (in Japanese).

Authors

Hiroshi TSUDA

Completed the doctorate course at the University of Tokyo in 1994. Doctor (Engineering). Has worked for the National Institute of Advanced Industrial Science and Technology since 1995 and has been a leader of the structural health monitoring research group since 2010. He was in charge of developing the optical measurement system.

Eiichi SATO

Completed the doctorate course at the University of Tokyo. Doctor (Engineering). Has worked for the Institute of Space and Astronautical Science since 1985 and is now serving as professor. He was in charge of providing experiments and administrating the research project.

Tomio NAKAJIMA

Received the master's degree in engineering from Tsukuba University in 1987. Worked for Nissan motors and IHI aerospace. Has worked for IHI Inspection & Instrumentation since 2005 and is now serving as manager. He was in charge of both designing and manufacturing the optical components incorporated in the measurement system and conducting experiments.

Akiyoshi SATO

Graduated from Aoyama Gakuin University in 1977. BS degree. Worked for Nissan motors. Now, works for IHI Aerospace and has been chief engineer since 2009. He was in charge of both designing and manufacturing the electrical components incorporated in the measurement system and conducting experiments.

Discussions with Reviewers

1 Overall evaluation

Comment 1 (Shingo Ichimura, AIST)

The paper describes the development of an FBG sensor system and its application to monitoring the health of a space structure. The major accomplishment of this study is to establish the technology for measuring strain and AE simultaneously using an FBG sensor. I think the development of a novel technology to detect AE using an FBG sensor in particular is especially worthy. However, the authors should write more clearly about the synthesiological approach that is the focus of the journal *Synthesiology.*

Comment 2 (Mitsuru Tanaka, AIST)

This paper is well worth reading because there are twists and turns in the story of the system development. I advise the authors to add a diagram sketching the twists and turns during the system development. I made several comments for better understanding of this paper.

2 Objectives and chapter titles

Comment 1 (Mitsuru Tanaka)

I think that the main point of the system development is not to improve high sensitivity, but is multifunctionality in the frequency domain. If it is so, readers are likely to misunderstand the authors' achievement because the terms relating to high sensitivity are often used in the manuscript. The manuscript in the chapter "Introduction" should be revised in accordance with this comment.

Answer 1 (Hiroshi Tsuda, AIST)

The major achievement of this study is indeed the development of an AE measurement system that has high sensitivity and is also compact. The multifunctionality in the frequency domain that allows the simultaneous measurement of both strain and AE can be achieved by combining the newly developed AE measurement system with a conventional strain measurement system.

Comment 2 (Shingo Ichimura)

It is better to change the chapter titles as follows: "4. Development of an AE measurement system employing an FBG" and "4.1 AE measurement by a laser demodulation technique."

Answer 2 (Hiroshi Tsuda)

The titles of chapter 4 and subchapter 4.1 were changed as suggested. In accordance with the change, the title of subchapter 4.2, "The attempt of AE measurement by an optical filter demodulation technique" was changed to "AE measurement by an optical filter demodulation technique."

3 Technical terms

Comment 1 (Shingo Ichimura)

The terms of "damage tolerance design" and "smart structures" are used in chapter 2. However, the concept of damage tolerance design, and the relation between damage tolerance design and smart structures are not well explained. The authors should add a supplemental explanation.

Answer 1 (Hiroshi Tsuda)

The supplemental explanation was added in the first paragraph of chapter 2.

4 Description of element technology

Comment 1 (Shingo Ichimura)

This paper shows measurement ranges and describes shortcomings of conventional vibration sensors, such as strain gauges and piezoelectric sensors. A table that compares the features and the measurement range of both an FBG sensor and conventional sensors would help the readers to better understand the topic.

Answer 1 (Hiroshi Tsuda)

As suggested, Table 1 showing the features of respective sensors, was added in the 4th paragraph of chapter 1.

Comment 2 (Shingo Ichimura)

The title of subchapter 3.1 is "The working principle and sensor function of an FBG." However, there is no explanation about the working principle in the subchapter. Moreover, there is a statement that says, "In such harsh environments, there is a time limitation of the application of FBG sensor…" This statement gives a contradictory impression to readers because there is a statement that says, "A fiber optic sensor can solve problems faced by electric sensors" in chapter 1. The authors should provide a consistent description.

Answer 2 (Hiroshi Tsuda)

As suggested, the title of subchapter 3.1 was changed, and a supplementary explanation was added to the end of the first paragraph of subchapter 3.1.

Comment 3 (Mitsuru Tanaka)

I cannot understand the necessity of the comparison between a laser demodulation technique and an optical filter demodulation technique. The authors should write more concisely or delete this comparison if the comparison is not essential to this paper.

Answer 3 (Hiroshi Tsuda)

The description in the second paragraph in subchapter 3.1 might cause misunderstanding. The description explaining that a dynamic change in the Bragg wavelength could be detected using both demodulation techniques was added there.

5 From the viewpoint of "synthesiology"

Comment 1 (Shingo Ichimura)

The authors mention that a novel vibration measurement principle utilizing the wavelength dependence of the light output of the light source was found by chance. The author should describe in detail the research process and approach that led to the finding of the new technology in subchapter 4.3. The research approach seems to be valuable and universal even for researchers in other fields.

Answer 1 (Hiroshi Tsuda)

The 3rd paragraph in subchapter 4.3 was revised and Figs. 5 (a) and (b) were added there. Moreover, Fig. 11 was added in chapter 6 to illustrate the system development process.

Comment 2 (Mitsuru Tanaka)

1. Describe in detail the research process that led to the use of a fiber ring laser.
2. A tunable laser was used as a light source in the system shown in Fig. 4. I would like to confirm whether a fiber ring laser consisting of four optical amplifiers is used as a light source in the system shown in Fig. 10.
3. I would like to confirm whether the allocation of frequency band is a problem to be solved in the future. If it is so, redraw Figs. 4 and 10 so that the present technology can be distinguished from the future tasks.

Answer 2 (Hiroshi Tsuda)

1. The research process that led to the usage of a fiber ring laser had been described in the 3rd paragraph in subchapter 4.3, and Figs. 5 (a) and (b) were added for better understanding. The system development process was schematically shown in Fig. 11 in chapter 6.
2. The fiber ring laser works as the light source in the system shown in Fig. 10. The system emits a laser by repeating optical amplification of a narrowband light at the Bragg wavelength of the FBG sensor.
3. In the present technology, optical amplifiers are required for the respective FBG sensors. The authors would like to develop a sensing system consisting of a single optical amplifier. Both the present technology and the future tasks are schematically shown in Fig. 11.

Comment 3 (Shingo Ichimura)

This paper deals with the R&D of an FBG sensor system for monitoring the health of an aerospace structure. The focus of the present paper is on the development of technology to overcome the technical barrier written in Note 2 of Table 1. The technical tasks confronting the AE measurement with an FBG sensor and the developed system are described in subchapter 3.2 and chapter 4, respectively. The research process is schematically shown in Fig. 11. However, the relation between the technical tasks and the solutions remains still vague. It is better to add a new table showing the features of AE measurement technology adopted in the present study.

Answer 3 (Hiroshi Tsuda)

Table 2 was added to chapter 6.

Comment 4 (Shingo Ichimura)

As listed in Table 1, there seems no technical task in strain measurement using an FBG sensor. However, strain measurement technology is listed in Fig. 11 that illustrates the system development process. I do not know what kind of technical tasks have been solved using an optical filter for CWDM. The authors should revise the manuscript, Fig. 11 and Table 1 for better understanding.

Answer 4 (Hiroshi Tsuda)

The aim of our JAXA Space Open Lab project is to develop a multi-channel FBG sensor system that measures both AE and strain simultaneously. The developed system was built by integrating a novel AE measurement system into a conventional strain measurement system. For better understanding of the developed system configuration, a column indicating that an FBG can measure both AE and strain simultaneously was added to Table 1. Moreover, Fig. 11 was revised to show which element technology was used to measure AE and strain. The developed system integrating an AE system into a strain measurement system is compact because the system shares the same light source. The feature of compactness is listed in Table 2. The manuscript was modified to clarify that the developed system is capable of measuring both AE and strain simultaneously.

Editorial Policy

Synthesiology Editorial Board

Objective of the journal

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

Content of paper

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

Subject of research and development

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

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

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

Peer review

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

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

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

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

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

References

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

Types of articles published

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

Required items and peer review criteria (January 2008)

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

Instructions for Authors

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

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

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

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

4 Submission

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

Synthesiology Editorial Board
c/o Website and Publication Office, Public Relations Department, National Institute of Advanced Industrial Science and Technology(AIST)
Tsukuba Central 2 , 1-1-1 Umezono, Tsukuba 305-8568
E-mail: synthesiology-ml@aist.go.jp

The submitted article will not be returned.

5 Proofreading

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

6 Responsibility

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

7 Copyright

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

Inquiries:

Synthesiology Editorial Board
c/o Website and Publication Office, Public Relations Department, National Institute of Advanced Industrial Science and Technology(AIST)
Tel: +81-29-862-6217 Fax: +81-29-862-6212
E-mail: synthesiology-ml@aist.go.jp

Letter from the editor

The synthetic approach in basic research is currently drawing interest as discussed in the roundtable talk of this issue.

Problems faced by humankind in the 21st century are complicated and complex such as environment, energy, and safety including nuclear power plants as a recent example. It is recognized that such problems cannot be solved solely by the analytic approach that has been the stronghold of scientific research. It is also a fact that most of the R&D activities in industries are accomplished by the synthetic approach. To utilize results of basic researches for innovation, I think a new methodology of science and technology research is necessary where both the analytic and synthetic approaches are conducted concurrently and coherently.

Synthesiology is a journal of original research papers that describe synthetic researches. Five years have passed after the first publication of the journal in 2008. I have acted as the editor-in-chief of the journal since its launch until March 2012. I shall reflect on the five years of the journal.

About one hundred research papers have been published in the journal so far. These describe scenarios that were originally created by the authors to achieve research objectives that are closely related with societal values.

There are many ways in which the authors write scenarios for the synthetic researches. Yet, these have hardly ever been disclosed despite being the most important part of the researches. After launching *Synthesiology*, it was found that scenarios for the synthetic researches could be understood by people of different expertise. Considering the state of modern science and technology where the research disciplines are highly segmented and the mutual communication among the disciplines have become extremely difficult, it is rather surprising that researchers and engineers are able to mutually communicate, understand, and learn from each other by the aid of scenarios regardless of their own disciplines.

Other than the roundtable talk of this issue, I have heard thoughts from knowledgeable persons in various disciplines on the value and promotion of synthetic researches, and they were published in the previous issues of *Synthesiology* as articles, interviews, and roundtable talks. We received a lot of responses from the readers ever since the launch, and had many positive comments including such comments that researches in different disciplines can be understood and it is good reference on how to conduct corporate R&D. The authors of *Synthesiology* commented that there were many things they could not write about in the existing academic journals even though certain points were crucial in the research, but such crucial points can be written in this journal.

One of the characteristics of this journal is that discussions between the reviewers and the authors are placed at the end of the individual papers. In the review processes, the name and affiliation of reviewers are disclosed to the authors and readers. This practice was started with the intention of openly discussing and developing the way of paper writing with this journal because the format of paper writing for synthetic researches had not been well established. However, there was an unexpected side effect. Since the names are disclosed, the reviewers could not make biased remarks and provided responsible, fair comments. Also, the discussions between the reviewers and the authors provided important information to the readers that were often useful for the readers to understand the papers.

The journal *Synthesiology* is a strong bond that joins basic researches of science and technology to innovation in society. We would like to ask for continued support of the readers for this journal which incorporates many new approaches. We welcome submission of papers from people of various industries and academia where synthetic researches are actually being practiced.

I hope new R&D of science and technology and innovation are created from this journal.

Editor
Akira ONO

Letter from the editor

This issue is topped by the fifth anniversary roundtable talk. People in important positions convened, and engaged in an extremely deep discussion on what should be done to link R&D and society. I am grateful to the participants.

There are four research papers in this issue. Tanaka's paper is on the promotion of the practical use of solid oxide fuel cell (SOFC), and the development and standardization of the performance evaluation method needed when this technology becomes available on the market. Koizumi's paper is the development of the technology for predicting earthquakes from the changes in groundwater level and the construction of the groundwater level detection system. Sagawa's paper is the research for determining the font size legible for the elderly according to brightness and visual distance to the letter, and the establishment of a standard. Tsuda's paper is the description of the development of the sensor for strain and acoustic emission using optical fiber and its application to the vibration detection in space structures. The two papers on standardization address the standard for performance evaluation for industry, and the standard to support product design for the elderly. The two standards are very different, but both R&Ds were conducted considering what were necessary to deliver good products to the market. The studies of groundwater level change have been done, as it was academically recognized effective for earthquake prediction. However, the groundwater level detection system must be set in necessary places in order for this technique to be useful in society. These researches were conducted based on the scenario with strong awareness of delivering the technologies to society. In the optical fiber vibration detector, there was serendipity where a breakthrough occurred because of a certain mistake, and the R&D is being done after solving various issues to fulfill the technical limitation of use in space structure. By setting the highly limiting space structure as the goal, technologies that can be applied to many places become possible. Although the timeframes required for R&Ds are varied, from a few years to over 20 years, these papers remind us that it is important not to forget the goal.

Executive Editor
Motoyuki AKAMATSU

Synthesiology - English edition Vol. 6 No. 1, Jun. 2013
Edited by *Synthesiology* Editorial Board
Published by National Institute of Advanced Industrial Science and Technology (AIST)

Contact: *Synthesiology* Editorial Board
c/o Website and Publication Office, Public Relations Department, AIST
Tsukuba Central 2, Umezono 1-1-1, Tsukuba 305-8568, Japan
Tel: +81-29-862-6217 Fax: +81-29-862-6212
E-mail: synthesiology-ml@aist.go.jp
URL: http://www.aist.go.jp/aist_e/research_results/publications/synthesiology_e

Synthesiology Vol.6 No.1 June 2013
-English edition

"Synthesiology-English edition" is a translated version of "Synthesiology," which is published quarterly, ISSN 1882-6229, by AIST. Papers or articles published in "Synthesiology-English edition" appear approximately four months after the publication of the original "Synthesiology."

AIST11-A00005-8 Published by AIST