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Highlights of the Papers in *Synthesiology* Volume 8 Issue 2 (Japanese version May. 2015)

Synthesiology is a journal that describes the objectives and social value of research activities that attempt to utilize the results in society, the specific scenarios and research procedures, and the process of synthesis and integration of elemental technologies. To allow the readers to see the value of the papers in a glance, the highlights of the papers characteristic to *Synthesiology* are extracted and presented by the Editorial Board.

***Synthesiology* Editorial Board**

Development of material testing equipment in high pressure gaseous hydrogen and international collaborative work of a testing method for a hydrogen society
— Toward contribution to international standardization —
The safety of high-pressure hydrogen containers is essential for the diffusion of fuel cell vehicles and hydrogen gas stations. Iijima (AIST) *et al*. developed an evaluation method that ensures the reliability of metal materials used in high-pressure hydrogen gas environment, jointly with an American research institution. The scenario for the international standardization of the successfully developed evaluation method is also discussed.

Research on social benefits resulting from NEDO projects
— Study of the top 70 NEDO Inside Products —
Since the commencement of NEDO projects about 30 years ago, about 3 trillion yen of development funds have been invested. However, a methodology for analyzing the effect of such national investment has not been established. Yamashita (NEDO) *et al*. offer a general discussion on the effects, not only in terms of sales but also in terms of job creation and CO_2 reduction, for the 70 products of NEDO projects that were successfully put to practical use and commercialization and show good sales. This is a valuable paper that presents the methodology for analyzing the cost-effectiveness.

Application of laser Compton photon beam to nondestructive tests
— A spin-off technology from nuclear physics —
Toyokawa (AIST) applied technologies used in the atomic nucleus research to nondestructive tests, and conducted development and improvement as well as selection and integration of the elemental technologies to establish them for industrial use. Toyokawa positions bridging (translational) research as “work where one’s concerns and thinking are organized and gradually shaped into a form that can be readily accepted by society.” This paper describes the processes by which the users’ voices were heard and the direction of research was adjusted.

Detection of influenza viruses with the waveguide mode sensor
— Development of a palmtop sized sensor —
Awazu (AIST) *et al*. developed an intermediate integrated technology that involves the size reduction of a sensor through the integration of elemental technologies, toward the goal of “realizing a simple and highly sensitive influenza virus detector,” and structured the integrated technology through their combination. This is an interesting paper that describes the process of fusion of different fields through joint research by experts in surface chemistry and virology, in addition to the technologies that the authors have already accumulated.

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Development of material testing equipment in high pressure gaseous hydrogen and international collaborative work of a testing method for a hydrogen society

— Toward contribution to international standardization —

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[Translation from *Synthesiology*, Vol.8, No.2, p.62-69 (2015)]

To commercialize fuel cell vehicles and hydrogen filling stations, and to achieve a reliable and economical "hydrogen society," international accordance of the material usage standard for high pressure gaseous hydrogen equipment is regarded as an important issue. Therefore, a precise method to evaluate the effect of gaseous hydrogen on structural metallic materials is required to qualify the materials compatibility for high pressure gaseous hydrogen equipment. For this purpose, our research group developed testing equipment capable of such examinations as slow strain rate tensile tests, fracture toughness tests, and delayed fracture tests up to 120 MPa of gaseous hydrogen. We acquired operation expertise of the equipment and testing data of commercialized metallic materials. In particular, fracture testing methods of Cr-Mo standard steel in Japan and USA were compared in an international collaborative study between Sandia National Laboratories, Livermore and our research group. We concluded that estimating fracture toughness with a rising displacement is essential for testing methods in a high pressure gaseous hydrogen environment.

Keywords **:** hydrogen embrittlement, fracture toughness, material testing, fuel cell vehicle, hydrogen filling station

1 Introduction

There is a plan to commercialize fuel cell vehicles (FCV) by FY 2015 with the goals of diffusion of about 2 million FCVs that use 70 MPa high-pressure gaseous hydrogen by FY 2025 and installment of about 1,000 hydrogen filling stations.[1] In June 2014, Toyota Motor Corporation showcased an FCV scheduled for commercial sales.[2] To realize these goals, the pricing of FCV and the reduced construction cost of hydrogen filling stations are important, and the "Strategic Road Map for Hydrogen and Fuel Cell" was released to achieve a hydrogen society.[3] The high-pressure hydrogen vessel is the most expensive part of the high-pressure gaseous hydrogen equipment used in 70 MPa FCV and hydrogen filling stations. With FCV, it is called the on-board container with assumed hydrogen gas pressure of 70 MPa. It is called the pressure vessel for hydrogen stations, and the hydrogen gas pressure of 82 MPa is assumed.[4] The accumulation of material database and the establishment of evaluation technology for the effect of hydrogen on materials including pipes, valves in high-pressure gaseous hydrogen condition over 100 MPa, particularly for hydrogen embrittlement of metallic materials, are important topics in achieving a safe and economic hydrogen society. Also, harmonization of the domestic and overseas standards for materials that are used for high-pressure gaseous hydrogen equipment is expected to promote the development of low-cost equipment and parts, as well as strengthen international competitiveness of automotive and infrastructure industries.

Due to such a background, we believe the development of an experimental equipment that allows material testing in hydrogen gas surpassing 100 MPa, the establishment of a material testing method that allows accurate evaluation of hydrogen embrittlement and accumulation of test data using such equipment, and the diffusion to and sharing of knowledge of such material test data with related industries will greatly contribute to the international standardization of the evaluation method and qualification of materials compatibility for high-pressure gaseous hydrogen equipment. In this paper, we overview the properties of metallic materials that are demanded for use in high-pressure gaseous hydrogen equipment, including the situations in Japan and overseas. Next, we discuss the material testing equipment in high-pressure gaseous hydrogen at AIST, review the material testing methods using such equipment, and describe the international comparison of the material testing methods. Then we discuss our contribution that we may make toward the international standardization of the material testing method.

2 Properties demanded for the metallic materials used in high-pressure gaseous hydrogen equipment

2.1 What is hydrogen embrittlement?

When a metallic material is exposed to hydrogen atmosphere,

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the hydrogen atoms diffuse in the metal lattice, and the material property of the metal declines. This is called hydrogen embrittlement. Specifically, when tensile tests for metallic materials are conducted in high-pressure gaseous hydrogen environment, or when tensile tests for metallic materials that are hydrogen-charged by exposure in testing chambers of hydrogen environment are conducted in atmosphere (in inert gas), the strength properties such as yield stress and tensile strength or the ductilities such as breaking elongation and reduction of area are reduced. Due to the word "embrittlement," it may present the impression that "hydrogen embrittlement" is a breakage within the elastic range of metallic materials where no elongation takes place. Of course, some materials may break within the elastic range in the hydrogen atmosphere, but most materials show plastic deformation. Therefore, Murakami *et al.* described hydrogen embrittlement as "ductile fracture that is accompanied by microscopic plastic deformation."[5]

Up to the present, so many research works have been performed for the effect of hydrogen on the strengths and ductilities of various materials. As a result, it became clear that while there is no metallic material that does not show some degree of hydrogen embrittlement, the materials can be roughly categorized as follows: (1) materials that cannot be used due to large effects of hydrogen embrittlement such as fractures occurring in the elastic range, (2) materials that may be used in certain conditions although ductility such as elongation and reduction of area may decrease due to the effect of hydrogen embrittlement, and (3) materials that receive little effect of hydrogen embrittlement under limited conditions. The materials categorized in (3) include austenitic stainless steel with high nickel content and aluminum alloys. One of the materials categorized in (2) is low-alloy steel. Low-alloy steel is a material used widely as structural material in various fields such as chemical plants, and it is characterized by having higher material strength and being less expensive than austenitic stainless steel.

2.2 Standards for qualifying the materials compatibility of high-pressure gaseous hydrogen equipment

Determination and review of the standards for FCV on-board containers and hydrogen station vessels are being conducted around the world. Characteristically, since the hydrogen filling stations are installed domestically compared to FCVs that will be distributed widely around the world, the domestic considerations are reflected strongly in hydrogen filling stations.

For on-board containers, it is designated by the "Exemplified Standard for Container Inspections, etc." (2013), which is the technical standard set by the Safety Regulations for Containers of the High-Pressure Gas Safety Law in Japan, that the maximum fill pressure of the compressed hydrogen FCV on-board container shall be 70 MPa, and the materials that can be used for such containers are austenitic stainless steel (SUS316L) containing specific nickel content (nickel equivalent) and aluminum alloys (6061-T6).[6] In the USA, the 6061 aluminum alloys and high nickel SUS316 are designated as materials that can be used for on-board containers for 70 MPa compressed hydrogen FCV in the annex of SAE J2579 (2009) of the Society of Automotive Engineers (SAE). If any other materials are to be used, they must be subject to designated material tests: (1) slow strain rate tensile tests in hydrogen or of hydrogen-charged material, (2) fatigue tests in gaseous hydrogen, and (3) crack growth tests in gaseous hydrogen condition.[7] The standard for 70 MPa on-board containers in Europe used to follow the ISO/TS 15869 (2009) "Gaseous Hydrogen Blends & Hydrogen Fuels: Land Vehicle Fuel Tanks." However, as the review of the global standard was started by the United Nations, as will be explained later, the review by the ISO Technical Committee (TC197/WG18) has started from 2013.[8] In the World Forum for Harmonization of Vehicle Regulations (WP29) of the United Nations Economic Commission for Europe (UNECE), the need to promote international mutual recognition of global standards with international harmonization was recognized to diffuse automobiles with excellent safety and environmental performance. Therefore, the creation of the "Global Technical Regulation for Hydrogen and Fuel Cell Vehicles (HFCV global technical regulations)" was started from 2007, and gtr Phase 1 was adopted in 2013. In accordance to this, the items of the Safety Regulations for Containers were revised in June 2014 in Japan.[9] However, the deliberation for the materials compatibility of on-board containers will be continued in gtr Phase 2.

For the vessels, Japan designates stainless steel (SUS316, SUS316L) as the compatible material for the compressed hydrogen vessels and the pipes through which compressed hydrogen passes, and designates the chemical composition (nickel equivalent) at normal operation pressure (82 MPa) and normal operation temperature (−40~250 ºC), in the Exemplified Standard for Security Regulation for General High-Pressure Gas Safety Regulations (2014) of the High-Pressure Gas Safety Laws. It also allows the steel for machine structural use (SCM435) to be used for vessels at normal operation pressure of 40 MPa or less.[10] In the USA, alloy steels such as SA-372 and SA-723, stainless steels such as SA-336 and Gr.F316, and aluminum alloys such as 6061-T6 are indicated as compatible materials in high-pressure gaseous hydrogen up to 103 MPa, according to Article KD-10 in Division 3: Special Requirement for Vessels in Hydrogen Service (2010) of the American Society of Mechanical Engineers (ASME). For actual use, it requires evaluations of the following: (1) plane strain fracture toughness value K_{IC} by rising load and rising displacement in atmosphere (crack-initiation threshold test in accordance to ASTM E399 or E1820), (2) fracture toughness value K_{IH} by constant load or constant displacement in gaseous hydrogen (crack-arrest threshold test in accordance to ASTM E1681), and (3) crack growth rate *da/dN* in gaseous hydrogen.[11]-[15] In Europe, high-pressure gas vessels are designated in the European Norm EN13445 (1999, Unfired Pressure Vessels) under PED97/23/EU (1997, Pressure Equipment Directive) that is equivalent to the High-Pressure Gas Safety Laws of Japan, but the evaluation of hydrogen embrittlement of materials follow ISO 11114-4.[16][17] The ISO 11114-4 (2005) requires the hydrogen embrittlement evaluation testing method when Cr-Mo alloy steel with tensile strength up to 950 MPa is used as the material for the gaseous hydrogen pressure vessel with normal operation pressure of 30 MPa or less as follows: (1) a rupture test where a crack is produced by increasing the pressure of gaseous hydrogen applied to one side of a discoid sample, (2) a crack-initiation threshold test where the load is increased in steps in gaseous hydrogen of 15 MPa, and (3) a crack-arrest threshold test at constant displacement or constant load in gaseous hydrogen of 15 MPa. However, since this test pressure in gaseous hydrogen is insufficient for the material testing method of hydrogen station vessels for which the normal operation pressure is 82 MPa, review is being continued for the standard of hydrogen station vessels at the ISO Technical Committee (TC197/WG15).

As it can be seen, the material compatibility standards for high-pressure gaseous hydrogen equipment such as FCV on-board containers and hydrogen station vessels are in the process of being established worldwide. Since SUS316L stainless steel and A6061aluminum alloys are expensive, it is necessary to increase the choice of materials that can be used for the vessels and pipes of high-pressure gaseous hydrogen equipment to achieve cost reduction that allows the diffusion of FCVs and hydrogen filling stations. Therefore, for low-alloy steel that has potential to be used in certain conditions although it may be affected by hydrogen embrittlement, it is necessary to consider the material evaluation technologies for fatigue property and fracture toughness in high-pressure gaseous hydrogen condition from the perspective of finite life design, and to establish a method for accurately evaluating the material behavior in high-pressure gaseous hydrogen. We aim to contribute to the international standardization of the testing method of materials compatibility in high-pressure gaseous hydrogen equipment, by developing material testing equipment for high-pressure gaseous hydrogen of 100 MPa or more, obtaining material test data using such equipment, investigating the efficacy of the testing method through accurate evaluation of hydrogen embrittlement phenomena and understanding the embrittlement mechanism, providing and diffusing this knowledge to the industry through creation of a database of the material evaluation results, and approaching the related organizations involved in standard formulation (Fig. 1).

3 Development of the material testing equipment for high-pressure gaseous hydrogen

Globally, there are not many research institutes that possess material testing equipment for gaseous hydrogen pressure of over 100 MPa. In Japan, as of October 2014, Kyushu University (120MPa), Energy Technology Research Institute, AIST (120 MPa), and a few private companies have materials testing equipment for 100~120 MPa. In USA, the Sandia National Laboratories (140 MPa); in Europe, The Welding Institute of Britain (100 MPa); and in Asia, China and Korea each has material testing equipment for 120 MPa.

In our research group, we accumulated the operational know-how by gradually increasing the pressure of the gaseous hydrogen used from 1 MPa, 40 MPa, 70 MPa, and then to 120 MPa. Based on the know-how, we further improved the safety for experiments using high-pressure gaseous hydrogen in 2011, through simplification of the system by integration of high-pressure gaseous hydrogen gas supply systems, remote control using PCs, introduction of monitoring cameras and an emergency shut-down system, and automation of the testing area by mutual isolation of individual testing devices using protective shields. The fatigue testing device, slow strain rate tensile testing device, and exposure chambers are connected in line to the 120 MPa compressor. The operations of the compressor and each valve are done by remote control using the PC mouse from the control room shown in Fig. 2, and hydrogen gas cannot be supplied all at once to the devices. As shown in Fig. 3, a protective shield is installed in the explosion-proof area surrounded by fireproof walls to isolate the individual testing devices. Moreover, high-pressure gaseous hydrogen is sealed in the test vessel, and after the gaseous hydrogen is introduced into the test vessel, the gas inside the pipes and the compressor is released and decompressed to atmospheric pressure. It is designed so that even if the gaseous hydrogen leaks from the test vessel during the material test, the hydrogen concentration in the

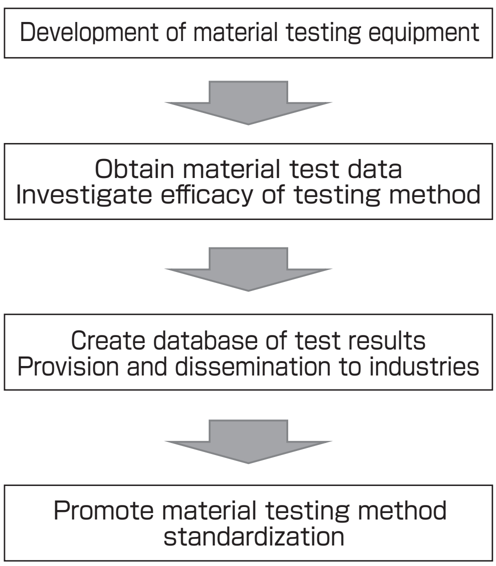

Fig. 1 Work toward contribution to international standardization

laboratory space will be much lower than the explosion limit.

The shapes of the main testing devices are shown in Fig. 4. The fatigue testing device of Fig. 4(a) has the signal output port and internal load cell using strain gauge that functions stably in hydrogen. It is capable of conducting fatigue tests at load cycle 1 Hz, crack growth tests, and fracture toughness tests by a rising displacement method, in gaseous hydrogen atmosphere at normal operation pressure of 115 MPa and room temperature. The slow strain rate tensile testing device shown in Fig. 4(b) is capable of tensile tests at a rate of $1 \times 10^{-5} S^{-1}$ in gaseous hydrogen atmosphere at normal operation pressure of 70 MPa and room temperature. The exposure chamber of Fig. 4(c) has a signal output port, and is capable of hydrogen charging materials at operation pressure of 115 MPa and temperatures from room to 350 °C, as well as fracture toughness tests (delayed fracture tests) by a constant displacement method.

4 International comparison of fracture toughness testing methods

4.1 Consideration of fracture toughness evaluation method for finite life design

In the vessels and pipes to which stress is repeatedly applied due to the cycle of filling and releasing of gaseous hydrogen, in order to attempt finite life design based on the leak-before-break (LBB) thinking and supposition of fracture critical crack length, it is important to calculate the fracture toughness value of the materials in high-pressure gaseous hydrogen environment. As mentioned earlier, in the ASME Article KD-10 in Division 3, which is one of the testing standards for high-pressure gas vessel materials, the execution of fracture toughness tests by the constant displacement method or constant load method in gaseous hydrogen are required.[11]

However, the Sandia National Laboratories recently conducted research on ferrite steel with relatively low

Fig. 2 PC control system installed in the control room

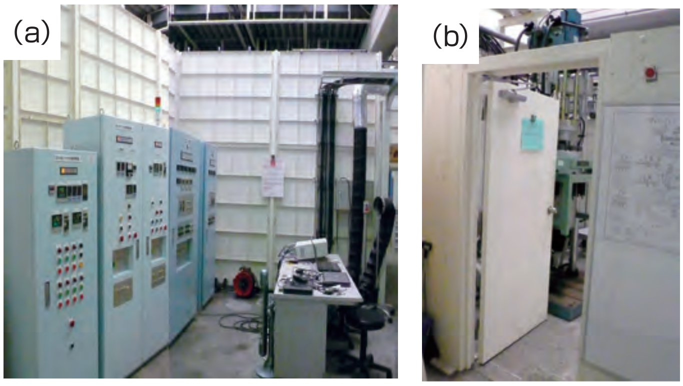

Fig. 3 (a) Fireproof wall and control panel installed in non-explosion-proof area and (b) protective wall isolating the individual testing devices

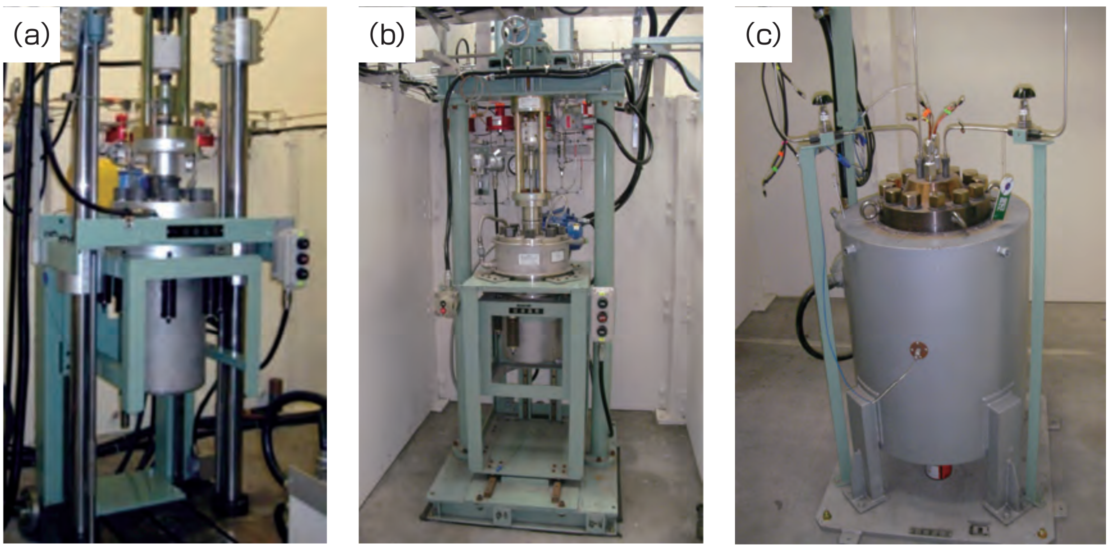

Fig. 4 (a) Fatigue testing device: normal operation pressure of 115 MPa, room temperature. (b) Slow strain rate tensile testing device: normal operation pressure of 70 MPa, room temperature. (c) Exposure testing chamber: normal operation pressure of 115 MPa, room temperature ~ 350 °C

Table 1. Material properties and compositions of SCM 435 and SA-372 Grade J

	Yield stress	Tensile strength (MPa)	C	Cr	Mo	Mn	Si	P	S	Fe (mass%)
SCM 435	700	828	0.38	1.1	0.23	0.79	0.22	0.006	0.004	Bal
SA-372 Grade J	762	889	0.49	0.99	0.18	0.93	0.28	0.008	0.004	Bal

strength and high toughness with tensile strength of 950 MPa or less that is expected to be used in high-pressure gaseous hydrogen equipment. As a result of comparing the fracture toughness value calculated by the constant displacement method (K_{THa}, crack-arrest threshold) and the fracture toughness value calculated by the rising displacement method (K_{JH}, crack-initiation threshold) in 103 MPa high-pressure gaseous hydrogen atmosphere, the K_{JH} value was lower than the K_{THa} value, and as a fracture resistance value, KJH was shown to be a conservative value.[18][19] The constant displacement method is a testing method in accordance with ASTM E1681, where the bolt-load compact specimen (Fig. 5(a)) ,which is pre-cracked in advance, is used, the crack opening displacement is held constant by tightening the bolt, the load is applied to the tip of the crack, and the load is maintained until the crack grows and stops under certain conditions.[15] This is also called the delayed fracture test. At the Sandia National Laboratories, the fracture toughness value was calculated from the length of the crack that finally stopped after tightening the bolt in inert gas conditions and then maintaining the specimen to a maximum of 3,800 hours in high-pressure gaseous hydrogen. Since the fracture toughness value of the crack arrest is calculated, it can be considered as a crack growth stop test. The rising displacement method is a material test where the load is applied continuously to the pre-cracked compact specimen (Fig. 5(b)) in the high-pressure gaseous hydrogen atmosphere, so the crack opening displacement will increase, and this method is in accordance with ASTM E1820.[13] At the Sandia National Laboratories, the crack opening displacement was measured with the linear variable differential transformer (LVDT) and the crack length was measured by the direct-current potential difference (DCPD) method, and the fracture toughness value of the crack initiation under the continuously rising displacement is calculated from the load, opening displacement, and crack length. Therefore, this can be considered the crack growth starting test.

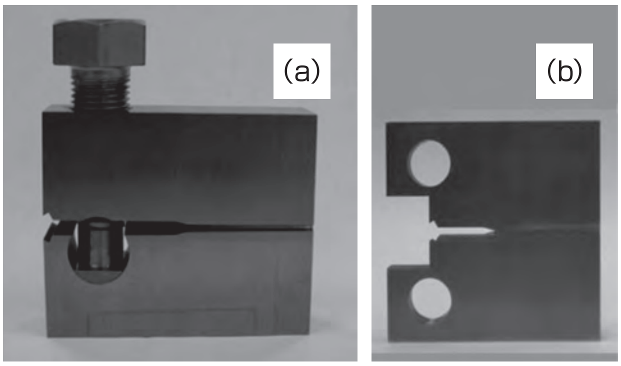

Fig. 5 (a) Bolt-loaded compact specimen and (b) compact specimen

4.2 Fracture toughness evaluation using the unloading elastic compliance method

In our research group, the rising displacement test was conducted using the unloading elastic compliance method that is another crack length measurement in accordance with ASTM E1820, and we attempted direct comparison with the measurement data obtained at the Sandia National Laboratories.[20] The rising displacement test using the unloading elastic compliance method is a method of calculating the fracture toughness value of the crack initiation, as the crack opening displacement of the pre-cracked compact specimen (Fig. 5(b)) is increased at a certain rate, part of the load is removed at arbitral crack opening displacement, and then the crack length from the relationship of the crack opening displacement and load at that moment is calculated. For the experiment, SCM435 (Japan standard) and SA-372 Grade J (American standard; supplied by Sandia National Laboratories) were used. These are standard materials of the Cr-Mo alloy steel and are expected to reduce the cost of high-pressure gaseous hydrogen equipment in the future. Table 1 shows the material properties and composition of SCM435 and SA372 Grade J. The outline of the testing conditions by the unloading elastic compliance method is presented in Reference [20].

4.3 Direct comparison of Japanese and American data for fracture toughness evaluation

Figure 6 shows the load vs. crack opening displacement (*P-COD*) curve calculated using the unloading compliance method in 115 MPa gaseous hydrogen for SCM435. The relationship between the J integral value and crack growth length (R curve) was calculated, and the fracture toughness value (J_{IC}) of crack-initiation was determined. Using the relation equation between J and K described in ASTM E1820 shown below, the stress intensity factor ($K_{JIC,H}$) of the minimum limit of crack-initiation was derived. Here, Young's modulus was E = 206 GPa and Poisson ratio was ν = 0.3.

$$K_F = \sqrt{\frac{EJ_F}{1-\nu^2}}$$

The fracture toughness value of SCM435 obtained by this

Table 2. Fracture toughness of SCM435 and SA-372 Grade J[20]

	Yield stress σ_{ys} (MPa)	115 MPa in H_2 $K_{JIC,H}$ (MPa $m^{1/2}$)
SCM 435	700	63
SA-372 Grade J	762	66 ($K_{Q,H}$)

experiment was $K_{JIC,H}$ = 63 MPa $m^{1/2}$ in 115 MPa gaseous hydrogen. The fracture toughness value of SA-372 Grade J was $K_{Q,H}$ = 66 MPa $m^{1/2}$ in 115 MPa gaseous hydrogen.[20] The fracture toughness values of SCM435 and SA-372 Grade J in 115 MPa gaseous hydrogen are shown in Table 2.

Figure 7 shows the relationship between the material strength and fracture toughness values in high-pressure gaseous hydrogen (103 MPa) obtained by the constant displacement method (K_{THa}) and the continuously rising displacement method (K_{JH}) at the Sandia National Laboratories,[18] and the fracture toughness value ($K_{JIC,H}$) in high-pressure gaseous hydrogen (115 MPa) obtained by the rising displacement method using the unloading elastic compliance method. It can be seen that the fracture toughness value $K_{JIC,H}$ obtained by the unloading elastic compliance method, one of the rising displacement methods, showed almost equivalent values as K_{JH} obtained by the continuously rising displacement method at the Sandia National Laboratories, and was lower than K_{THa} obtained by the constant displacement method.

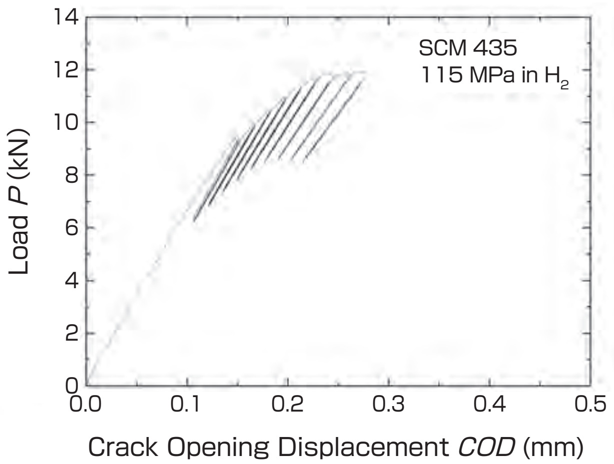

Fig. 6 *P-COD* curve of SCM435 by the unloading elastic compliance method

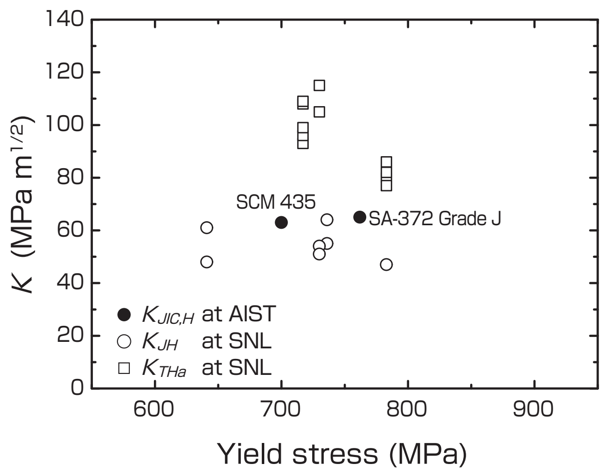

Fig. 7 Relationship between yield stress and fracture toughness of Cr-Mo low-alloy steel[18][20]

This indicates that although the detailed measurement conditions such as the displacement rate, load-unloading process, hydrogen purity, and pre-crack formations, as well as the form of the testing device and the measurement know-how such as hydrogen replacement procedures may be different, there is no major difference in the fracture toughness evaluation results by the rising displacement method, and that this method possesses universality as an evaluation method. Also, since the K_{JH} and $K_{JIC,H}$ calculated by the rising displacement method were lower than the K_{THa} calculated by the constant displacement method, the fracture toughness value obtained by the rising displacement method is a conservative value, and it can be considered an effective method for quantitative evaluation of the metallic materials in high-pressure gaseous hydrogen conditions.

5 Summary

To establish a testing method of the hydrogen effect on the metallic materials used in high-pressure gaseous hydrogen, our research group developed a set of material testing devices that allows tensile tests, fracture toughness tests, and delayed fracture tests in high-pressure gaseous hydrogen up to normal operation pressure of 115 MPa. Using such testing devices we gathered data for materials in high-pressure gaseous hydrogen for general-use metallic materials to increase the choice of materials that can be used for the vessels and pipes of high-pressure gaseous hydrogen equipment. Particularly, with the cooperation of the Sandia National Laboratories, we conducted international comparison of the fracture toughness testing method for the standard material of Japan and USA for Cr-Mo low alloy steel that is expected to contribute to reducing the cost of high-pressure gaseous hydrogen equipment. As a result, it became clear that the fracture toughness test using the rising displacement method in high-pressure gaseous hydrogen was effective as a material testing method that allows quantitative evaluation of hydrogen embrittlement of general-use metallic materials. In the future, by accumulating data of the effects of various testing conditions, particularly of hydrogen gas pressure and displacement rate, we can review the effectiveness of the fracture toughness test by the rising displacement method in high-pressure gaseous hydrogen. We also plan to consider whether we can contribute to the international standardization of the testing method for materials to be used in high-pressure gas equipment, through collaboration with related research institutes including the Sandia National Laboratories.

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Discussions with Reviewers

1 Overall

Question & Comment (Mamoru Nakamura, AIST)

The establishment of a material evaluation system to guarantee the reliability of metallic materials that can be used in high-pressure hydrogen conditions and the establishment of its international standard are essential for the construction of hydrogen storage and a supply system to enable practical use of FCVs. This paper is very interesting as it describes the results of joint research with an American national institute for an evaluation method of the material properties, particularly, fracture toughness.

Question & Comment (Hiroaki Hatori, AIST)

The history of development of the material evaluation method for high-pressure hydrogen storage vessels that are essential for realizing FCVs is interesting in terms of synthesiology, and this is a technological development field that is clearly related to society. The international standardization strategy that is currently in progress will be a key to the further diffusion of FCVs, and I think there is great significance in conducting a synthesiological consideration with an eye on future efforts.

2 Current situation of the research pertaining to standardization in Japan and overseas, and organization of the descriptions of international standardization strategies

Question & Comment (Mamoru Nakamura)

The international standardization of the evaluation method for fracture toughness of metallic materials that can be used under hydrogen pressure is still in the phase of comparing three methods, and there is no indication of the direction or strategy for standardization. It will be easier for readers of this paper to understand, if you first describe the overall picture and the current situation of property evaluation under hydrogen pressure in Japan and overseas, then explain the positioning of fracture toughness that is discussed here, and then describe the result of the international joint research.

Specifically, the relationships among some of the ASME standards described in “2.2 Use standard of the materials used in high-pressure gaseous hydrogen equipment” and “4.1 Consideration of the fracture toughness evaluation method for finite life design,” the Japanese standard (is it in a preparatory stage?), and the international standard are unclear. I think you should organize and describe them carefully.

Answer (Takashi Iijima)

For the standardization in Japan, USA, and Europe, I organized the situations of the FCV on-board vessel and the hydrogen filling station vessel in chapter 2, and described the strategy for contributing toward the international standardization of material testing methods. The situation of testing equipment for high-pressure gaseous hydrogen condition in the world was overviewed in chapter 3, and we explained our efforts in developing the equipment. Also, for fracture toughness value, as mentioned in chapter 2, various evaluation methods are being suggested and searched. We described the result of international joint research with the Sandia National Laboratories for the fracture toughness evaluation method by the constant displacement method and the rising displacement method in chapter 4.

Question & Comment (Hiroaki Hatori)

Comment 1: For chapter 3, I think it is necessary to strengthen the synthetic consideration of the process (scenario, hypothesis) to realize the research goal for the material evaluation method that you succeeded in developing, as well as the selection and integration of the elemental technologies. Along with the efforts toward future international standardization in chapter 4, I think the readers will understand better if you add a figure that summarizes the scenario and strategy of R&D as a model. For the details of technology in chapter 4, the explanation should be simplified and some parts should be left to the reference material, and the discussion should focus on the scenario and strategy.

Comment 2: Pertaining to international standardization, while the technological comparison with USA is clearly presented in this paper, there is no description of the situation in Europe. Doesn't the trend in Europe have effect on the international standardization in this field? Including the perspective of social demand of this technological field, I think the international standardization strategy will become clearer by considering and comparing Japan, USA, and Europe.

Answer (Takashi Iijima)

As you indicated in Comment 2, there was no description of the trend in Europe including that of ISO. Therefore, we described the trend on the standardization in Japan, USA, and Europe for on-board vessels and hydrogen station vessels in chapter 2. Then we discussed the R&D scenario toward international standardization and added the schematic diagram (Fig. 1) of the development model. Since we are not in the position to directly promote standardization, we used the expressions "approach" or "contribute" to the international standardization of the material testing method. Also, in terms of capturing the efforts in Japan, USA, and Europe, we added the global situations of the testing equipment for high-pressure gaseous hydrogen in chapter 3.

Following Comment 1, we simplified the description on the technological details in chapter 4, and the data for SA-372 Grade J are referred to the paper published in July 2014.

3 Comparison of the fracture toughness value in gaseous hydrogen evaluated by different methods

Question & Comment (Mamoru Nakamura)

In the "direct comparison of Japanese and USA fracture toughness evaluation data" in this paper, the crack growth behaviors in gaseous hydrogen for SA-372 Grade J and SCM435 are quite different, and therefore, you describe that different evaluation methods were used for SA-372 Grade J, but the fracture toughness values obtained were almost the same. I felt it was rather unnatural that the fracture toughness values were almost the same, despite the greatly different crack growth behaviors. Do you mean to say that the obtained evaluation values of the fracture toughness were quite different by different evaluation methods, but in this case, you obtained the same values using different methods by "coincidence"?

Answer (Takashi Iijima)

As you can see from the experimental data, the fracture toughness values of SA-372 Grade J and SCM435 in 115 MPa gaseous hydrogen became very low, and although the detailed mechanisms are unknown, it is assumed that the behavior is somewhere between linear elastic fracture and elastic-plastic fracture. For this point, I think we have to do further, careful experiments. The ASTM E1820 describes the method for evaluating the fracture toughness of samples that show unstable crack extension and stable crack extension, where the fracture toughness values are derived using the J-R curve calculated from the unloading elastic compliance method. At the same time, in the case where the unstable crack extension is mainly seen, the method for calculating the fracture toughness value from the P-COD curve without unloading is mentioned in ASTM E1820 Annex A5. Therefore, the fracture toughness values of SA-372 Grade J and SCM435 turned out to be the same values not by "coincidence," but we determined that they are comparable values obtained in the material test based on ASTM E1820. The details of the evaluation of fracture toughness value of SA-372 Grade J are described in Reference [20].

Research on social benefits resulting from NEDO projects

— Study of the top 70 NEDO Inside Products —

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“NEDO Inside Products” are defined as products or processes using core technologies resulting from NEDO’s research and development projects. In this study, we analyzed and estimated the creation, and CO_2 emission reduction. Our analysis revealed that NEDO Inside Products sales in 2010 amounted to 4.08 trillion yen while projected sales from 2011 to 2020 are estimated to increase to 69.1 trillion yen. Job creation estimates between 2011 and 2020 range from 109 to 185 thousand people per year, and CO_2 emission can be reduced by 53 million tons per year. Furthermore, in-depth and systematic analysis showed that many NEDO Inside Products developed after 1999, including components and manufacturing technologies, are being utilized in the latest household electric appliances, computers, and automotive products. Lastly, we found that NEDO projects have significantly contributed to the establishment of various types of recycling systems: Another example of the extensive benefit to the society brought about by NEDO’s research and development projects.

Keywords **:** Follow-up monitoring, national project, development result, impact evaluation, gross social benefit

1 Introduction

There has been a number of research conducted on the economic evaluation of government-funded R&D projects in Japan, but they tend to be limited to estimates and sensitivity analyses under limited conditions: It is not simple to identify the factors necessary for the evaluation of cost-effectiveness of R&D projects (i.e., the contribution rate of project outcomes, basic production unit, etc.). Shiotani *et al*. carried out a return on investment analysis of nuclear power generation, taking the following effects into account: generation costs reduction, environmental load reduction, risk to life reduction, energy security improvement, resource depletion control, and fuel import reduction.[1] Yanagisawa *et al*. estimated the cost-effectiveness of the products utilizing radiation on various grounds, considering the factors including device costs, radiation dosage, and the contribution rate to added product value.[2] Kimura *et al*. qualitatively evaluated the impact of energy-saving effects of thermal energy related projects as an economic evaluation of national projects.[3] Besides, there are several accounts on different types of economic evaluation and benefit of public policies;[4]-[10] however, all these reports lack details on parameter settings and variables related to the influence of market conditions as well as the contribution rate of project outcomes to practical applications, selling price, and changes in sales volume. Nonetheless, they seem to simply focus on identifying certain trends. In contrast, G. B. Jordan *et al*. of the US Department of Energy compiled a detailed guideline of benefit-cost analysis comprising economic benefits, energy benefits, environmental benefits, energy security benefits, and knowledge benefits for the development of renewable energy and energy saving technologies through US public R&D projects. They introduced a series of case studies to demonstrate the analyses using time adjustment factors and sensitivity analysis.[11]

Since the projects conducted by New Energy and Industrial Technology Development Organization (NEDO) are funded by taxes, they must be accountable to taxpayers by showing how effectively the investment in development are being returned to the public. To meet such demand, NEDO initiated the selection of “NEDO Inside Products” – the products or the processes in which any NEDO project outcome is being used as their core technology (i.e., innovative technologies that are essential to practical applications and cannot be emulated by others; including those enabling the emergence of new functionality, newly integrated technologies, innovative manufacturing and processing technologies, highly reliable characterization technologies) in FY 2009. Assuming the contribution rate of the project outcomes against the products’ sales being 100 %, these products’ economic impacts such as net sales have been estimated.[12]-[18]

In this research, we conducted survey, and made evaluations and analyses to identify the social impact of “Top 70 NEDO Inside Products”: The net sales, induced economic effects, technological ripple effects, and gross social benefit (e.g., CO_2 reduction, energy saving, and job creation) of the project outcomes that have been remarkable success and eventually generated strong sales through the fundamental and core projects as well as the projects aimed at practical application

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(Fig. 1). Note that we are well aware that the companies require over ten times the amount NEDO invest in an R&D project for the practical application and commercialization of the project outcome; we were unable to take this into account because the information regarding the companies' actual expense is not always available. Yet, the method for comprehensive impact we present in this research will help clarify the direction of future R&Ds by giving ballpark figures of the R&D project outcomes in which NEDO invested, and we believe that this study should be of great significance to academic, socioeconomic, and public policy research.

2 Selection of NEDO Inside Product candidates

NEDO's R&D projects started in FY 1980; 100~200 projects or more are conducted each year, and over 3 trillion yen of development fund have been invested so far. At first, it was exceptionally painstaking to find out how many of NEDO project outcomes had actually been put to practical use and directly contributing to the products' sales. Hence, we decided to extract the products and the processes that were considered to be the products of NEDO project outcomes from NEDO's 20-year, and 30-year achievement reports. The preliminary selection of candidate products was subsequently made by perusing past press releases, corporate web-sites, journal articles, NEDO accomplishment reports, and follow-up surveys. For the secondary selection, questionnaire surveys and interviews to the participants and others involved in the projects were carried out. A group of external experts examined the degree of contribution to practical application and the sales status of the project outcomes, and finally, prospective "NEDO Inside Product" candidates were selected. The selection criteria are explained below.

2.1 Selection method for "NEDO Inside Product" candidates

In selecting "NEDO Inside Product" candidates, the products with most recent sales figures being substantial, and those with marginal sales figures but bringing about extensive gross social benefit are extracted referring to the publications including industrial reports, NEDO achievement reports,

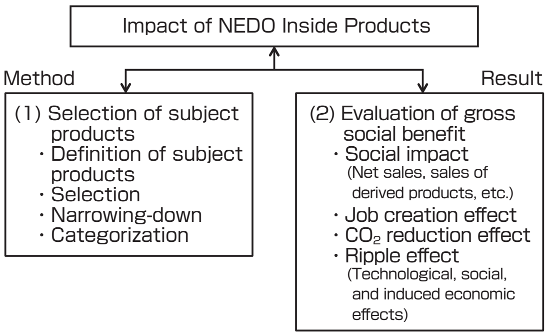


Fig. 1 Structure of the selection method and gross social benefits of the NEDO Inside Products

and corporate reports; which is followed by questionnaire surveys (on current and future sales and gross social benefit) and interviews to the companies participated in NEDO projects at the time of development. The sales figures and gross social benefit listed in the corporate survey are carefully reviewed through the interviews to industrial associations or at a committee of experts. In cases where the answer to questionnaire does not provide sufficient amount of information, we perform supplementary calculations using the data published by industrial associations and private research institutions. These results are adopted after consulting with the participating companies and industrial associations. This specific survey method and the selection method of 70 products are explained as follows.

2.2 Scope of NEDO Inside Products

NEDO projects are generally designed to commercialize basic research findings from universities or public research institutes which have been major academic impact. In an effort to tackle complex social issues which cannot be resolved by a single group or company for their risky nature, particularly in case of emergency, NEDO also manages technology development projects in collaboration with industry and academia with practical application in mind. For these reasons, many of NEDO Inside Products are the products of core technologies evolved from NEDO projects, having achieved remarkably high development targets and utilized their realization/commercialization know-how. The core technologies developed in NEDO projects can be defined as the technologies developed via industry-academia-government collaboration, and innovative technologies essential for practical applications. Specifically, they include the technologies which enable high conversion efficiency, high-speed separation, high-speed reaction, ultra-long life span, ultra-lightweight, high durability, surface control, energy savings, high-efficiency combustion control, high-reliability evaluation, and the emergence of reciprocal functions. The reason for setting the contribution rate of the project outcomes 100 % is that almost all the eligible products: (1) were developed through multiple mid-to long term projects; (2) addressed topics the companies would seldom consider and had difficulty obtaining funding for the purpose; (3) were in need for support from external experts, which was difficult to obtain in corporate research, (4) would never be put to practical application if it were not for the NEDO project outcome; (5) must be realized as corporate obligation owing to the funding support from the tax during the critical phase of development; (6) may differ in contribution rate and the companies are unable to grasp; and (7) were realized following the completion of the project and their subsequent commercialization was more likely due to the know-how and the companies' manufacturing effort rather than the funded research opportunity. As all the products share at least two of the points above, the calculations are performed with 100 % contribution rate on the assumption that practical applications could not have been achieved without NEDO projects. Nevertheless, the sales information regarding the products of NEDO projects is only a fragment even at this point. Having selected the products, NEDO Inside Products are first categorized as follows: (i) New products which led to the establishment of new business divisions within the participating companies with most recent annual sales of 100 billion yen or above; (ii) new products with most recent sales between 10 billion and 100 billion yen; and (iii) the products with meager sales but with great potential for gross social benefit. The specific procedures of categorization are explained below.

2.3 Definition of NEDO Inside Products

The candidates of NEDO Inside Products are defined as follows:

1) The products are included if their core technologies were developed in the course of NEDO project and contributed greatly to realization and commercialization of the products, even if the companies participated in other R&D project(s) before or after the NEDO project.
2) The products are considered if the technologies developed by the participating universities and public research institutes were transferred to their co-participants for realization and commercialization.
3) The products are NOT considered if they were the outcomes of NEDO's funding aid or grant projects and, "International Demonstrations/Joint Projects" whose purpose is to introduce and disseminate the products.
4) The products are NOT considered if they were the outcomes of research-only projects.

2.4 Points of corporate questionnaires

The following is the list of questions to the companies that participated in NEDO projects: (1) Product name; (2) project name, project period, and allocated budget; (3) the outline of project outcome(s) and in which part of the NEDO Inside Product the project outcome is used; (4) the names of the co-participants in charge of sales; (5) the product's cumulative sales figures for the past five years for each participating company, or the sales data of the overall industry;[19]-[23] (6) most recent sales figures as of 2010, and the sales forecasts for 2011-2020; (7) the evidence used for estimating items (5) and (6) (e.g., published data and journal articles); (8) gross social benefit (e.g., the amount of CO_2 reduced, energy efficiency, and job creation); and (9) patents and journal articles, know-how, the potential ripple effect to other products, awards, and other notable information. In cases where sufficient information could be obtained from the questionnaire, the following data are utilized: (10) Data published by industrial associations; and (11) data published by public bodies and private research companies. (12) In addition, any other missing data are complemented by our calculations based on different sales figures and gross social benefit, and we use these data after obtaining approval from the participants.[12]-[16]

2.5 Narrowing down the NEDO Inside Product candidates

The narrowing-down of NEDO Inside Products involved a four-step process as shown in Fig. 2: Data collection/extraction, preliminary narrowing-down, secondary narrowing-down, and verification. The following five means were taken in data collection and extraction: (1) Follow-up questionnaires, interviews, etc.; (2) patent specifications, literature, industry journals, NEDO related documents, etc.; (3) press releases, investor relations data, press reports, etc.; (4) reports from project participants; and (5) product reviews from key persons of the industry. All these means had both advantages and disadvantages, and it was practically impossible for NEDO Inside Products to form a population based on a single information source.[24] For (1) to (4), while it was more likely that we find the details on practical application, the current market trends remained unclear in most cases. It was often the case that available information could only be traced back to the time of market release: The longer the time after the development and the more the market being niche, the slimmer the chance of obtaining the figures. On the other hand, (5) was an efficient way to collect the information on the products' market release, but the information on their relevance to specific NEDO projects at the time of development were not available in many cases. As far as the relevance to NEDO projects are concerned, the information could be verified referring to NEDO database and other sources. However, sufficient amount of information was not available for many of the projects dating back to the 1980s. As a consequence, NEDO Inside Product candidates were selected by combining the information from (1) to (5).[12]-[16] After conducting the preliminary narrowing-down of candidates using (1) to (3), the secondary narrowing-down was carried out using the questionnaires and the interviews ((4) and (5)), and the information was confirmed by a committee of external experts. This was how we selected Top 70 NEDO Inside Products.

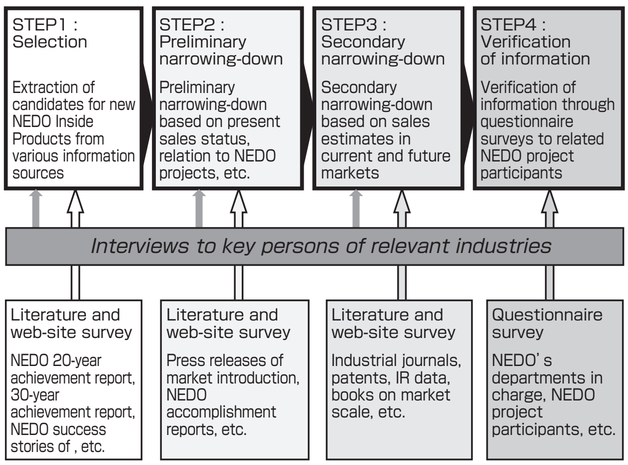


Fig. 2 Selection scheme of NEDO Inside Products

Table 1. Categorization of Top 70 NEDO Inside Products

Index	Aim	Outline	Effect	Specific NEDO Inside Products (in order of products and parts)
1.【Pioneers of new market】	Take lead in creating new markets!	Create new markets and provide mid-to long-term support for innovative R&D that is too risky to be undertaken by a single private company.	· Market creation · Sales · Employment	[12 products] Solar power generation, Blu-ray Disc related technology, residential heat pump hot water supply systems, wind power generation, residential fuel cells, robots (industrial, motion assistant, etc.), clean diesel vehicles, natural gas vehicles, superconducting wire rods, mobile batteries, high-output secondary batteries
2.【Boosters of Japanese industry's international competitiveness】	Take advantage in industrial competitiveness through world-leading technologies!	Strengthen Japan's industrial competitiveness by accelerating the technological development in highly competitive areas.	· International strategies · Sales · Presence	[15 products] High-performance stoker furnaces, excimer laser semiconductor devices, large catalytic chemical vapor deposition (CAT-CVD) machines, turbo refrigerators, semiconductor evaluation technology devices, energy sharing technology of plant community by pinch technology, high-performance LED materials, hard disk drives, nonvolatile semiconductor memories, stacked dynamic random access memories (DRAM), power semiconductor materials, storage batteries for space use, non-stage transmission for automobiles, polarizing film for liquid crystal displays (LCD), electric double-layer capacitors, electronic chip laminated films
3.【Technological stimuli to a wide range of fields】	Support innovation in wide-ranging fields of technology through core technology development!	Promote technological innovations in the development of materials and core technologies that may cost too much time and money for private companies to undertake.	· Industrial infrastructure · Social infrastructure · Academic ripple effects	[8 products] Industrial medium-scale power generators, casting simulation, high-function high-reliability servers, adhesive for resin parts, metal glass, photocatalysts, fine ceramics, micro electro mechanical systems (MEMS)
4.【Contributor to solving environment and energy issues】	Contribute to solving environment and energy issues through highly reliable technologies!	Contribute to creating an environment-conscious society through new technological development addressing serious environmental and energy issues (energy efficiency, new energy, reduction of hazardous substances, etc.)	· Regulatory compliance · Global environment · Energy efficiency · Comfortable and convenient	[16 products] Geothermal power generation, waste power generation, high-performance industrial furnace, low-emission hybrid diesel car, energy-saving construction machines, industrial heat pump, standby power digital copier, thermal storage transportation, next-generation adsorption refrigerator, cold heat storage system, submerged combustion method for chlorofluorocarbon decomposition, low fuel consumption tire, waste solid fuel, sulfur-free light oil, eco-cement, high-performance high-function vacuum insulating materials
5.【Agent for realizing safe, secure, and comfortable living】	Realize safe, secure, and comfortable lives through diverse technological repertoires.	Support safe, secure, and comfortable living of the people in Japan and the rest of the world by developing new technologies and making best of them.	· Safe and secure · Social contribution · Comfort and convenience	[19 products] Nano-ion products, 4D radiographic computed tomography (CT) diagnostic systems, microscopes for biological research, confocal laser microscopes, cryoelectron microscopes, short-leg braces, energy-saving large displays, gasoline vapor recovery devices, non volatile organic compounds (VOC) coating systems, rapid sensitive analyzing systems for oligosaccharides, body fat scales, twin-arm construction machines, membrane bioreactor (MBR) units, high-efficiency anaerobic biological treatment [such as up-flow anaerobic sludge blanket (UASB)], exhaust gas post-treatment systems, bio-remediation, insulating materials for electronic materials, cleaning gas for semiconductor manufacturing, asbestos substitute gaskets

Having examined the latest sales figures and noticed some similar products (robots and power semiconductors) of Top 50 NEDO Inside Products listed in our previous paper being integrated,[24] 50 products were reorganized into 47 products. Hence, we added 23 new products to the previous list for this research. To select new candidates, the involvement of NEDO projects was once again examined with documents such as project accomplishment reports or NEDO database.[25] Regarding the products' current market status, we collected the articles reporting the product deployment by searching press releases of the companies involved and the journals of relevant fields. We compared the products' cumulative sales for the past five years, most recent sales figures, future sales forecasts, and potential benefits to the society, and 154 products were extracted in the preliminary narrowing-down. In the secondary narrowing-down, the number of products was reduced to 72 after quantitative evaluations, interviews, and the discussion with the committee of external experts. Ultimately, 70 best-selling products were selected.

2.6 Categorization of NEDO Inside Products

The products were initially categorized in accordance with the project's basic plan and characteristics: That is, whether the product (1) is a pioneer of new market; (2) is competitive in international markets; (3) pushes the boundaries of the technology, and (4) addresses any social issue.[12]-[16] Half of these products fell under Category (4), in line with NEDO's mission. After in-depth analyses and discussions, however, we found out that the products (4) should be best categorized under social demands or everyday life issues. As it made the characteristics of products more evident, the products under (4) were re-grouped into "resources/ energy solutions" and "safety/security/comfort providers." Consequently, NEDO Inside Products were re-categorized into following five categories: (1) pioneers of new market: 12 products; (2) boosters of Japanese industry's international competitiveness: 15 products; (3) technological stimuli to a wide range of fields: 8 products; (4) solutions to resources and energy issues: 16 products; and (5) providers of safety, security, and comfort: 19 products (Table 1). As can be seen from this categorization, many of the technologies in these products and processes were developed with intent to address social issues (e.g., CO_2 reduction, energy saving, new energy, environment, reduction of hazardous substances, exhaust gas, quality of living, waste, and medical care). Despite their sales figures being insignificant, it can be said that a considerable portion of NEDO Inside Products make substantial contribution to the society by offering such technologies that deals with changes in regulations, and environmental problems, and support medical diagnosis, and medical/nursing-care.

2.7 Sales forecast of NEDO Inside Products

The sales figures of NEDO Inside Products fluctuate depending on years after market launch. In most cases, the product sales remains subtle for several years, shows a gradual increase, and becomes saturated after reaching a level of maturity. It eventually declines after a period of time. Figure 3(A) shows the life-cycle curve of the sales of a NEDO Inside Product. NEDO Inside Products are diverse in lifespan: From a solar power generation device with almost 30-year lifespan to electronic components that only last for few years. Therefore, it was crucial to adopt an optimal life-cycle curve by exploring a suitable timescale to define the characteristics of the product from different perspectives. To evaluate the sales impact of NEDO Inside Products, three types of figures, i.e., cumulative sales for the past five years, most recent sales, and sales forecasts, were estimated.

The sales figures could shift depending on the product as shown in (B), (C), and (D) of Fig. 3. Figure 3(B) demonstrates the products whose sales growth rate would continue to surpass the previous figures for a given period of time. This is based on the sales growth rate up to 2011 assuming that it should continue until 2020. In Figure 3(C), the curve denotes the products the industry and the government expect a certain level of growth each year. As for the products whose future sales forecasts were provided by the companies in reply to the questionnaire, we performed the calculation assuming that the sales would grow until 2020 at the growth rate from 2011 to a given time in future. Represented in Figure 3(D) are the products with short lifespan, or whose future sales are somewhat unpredictable. These figures are projected on the condition that there would be no growth after 2011 and therefore the figures should remain the same.[13]-[18][24] The products showing the curves (E), (X), and (Z) are those that are discontinued, have had negligible sales volumes if any, and had sales record in the past but currently almost none being sold respectively: We excluded these products or processes from the list of NEDO Inside Products candidates.

2.8 Success factors of NEDO Inside Products

Listed below are the major factors we identified from the questionnaires and the interviews, which led NEDO Inside Products to success: (1) The participants gained significantly larger amount of data, compared to their usual research situation; (2) the companies made use of a mechanism which brought about improved reliability and problem-solving strategies, and development, modification, and extension(scale-up) of research policies through joint research opportunity with universities; (3) the participants were reasonably confident with the technology from the start for its practical feasibility and commercial viability; (4) the participants kept the idea for long until the project launch; (5) the participants had already had unrivaled know-how and capabilities, which saw further improvement and were exploited in the course of the project; (6) the participants were skeptical about the market information and proactive in exchanging information within the team; and (7) the participants carried out prototype demonstrations and repeatedly verified and modified the technology to the point where it was elaborate enough to ensure its proximity to commercialization. We presume that there should be some other factor(s) involved, which need follow-up surveys to be clarified.

3 Impact evaluation of NEDO Inside Products

3.1 Characteristics of NEDO Inside Products

Groups of top 70 NEDO Inside Products, including solar power generation, wind power generation, gas turbines, residential heat pump hot water supply system, micro-electro-mechanical systems (MEMS), and clean vehicles, have recently recorded above100 billion yen sales showing an upward trend. In contrast, some of the products with recent sales between 10 billion yen and 100 billion yen, waste power generation and residential fuel cells, for example, did not show significant sales growth as expected. This implies that they have already completed their introductory stage, or the production has been too costly. The sales of

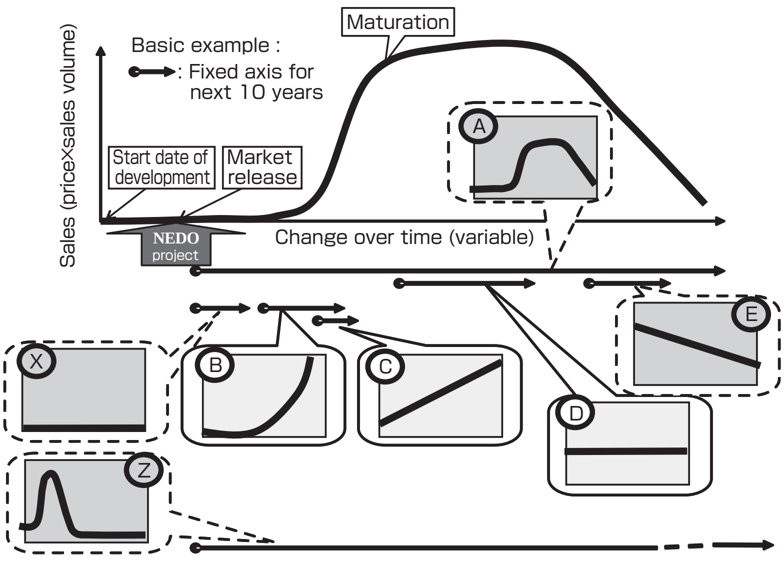


Fig. 3 Life cycle of sales of NEDO Inside Products

Table 2. Sales performance of Top 70 NEDO Inside Products and their sales forecast

(Unit: 100 million yen)	NEDO budget outlay		Sales performance		Future sales forecast (cumulative for 2011～2020)
	Average R&D cost per fiscal year	Cumulative R&D cost	Most recent sales per year (2010)	Cumulative sales for past five years	
Solar power generation	58	1,735	15,800	46,400	219,400
Wind power generation	4	85	2,600	7,300	41,100
Gas turbines	35	532	2,600	11,900	40,100
Residential HP hot water supply systems	12	154	3,400	16,000	38,500
Residential fuel cells	49	880	120	300	11,600
Blue-ray products	12	61	5,100	14,500	51,500
Semiconductor products	35	280	500	1,700	65,000
MEMS	18	250	400	1,200	6,700
Fine ceramics	5	123	100	110	10,500
High-performance industrial furnaces	11	80	20	400	1,100
Waste power generation	10	100	200	1,500	2,500
Water treatment (membrane separation, etc.)	19	118	400	1,300	6,000
Bio microscopes	20	98	100	90	1,200
Others	—	1,913	9,460	40,100	196,000
Total	—	6,409	40,800	142,800	691,200

Pioneers of new market | Boosters of Japanese industry's international competitiveness | Technological stimuli to a wide range of fields | Contributor to solving environment and energy issues | Agent for realizing safe, secure, and comfortable living

"Others" includes: Robots, large displays, waste power generation, vacuum insulators, chlorofluorocarbon decomposition, HD drives, semiconductor manufacturing technology, CNG vehicles, eco-cement, MEMS, body fat scales, semiconductor bonding technology, nano-ion products, x-ray CT diagnostic equipment, energy-saving construction machines, insulators for electronic materials, industrial heat pumps, standby power digital copiers , ice thermal storage systems, sulfur-free light oil, rapid sensitive analyzing systems for oligosaccharides, high-performance high-reliability servers, superconducting materials, stoker furnaces, photocatalysts, etc.

products intended for large-scale manufacturing facilities are particularly susceptible to general economic trends. Once these products are introduced, only the operational cost could be added to the sales figures; which is possibly a trend specific to the sector. In general, the products with large sales figures see a decline in unit price due to commoditization; however, their sales could be secured or even increased to certain degree by increasing sales volumes in/outside the country. We also find many of the products having marginal sales figures but contributed greatly to gross social benefit or industrial competitiveness (e.g., a significant CO_2 reduction and substantial international market share as a core product) under the categories addressing social issues (e.g., environmental issues, safety and security, and quality of living).

3.2 Evaluation of NEDO Inside Products' net sales

Table 2 shows estimated NEDO's investment, cumulative sales for the past five years, most recent sales, and sales forecasts for the next ten years of Top 70 NEDO Inside Products. In respect to these products' cumulative R&D expense, 640.9 billion yen, the most recent sales can be estimated 4.08 trillion yen; the cumulative sales for the last five years 14.28 trillion yen; and the 2011-2020 sales forecast 69.1 trillion yen. Because it is often problematic to disclose a product's sales recorded by a single company, the figures were aggregated when several companies deal in the same NEDO Inside Product. The proprietary products are placed in "Others" category.[19]

Since NEDO projects are funded by taxes, we also estimated future tax revenue and potential job opportunities Top 70 NEDO Inside Products would offer. To this date, 640.9 billion yen was invested in the projects associated with Top 70 NEDO Inside Products. The total amount of investment over the next ten years is, in turn, expected to be 69.1 trillion yen, and according to Eq. (1) below, the expected tax revenue will be 1.291 trillion yen. It is now clear that the tax revenue from the products' sales for the next ten years is likely to exceed the amount invested in NEDO projects.

Cumulative national expenditure for Top 70 Inside Products: Approx. 640.9 billion yen

- Corporate income tax (approx. 69.1 trillion yen) × 3.66 % (pre-tax profit rate[Term 1]) × 40.69 % (effective corporate tax rate) = approx. 1.291 trillion yen … Eq.(1)

NEDO have invested approximately 3 trillion yen in R&D projects over the past 30 years, and from the results above, 640.9 billion yen has contributed to sales. Nonetheless, it is still unknown how the remaining 2.36 trillion yen investment has contributed to the sale although this certainly has brought about vocational training opportunities and technological ripple effects. At this point, we have concluded that the sales of 69.1 trillion yen could be expected in the next ten years from the 3 trillion yen investment. Further investigation is needed in order to see to what extent the investment of 2.36 trillion yen that seemingly has no effect on the sales might be related to other economic impacts and gross social benefit.

3.3 Job creation (for 2010, and cumulative total for 2011-2020)

The impact of created job opportunities was calculated from the rate of labor cost against the product sales in domestic manufacturing sectors and the average income (FY 2004-2008 performance) based on the most recent sales and the

Table 3. CO_2 reduction effect of NEDO Inside Products

Category	Specific NEDO Inside Products	CO_2 reduction effect[1)] (ton-CO_2/year)
1. Pioneers of new market	[8 products] Solar power generation, residential heat pump hot water supply systems, wind power generation, residential fuel cells, mobile batteries, gas turbines, high-output secondary batteries, clean diesel vehicles	196,756,986
2. Boosters of Japanese industry's international competitiveness	[5 products] Power semiconductor materials, turbo refrigerators, non-stage transmission for automobiles (belt CVD), energy-sharing technology of plant community by pinch technology, high-performance LED materials	37,443,907
3. Technological stimuli to wide range of fields	[1 product] Industrial medium-scale power generators	231,250
4. Solutions to resources and energy issues	[14 products] Waste power generation, high-performance industrial furnaces, low-emission hybrid diesel vehicles, eco-cement, submerged combustion methods for chlorofluorocarbon decomposition, industrial heat pumps, high-performance high-function vacuum insulating materials, standby-power digital copiers, sulfur-free light oil, energy-saving construction machines, thermal storage transportation, geothermal power generation, waste solid fuel, low fuel consumption tires	274,152,410
5. Providers of safety, security, and comfort	[2 products] Insulating materials for electronic materials, cleaning gas for semiconductor manufacturing	20,968,776
	Total (30 products)	529,553,329

1) The amount of CO_2 reduced was calculated as the cumulative CO_2 reduction from the number of products expected to be introduced and the functions added in 2011～2020.

cumulative sales forecasts (2011-2020). This reveals that approximately 109,000 employment opportunities were created in 2010, and further 185,000 per year until 2020 [Eq. (2) and (3)]. In fact, the number of newly generated opportunities after 2011 had to be reduced to approximately 76,000 a year on the assumption that the same personnel remain employed [Eq.(4)].

- Approx. 4.08 trillion yen × 13.38 % (labor cost/product sales[Term 2]) ÷ 4,990,000 yen (average income) = approx. 109,000 jobs/year … Eq.(2)
- Approx. 69.1 trillion yen × 13.38 % (labor cost/product sales[Term 2]) ÷ 4,990,000 yen (average income) = approx. 1,850,000 jobs/10 years … Eq.(3)
- 1,850,000 jobs/10 years (the number of jobs increased since 2011) – 109,000 jobs/year (the number of people hired in 2010) = approx. 76,000 jobs/year … Eq.(4)

3.4 CO_2 reduction effect of 70 NEDO Inside Products

30 out of 70 NEDO Inside Products have the potential to reduce one million ton of CO_2 per year; these include solar power generation, wind power generation, residential heat pumps, highly-efficient gas turbines, power semiconductors, LED materials, waste power generation, chlorofluorocarbon decomposition processes, refuse-derived fuel, semiconductor clean gas, and highly-efficient industrial furnaces. The CO_2 reduction effect of these products is—in such cases as the replacement of existing products or chlorofluorocarbon decomposition—often represented in global warming potential (GWP) and expressed in CO_2 unit: Based on the unit, these products are considered to make substantial contribution to greenhouse gas reduction. The companies, industrial associations, or NEDO provided the CO_2 units on the assumption that these NEDO Inside Products replaced existing products, which were subsequently reviewed by a committee of experts, and the amount of CO_2 reduced were estimated.[17][18] As the result, these products and processes are expected to reduce the CO_2 emission for the next ten years by approximately 530 million ton/10 years (Table 3). Since the amount of CO_2 emitted in Japan FY 2012 accounted for 1.343 billion ton, it can be said that these products and processes should achieve a 3.94 % reduction per year.

4 Economic impact of NEDO Inside Products

The use of the inter-industry relations table enables us to figure out the (primary and secondary) induced economic effects of a NEDO Inside Product on the upstream and the downstream of its supply chain. However, the selection of the NEDO Inside Products viable for such estimation must be made with caution. The economic impacts presented in this research include "primary induced economic effect" by the products' "net sales" and the sales that are later derived from manufacturing, as well as "secondary induced economic effect" through payroll expenses. The terms above are defined as follows:

- Net sales: the sales figure of given product itself
- Primary induced economic effect: the sales effect of parts and materials that are necessary for manufacturing the product at the upstream of supply chain
- Secondary induced economic effect: the boost on employment and consumption resulted from the product's sales and primary induced effects

For the products with small sales figures and little statistical significance in the inter-industry relations tables, the estimation's margin of error possibly becomes larger;

which may represent an inaccurate overview of the project outcomes. Keeping this in mind, the products and the processes which meet the conditions below are subject to estimation.

4.1 Requirements of products that are subject to estimation of induced economic effects (primary and secondary)

In the fields of semiconductor, automobile, or energy, a number of NEDO project outcomes are incorporated into a range of materials, parts, manufacturing machines, as well as end products. On the other hand, technology/know-how by itself has limited effects on net sales. Thus, it is necessary to define the status of the technology/know-how in the sectors involved (e.g., parts, manufacturing machines/devices, end products, alternative products, etc.) in order to avoid the overlaps in the estimates of net sales and induced economic effects. To perform a series of calculations, 20 out of Top 70 NEDO Inside Products which meet the conditions below, are subject to induced economic effect estimations (i.e., the ripple effects on sales in other sectors found in the inter-industry relations table: see Table 4).

- The product has recorded a certain sales volume (e.g., >10 billion yen per year)
- The product has been disseminated and gained a degree of recognition in the market, and its economic effect is likely to increase
- The product potentially creates new industries, or transforms into other innovative products/processes rather than simply add value to existing products/processes
- The product has been statistically significant in the category to which the products/processes belong

4.2 Estimation of induced economic effects

There is a range of products and processes that utilize NEDO project outcomes, and the same sales estimation method is not always appropriate for all the products. Therefore, for each product and process, we discussed the induced economic effects of specific kind crucial for our purpose, having studied the characteristics of NEDO Inside Products. Note:

(1) The 2005 version of inter-industry relations tables (108 sectors across Japan) are used for the estimation with no adjustment to the figures provided.

(2) Difference between parts/materials and manufacturing machines;
In semiconductor production, NEDO project outcomes are, in many cases, being adopted as materials and parts. In contrast, the calculated economic effect of manufacturing machines (i.e., industrial machines) practically corresponds to their net sales at the time of market release. Hence, we only take the net sales into consideration for manufacturing machines, whereas both primary and secondary induced economic effects are estimated for the materials and parts since parts and materials take a significant portion in the figure.

(3) Overlaps in induced effect of parts/materials and end products;
In automobile industry, NEDO project outcomes are utilized in materials/parts, manufacturing machines, and end products (automobiles). In this paper, only the end products in which NEDO projects played major roles (i.e., low-emission hybrid diesel vehicles and clean diesel cars) are counted.

(4) Handling of the secondary induced effect by inter-industry relations analyses;
While the primary induced economic effect is an index that represents the economic impact on the upstream of a supply chain, the secondary induced economic effect is an index that represents the sales revenue (the net sales of the products and the processes utilizing NEDO project outcomes). The latter also includes payroll expenditures incurred by the primary induced economic effect. Instead of considering the secondary effect as an economic impact on a specific industry, it seems more appropriate to deem it as a social impact resulted from improved economic performance through increased employment opportunities.

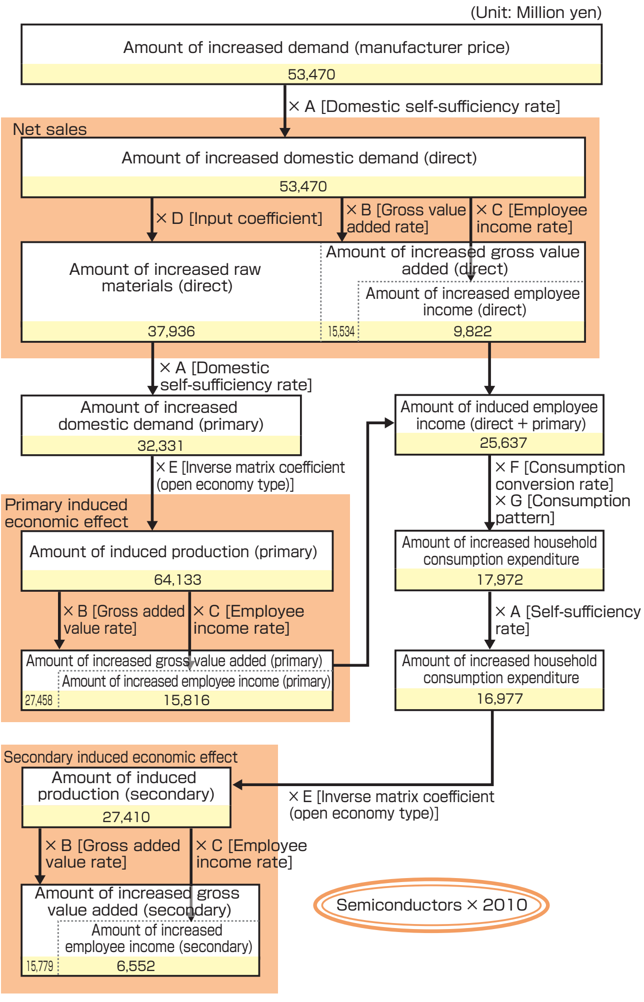
(5) Handling of the economic effects in the energy field;
The products other than energy storage are the machines and devices that generate electricity: Some of those supply renewable energy while others improve the energy efficiency of conventional energy. Renewable energy-related devices in particular (solar/wind/geothermal power generation) are a group of products that are exploring new markets. Added to the increased sales revenue in the upstream market of supply chain, there has also been a variety of impacts including increased sales of electricity and job creation. It should be noted that renewable energy-related devices, gas turbines, and fuel cells are the energy-saving devices which contribute to reducing the use of fossil fuel at the same time.

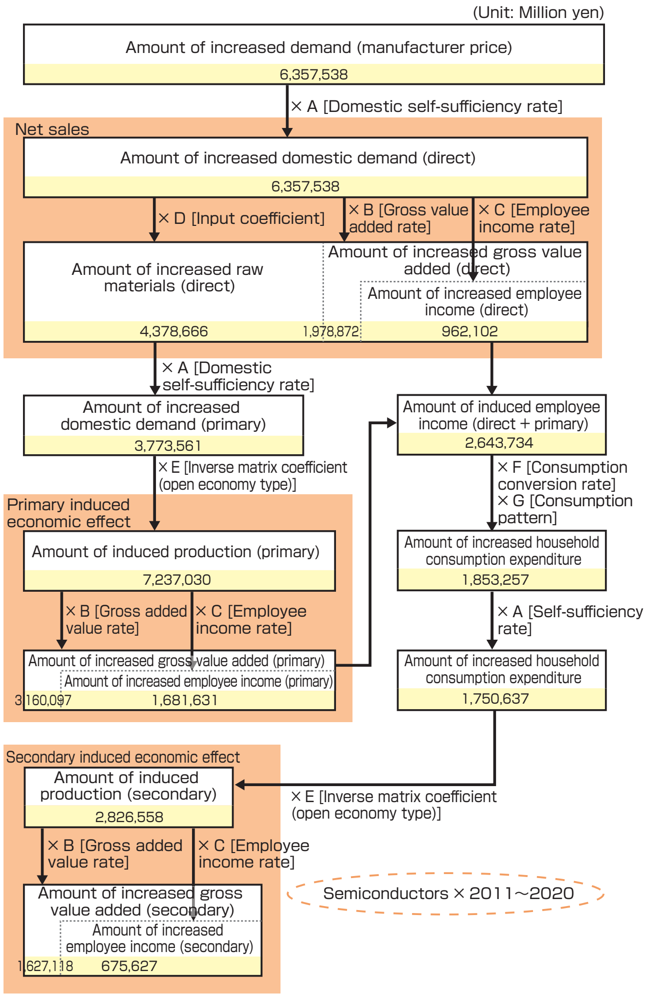
4.3 Calculation of the primary and secondary induced economic effects by the inter-industry relations analysis

In regard to the primary induced economic effect on the sectors involved in the manufacturing of NEDO Inside Products (the net sales associated with the production of NEDO Inside Products in the sectors shown in the inter-industry relationship), solar power generation for instance, the net sales we refer to only count the sales of solar panels with given technologies in domestic market. The demand price for each intermediate product during the panel production process was computed by the intermediate input coefficients of the inter-industry relations table. The result was subsequently multiplied by the end product’s domestic self-sufficiency rate and inverse matrix coefficient to calculate the primary induced economic effect (the amount of induced production).[26] Furthermore, the estimated "amount of increased employee income" resulted from the net sales and the primary induced economic effect was multiplied by consumption conversion rate to work out the "final demand of consumption demands." The amount of consumption demand of each industry was obtained by multiplying above mentioned "final demand of consumption demands and "private consumption expenditures by industry." The amount of consumption demand by industry was once again multiplied by the self-sufficiency rate and inverse matrix coefficient. Consequently, the secondary induced economic effect (the amount associated with the increased employment by the inter-industry relationship) was computed. The market size of the end product with given materials/parts was estimated using the information from the industrial relations chart by NEDO[27]-[30]and the statistics published by relevant bodies.[31]

4.4 Calculation of the primary and secondary induced economic effects of semiconductor products

The semiconductor-related products among NEDO Inside Products include semiconductor parts and semiconductor devices. For the reason given in (2) of Subchapter 4.2, the amount of increased semiconductor parts production (for those likely to bring about both primary and secondary induced effects such as cell phones, smartphones, portable game consoles, PCs, hard disk drives, automobiles, etc.) turned out 53,470 (million yen per year). Provided that all the parts are supplied domestically, the net sales could be 53,470 (million yen per year). By multiplying the input coefficient (of parts (materials)) to this figure, the value of intermediate goods produced owing to the sales is worth 37,936 (million yen per year). Since some of these intermediate products are of foreign origin, 37,936 (million yen per year) was multiplied by the domestic self-sufficiency of each product for the amount of increased domestic demand (primary), 32,331 (million yen per year). Followed by the multiplication of the inverse matrix coefficient to the primary domestic demand, the estimated primary induced economic effect was 64,133 (million yen per year). Next, the amount induced by employee income (direct + primary) was calculated by adding the increased employee income, 9,822 (million yen





*The amount of increased demand (manufacturer price) was calculated from the single-year sales and future sales of the products that are expected to generate primary and secondary induced effects.

Fig. 4-1 Economic ripple effect flow using the inter-industry relations table (semiconductor parts, 2010)

Fig. 4-2 Economic ripple effect flow using the inter-industry relations table (semiconductor parts, 2011~2020)

Table 4. Ten-year sales forecast of NEDO Inside Products and their induced economic effects

(Unit: 100 million yen)

Field	Specific NEDO Inside Products[1)]	Induced economic effect (2011~2020)		Net sales forecast[2)] (2011~2020)
		Primary induced effect	Secondary induced effect	
Energy	Solar power generation, wind power generation, residential fuel cells, gas turbines, waste power generation, etc.	360,539	154,440	319,811
Semiconductors	Dye bond films, MEMS, non-volatile memories, DRAM, insulating materials for electronic materials, power semiconductor materials, etc.	72,370	28,266	72,058
Automobiles	Products: low-emission hybrid diesel vehicles, clean diesel vehicles Parts: Desulfurization catalysts for sulfur-free light oil, sulfur-free light oil	68,406	17,488	162,404
Housing	Vacuum insulating materials, residential fuel cells, residential heat pumps, etc.	119,670	47,358	103,358
	Total	620,985	247,552	657,632

1) Further induced effect is expected for 20 products among Top 70 NEDO Inside Products
2) Total amount for all the products within the fields in question was calculated regardless of the value of primary or secondary induced effect

per year) generated by the sales revenue and the increased employee income from primary induced economic effect of 15,816 (million yen per year). The result was multiplied by the consumption conversion rate and consumption pattern, and the increased household consumption expenditures, 17,972 (million yen per year) was obtained. As the household consumption includes imported products, each product was multiplied by the domestic self-sufficiency rate, then the inverse matrix coefficients; the estimated secondary induced economic effect was 27,410 (million yen per year). Additionally, the full extent of cumulative economic effects for 2011 - 2020 is provided in Figs. 4-1 and 4-2. For other industries, net sales and primary and secondary induced economic effects were calculated likewise.

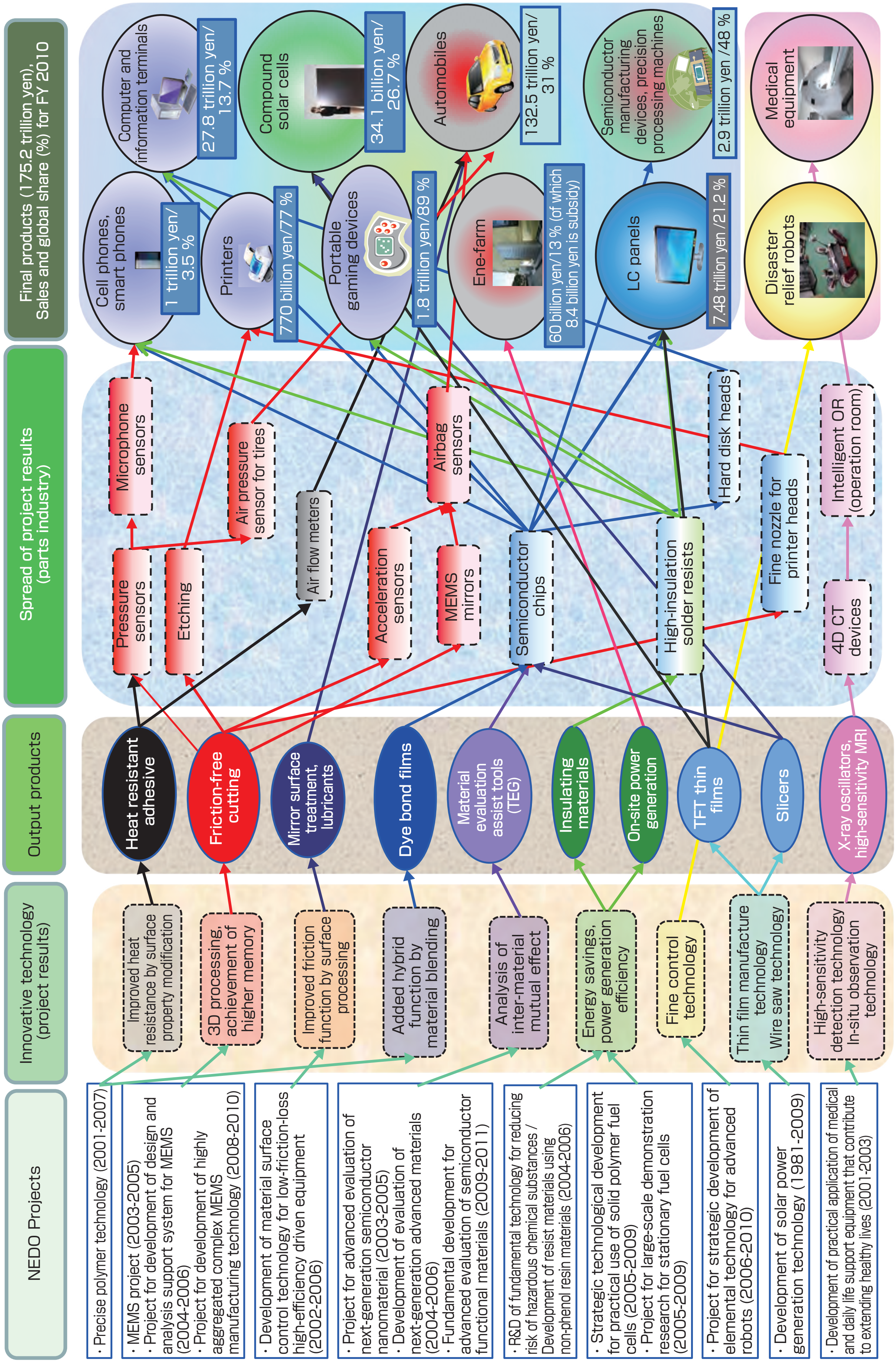
4.5 Calculation of the primary and secondary economic induced effects of NEDO Inside Products

By utilizing the inter-industry relations table, we found out that 20 of NEDO Inside Products are viable for the calculation of the induced economic effects (primary and secondary) on upstream and downstream of their supply chains: the technological fields specific to these products are energy, semiconductors, automobiles, and housing. The summary of 2011-2020 forecasted net sales and economic effects consisting of net sales (65.76 trillion yen), primary induced economic effect (62.1 trillion yen), and secondary induced economic effect (24.76 trillion yen) are shown in Table 4. It is now evident that the best-selling energy-related products have also had significant induced economic effects. For the net sales forecast, the sales forecasts of all the products in the fields concerned were aggregated, regardless of the values of induced effects. It can be seen from the results in Table 4, the secondary induced economic effects (the effect on employment) of energy and housing-related products are larger than any other products. This is possibly attributed to the additional tasks besides manufacturing such as installation and transportation. There are in fact countless NEDO R&D projects that have potential to increase employment opportunities within manufacturing sectors; however, the results above suggest that it is important to envision further job opportunities which involve product installation and transportation, particularly when carrying out the project specifically aims at expanding job creation effect.

5 Technological ripple effect of NEDO Inside Products

5.1 NEDO Inside Products that have technological ripple effects as generic technologies

NEDO Inside Products include parts/materials, processing technologies, and intermediate products which vastly contribute to the improvement of existing products despite their marginal net sales. Figure 5 shows the flow from the projects to the products (of high-functional parts and processes with far-reaching technological ripple effects, which are evolved from the NEDO projects after 2000), and their domestic sales and global market shares in FY 2010. Compared to the products and the processes which require long development period as in new energy and environmental products, the high-functional parts and the intermediate products with shorter product lifespan but highly versatile are rapidly spreading their technological ripple effects across the industries (e.g., automobiles, computer products, home appliances). In the interviews with the companies, we noticed their preference of the R&D of high-functional parts and intermediate products that can be carried out in a short period of time with lower development cost to the development of innovative large-scale machines or processes which are costly and time-consuming. The companies also seem to have positive outlook on the technological ripple effects of high-functional parts and intermediate products to other end products. Thus, we estimated that the sales effect on relevant products would reach approximately 175.2 trillion yen.[14][16][31] It is in fact relatively simply to calculate the sales of such end products as solar power generation, gas turbines, high-performance



*Created from NEDO Inside Products confirmed during Phase 2, in the Phase 1 and Phase 2 medium term projects.

Fig. 5 Innovative technologies born from NEDO projects and midterm outcomes

industrial furnaces, and residential fuel cells. However, the sales figures of parts/materials, processing technology, or intermediate products need to be inferred from the information given by the corporate researchers and the experts from industrial associations during the interviews, or from various other sources on how these products are incorporated into end products. For example, the core technologies developed in NEDO projects (e.g., MEMS, multilayered films, laser micro-processing, in-situ observation technology) benefit the production of functional intermediate products (e.g., pressure sensors, acceleration sensors, microphones); these technologies turned out to be incorporated into countless end products (e.g., automobiles, cell phones, game consoles) making a part of supply chains. It was also found out that a number of high-performance intermediate products among NEDO Inside Products have achieved more sophisticated functionality, lower cost, and energy efficiency by being combined with other NEDO Inside Products; which have been integrated into some major end products of the key industries in Japan.

5.2 NEDO Inside Products with significant gross social benefits

There is a number of NEDO Inside Products which are enormously beneficial to the society despite the fact that their net sales are not significant. This applies to some environmental and energy-saving products, CO_2 reduction and recycling (resource cycling and landfill waste reduction), for instance. NEDO Inside Products with notable CO_2 reduction effect include the chlorofluorocarbon destruction processes. A process that detoxifies HFC-23 (trifluoromethane), a byproduct of chlorofluorocarbon coolant process for air conditioning which is high in GWP is typical of such products. There are 14 plants in Japan and eight or more overseas plants in operation adopting this process, and the domestic plants are known to reduce 7 million ton (CO_2 equivalent) per year. In 2010, it made a significant contribution to achieving the goal of COP3 (Kyoto Protocol; Third Session of the Conference of the Parties to the United Nations Framework Convention on Climate Change).

It is notable that there is a group of NEDO projects that have promoted the institutionalization of public services: The development of recycling technologies. The R&D projects on over 100 topics have been conducted[16]-[18] in response to recent changes in regulation, and the project outcomes offer invaluable solutions to such social issues as shortage of landfill sites in Japan, hazardous substance control, and resource conservation. Figure 6 epitomizes the technology architecture of recycling systems. In the past decades, there was no appropriate measure being taken other than recycling, recovery and reuse of glass bottles and newspapers. In the face of it, NEDO initiated basic and advanced R&D projects for materials and resource recycling technologies; which have successfully reduced the processing cost through the progress in technology and the improvement of process capacity. The technologies have been applied to a range of wastes and semifinishied goods (mixed materials), and in turn, led to increased recycling rate. Moreover, the progress in soft technologies, namely, life cycle assessment (LCA) and design for the environment (DfE) has enabled mutual improvement of soft and hard technologies, as can be seen from the development of the products that are easy to recycle. The recycling technologies that considerably benefit the society include “recycling plant of the four ‘white goods’ (televisions, air conditioners, washing machines, and refrigerators)” and “re-resourcing of waste plastics (blast furnace injection; liquefaction; and refuse paper and plastic fuel (RPF).” Unlike automobiles, recycling of white goods was made obligatory for the manufacturing companies in Japan, and at the time, the industry as a whole was in need for economical recycling systems. Several home appliance manufacturers had taken charge of the development these devices by bringing their own expertise together, and produced optimal processing devices in a short period of time overcoming different corporate interests. After a series of demonstrations and long-time continuous operation, a new system was established. From the interviews with the companies, we found out that there are currently 49 plants using this system in Japan recycling 931.000 ton per year. It should also be noted that the most important core technology in the development of this entire system was “sorting.” Before the current recycling system was introduced, waste processing had been managed by local governments, and the majority of solid waste had been simply cut into pieces and buried. The advanced sorting technologies developed through NEDO projects allow the most of useful parts to be recovered efficiently at low cost and the recycling rate to see a rapidly increase.

On the other hand, waste plastics had been buried in landfills until new technology was developed. It triggered a range of social problems including the shortage of landfill sites, soaring cost for processing, and dioxin emission during combustion. After LCA and careful economic evaluations, it was found that waste heat recovery (in some cases, electricity) in the form of thermal recycling would bring an enormous economic advantage. Following this, a safe combustion process (i.e., exhaust gas management) was introduced; which led to a > 90 % increase in recycling rate (power generation or thermal recycling accompanying combustion). As for the resource recovery of waste plastics (liquefaction, etc.), practical application as a system was viable only if the technology complied with the revised laws and met the demands (e.g., traceability of the resource, the volume of waste, the presence of recycling businesses).[16]-[18] Thus, the R&D projects would frequently face termination or suspension due to the lack of sufficient amount of waste, or prohibitive costs for labor and transportation, notwithstanding the technological excellence.

In the development of devices and processes in NEDO projects in the 1990s, the government and the industry conducted a

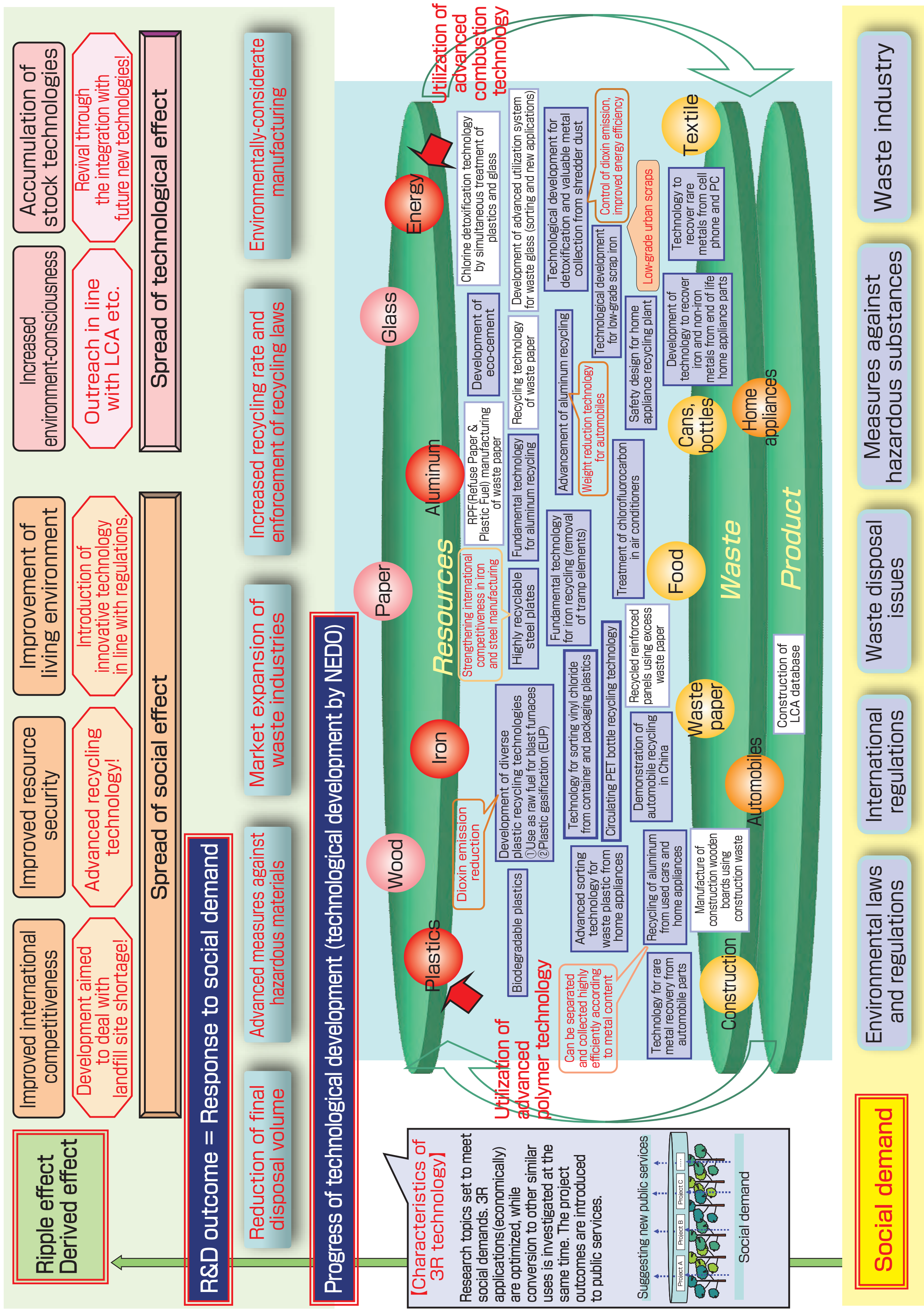


Fig. 6 Relationship between the NEDO projects and recycling systems

series of R&D projects aiming for instant practical application, while experiencing various failures. The major issue was the funding source: How to eke out the cost for recycling. Since the vast majority of the public saw no value in the spending on waste processing, it required awareness-raising as well as technological breakthroughs. Under such circumstances, NEDO collected a myriad of information, whereby they could develop the strategies for technology development. This provided hints for subsequent development plans and for other R&D projects.

As the result, the number of unsuccessful projects saw a sharp decline, and there were considerable benefits accrued to groups of developers and the parties directly involved (i.e., no redundancy in financial investment, schedule, and personnel). These are the findings from the corporate interviews.

6 Future challenges in expanding NEDO Inside Products

From the survey and the analyses of NEDO Inside Products, the following issues become evident, which need to be addressed for our future research to extend the scope of the products. Below is a summary of the discussions and possible solutions which we recognized in the course of this research.[17][18]

(1) Search for NEDO Inside Product candidates

It has been over 30 years since the establishment of NEDO. For their long list of projects, our research was not necessarily conducted in an efficient way: Listing promising products and processes which could be of past NEDO project outcomes, then referring to literature, reports, the interviews with participants, and other sources. Above all, it seems that the use of questionnaire survey to confirm the current market status of all the project outcomes is the most comprehensive and efficient way to explore NEDO Inside Products. NEDO, in fact, carry out six-year follow-up studies of the projects, and further five/ten/20-year follow-up surveys are also possible. Furthermore, it is crucial for the government to make efforts to help the public see NEDO project outcomes by the construction of a database for achievement reports and the additional interviews with retired employees of the participant companies for instance.

(2) Difficulty in gathering information on the old project outcomes

As a few of NEDO projects initiated back in the 1970s to 80s, it is extremely difficult to gather the information regarding the status of given project at the time, the process leading to the product's market release, and the overview of the technological progress. What we can do is to examine the current market's views on the R&D topics of three decades ago. Having said this, we once again emphasize the need for the interviews with the key in the field and the people in charge of these projects, as well as a database – an extensive record of "R&D heritages." These data will help us track where the current technologies stem from.[32]-[36]

(3) Rigidity in the evaluation of estimated sales

Based on the estimated market size and future outlook, the questionnaire surveys were conducted in order to verify and correct these figures. However, we noticed individual differences in the view on "the scope of NEDO Inside Products." If NEDO made the attempt to estimate the market scale themselves, for instance, they could possibly take advantage of the scope and methods of research. As in this research, the validity of the figures and findings must be ensured. It is thus recommended that the estimations and evaluations of benefits are made first of all, fair and square, and have external experts revise these figures and findings rather than the members actually managing given projects: Academics (e.g., project leaders or the chairs of academic societies) or the members of the industrial associations whose area of expertise is closely related to the projects may be best suited for such task.

(4) Problems associated with quantifying the effects other than sales

In this study, NEDO Inside Products were narrowed down according to the most recent sales figures and the sales forecasts. NEDO project outcomes offer a wide variety of benefits, and some of them deserve greater credit. For example, we made the evaluations in the light of contribution to improved quality of living and public satisfaction. Nevertheless, it is tricky to evaluate such benefit in the same way as the net sales since the opinions vary by individual, and it requires us to seek for a new method that allows these qualities to be comparable.[18] In effect, NEDO Inside Products that are not amenable for quantitative evaluation can be presented qualitatively. However, when the efforts made by different fields and other companies are all aligned, resulting set of efforts (NEDO projects) becomes all-inclusive and a specific impact (effect/benefit) may become hardly noticeable. We need to discuss how to shed light on these products by comparing with past products in the same field and category.

7 Summary

We conducted a questionnaire survey and interviews with the NEDO project participants and the members of relevant industrial associations, in an attempt to select top 70 of NEDO Inside Products based on the significance of the product's economic impact (i.e., sales figures and induced economic effects) and its contribution to the society. These NEDO Inside Products are subject to change in the order of few years as a consequence of a drop in retail price or fluctuations in sales volume. Thus, it requires consistent monitoring of their sales and ripple effects. All products are the results of further R&D activities and investments for practical application/commercialization: The effort participant companies made after the completion of NEDO projects. For the realization and commercialization of R&D outcomes, the companies are known to make investment an order of magnitude larger than the funding awarded by NEDO; however, business investment against sales revenue was out of our scope since every single amount of business investment was hardly obtainable. It should be noted that it often takes over 10 or 20 years for the practical application and commercial production of an innovative technology.[24] This implies that it is a long-term research investment that can develop unique and unrivaled expertise, turn young researchers into leading figures, and lead to preemptive investment for future R&Ds.

By assuming the contribution rate of NEDO project outcomes to be 100 %, we could present maximized sales revenue and contribution estimates of the R&D outcomes . We could also grasp the general trend of project outcomes and the milestones towards practical application (the effectiveness of industry-government-academia collaboration, success factors in management (see Subchapter 2.8), adaptability to regulations, overcoming of failures, etc.). What is more, the study enabled us to roughly evaluate NEDO's development investment from their project outcomes in terms of overall impact to the society-induced economic effects and gross social benefit (e.g., CO_2 reduction, energy efficiency, and job creation), added to the products' sales.

30 years have passed since the first NEDO project, and approximately 3 trillion yen has been invested as development fund. To make above estimates, we chose only a portion of prospective products on grounds of sales performance. The ripple effects, the impact from the know-how, and gross social benefit of the rest of the products were excluded. Figure 7 illustrates NEDO Inside Products' impact on economy, technology, and the emergence of further functionalities. The industry would regard the economic effects including sales and job creation, while research communities may benefit from the technological effects through paper submissions, patent applications, and awards. On the other hand, consumers' perspective lies heavily on the products' gross social benefit such as the improvement in quality of living and safety and security measures. In sum, the purpose of our research was the evaluation of overall impact induced by NEDO Inside Products in the light of economic effects and gross social benefit. The economic effects could withstand quantitative evaluation to certain extent; the benefits such as CO_2 reduction or job creation could be expressed in figure although some others including quality of living and a sense of convenience are not fit for quantitative measurement. In future, it is necessary for us to elaborate the impact evaluation methods while extending our research on the products' emerging functionalities for the improvement in quality of living and public services; reduction in public investment; added convenience, safety and security; and health maintenance. Also, another research on the intellectual property of NEDO Inside Products is underway, and a paper is forthcoming.

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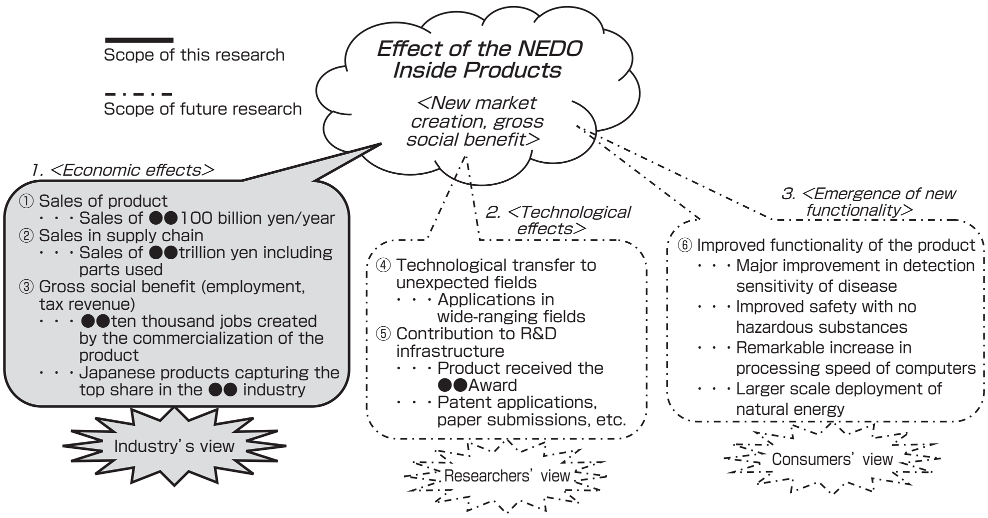

Fig. 7 Ripple effect of NEDO Inside Products

Terminologies

Term 1. Pre-tax profit rate: Net profit divided by net sales prior to tax deduction (See *Financial Statements Statistics of Corporations by Industry*, Ministry of Finances[27] (average 2004-2008 performance value)). Tax revenues from the investment of development expenses (cumulative total for 2010-2020) were estimated using the pre-tax profit rate (average 2004-2008 performance value of domestic manufacturers).

Term 2. Personnel expense percentage: The percentage for manufacturing sectors. (See *Financial Statements Statistics of Corporations by Industry*, Ministry of Finances[27] (average 2004-2008 performance value)). Average income refers to the average income of manufacturing industry (sum of chemical, metal machining, textile, and others) based on *Private Sector Wage Fact-Finding Survey*, by National Tax Agency (average 2004 – 2008 performance value).

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Discussions with Reviewers

Overall

Comment (Akira Kageyama, Research and Innovation Promotion Headquarters, AIST; Naoto Kobayashi, Center for Research Strategy, Waseda University)

There is a social demand for the assessment and disclosure of the cost-effectiveness (effect of investment) of national-funded R&D projects. While the methodology has yet to be established, this is a valuable paper which has discussed the cost-effectiveness of selected 70 products in NEDO projects which were successfully put into practical application and turned to commercial products recoding significant sales figures. As for the project outcomes in particular, the paper provides analyses and discussions not only of the sales effects of listed products, but also the gross social benefit such as induced economic effects, job creation, ripple effects to other technologies, and the reduction of CO_2 emissions. Furthermore, the paper extracts and presents the success factors of NEDO Inside Products, which are remarkably useful for the future R&D projects and innovation policies in Japan.

1 Positioning of the paper

Comment (Ayu Washizu, Faculty of Social Sciences, Waseda University)

While the public seek for the clarification of cost-effectiveness of science and technology budget, it is generally difficult to indicate how specific funding results in specific outcomes. However, this study demonstrates that based on the research findings which could only be possible by such agency as NEDO, and this can be a valuable academic achievement.

Comment (Akira Kageyama)

This is an invaluable piece of work that discusses the cost (investment) effectiveness by selecting 70 products from the themes NEDO's R&D projects tackled. In regard to the effects, not only does the paper discuss the sales effects of listed products, but also the gross social benefit such as induced economic effects, job creation, ripple effect to other technologies, and the reduction of CO_2 emissions; which makes characteristic of this research. It becomes even more complex as time lapses and the lines linking technological ripple effects increase. This will certainly make the survey and analysis more complex, but the effort (or perhaps, challenge) of changing what was conventionally deemed as tacit knowledge into explicit knowledge is essential for both NEDO and the industries. Since both parties are accountable for NEDO projects, I hope this step to be incorporated into the evaluation system with NEDO taking leadership. Moreover, you successfully extracted and presented the success factors of NEDO Inside Products after the discussions with reviewers; which carries considerable implications for R&D project management in future. I believe that this paper is also beneficial as a study on R&D methodology.

Comment (Naoto Kobayashi)

This paper successfully shows useful cases investigating the effectiveness of the national investment in R&D. In conducting NEDO projects, it is crucical that all the research promotion organizations prepare adequate research data accumulation methodologies in advance, which will be useful for future policies on R&D and innovation in Japan.

Comment (Ayu Washizu)

This research is also a summary of how individual science and technology developed in NEDO projects interrelate with each other and consequently comes to fruition as a commercial product, and the follow-up study of this whole process in detail. This tallies with *Synthesiology*'s objective.

Answer (Masaru Yamashita)

I have considered it crucial to show the project outcomes quantitatively as NEDO projects are run by national funding. Thus, we submitted this paper in the hope that this would be a chance to prove their benefit. I am grateful to the people involved for giving us this opportunity. When we had an oral presentation at the American Evaluation Association a few years ago, our work was fortunate enough to receive credit from the experts around the world. As a result, last year, we submitted a paper to *Research Evaluation*, a journal published by AEA. We later conducted additional research with new perspective, and submitted this highly original paper to *Synthesiology*. I presume that this article has become more elaborate by specifying the success factors of NEDO Inside Products with certain degree of precision, reflecting invaluable comments from the reviewers. To this date, the description of project achievement available for external viewers remained qualitative. We presented semi-quantitative evaluations and visualized invisible results, and the resulting paper turned out successful in enhancing the quality of research by alluding to challenging issues.

Such effort we made in this research must be carried on for a mid- to long-term. I notice the importance of follow-up surveys, and continuous revision of the figures and search for new directions must be done at the same time. Additionally, it is strongly recommended that NEDO establish a system that can measure the effectiveness of their project management with the help of our result. In the course of this research, we came across a number of new findings. It would be grateful if we attract a wider readership in research communities and businesses in Japan, so that we can continue to provide information as hints and implications for successful R&D projects by NEDO, companies, or universities.

2 Structure of the paper

Comment (Naoto Kobayashi)

The goal of this paper is the "evaluation of gross social benefit of NEDO Inside Products developed with national funding." Two major elements to achieve this are: (1) the selection of NEDO Inside Products, and (2) the evaluation of gross social benefit of NEDO Inside Products. The sub-factors of (1) include the methodologies such as the definition of NEDO Inside Products, and the selection procedure. The sub-factors of (2) include economic evaluations, job creation, CO_2 reduction, and the projection of ripple effects. I would recommend you to clarify the structure of this research you have in mind by showing that in a diagram at the end of chapter 1.

Answer (Masaru Yamashita)

Thank you for your valuable advice. We have added Fig. 1 at the end of chapter 1, so that our readers can see the outline of this paper.

3 Categorization and inter-industry relations analysis

Question and Comment (Ayu Washizu)

You defined new product categories since the existing ones had been insufficient. As categorization is the basis of analyses and therefore is of vital importance, it seems necessary to discuss more in detail (drawing upon previous research) why you decided on this categorization. In general, innovation can be divided into product innovation and process innovation. Perhaps the former can be further divided into the creation of an unprecedented product and the improvement of existing products. The latter may be the innovation of manufacturing machines and the development of materials to be incorporated into products. Such categorization should be relevant to the discussion on the characteristics of social effects that innovation may bring about. Thus, I suggest you expound more on your categorization.

The input-output analysis is used as the method to calculate the indirect effect against the direct effect. How you use the table in the paper is not an unusual one.

However, as the inventor Leontief notes, the input-output table is a method to analyze the effect of technology changes by treating the change in technology as the change of input coefficients. Recently, it has been applied to LCA in engineering field, and adopted to analyze environmental impact and the ripple effects of CO_2. It is preferable if you consider this way of using the table in future input-output analysis. It is difficult for the public to obtain the information on how innovation can be reflected in the input coefficient, but such organization as NEDO should be capable of acquiring the data. As your future topic, and as a part of NEDO's product evaluation activity, the implementation of the new method of exploiting the table deserves further discussion. In addition, the selection criterion for the calculation method shown in Fig. 4 may need an explanation referring to past literature.

Answer (Masaru Yamashita)

I appreciate your corrective guidance. In this paper, we aimed to demonstrate the impact of NEDO Inside Products on society. NEDO's mission is to promote national projects in the areas of environment, energy, and industrial technologies. From this standpoint, each product falls under one of the following categories: The product "(1) is a pioneer of the market, (2) is competitive in international markets, (3) pushes the boundaries of the technology, and (4) addresses any social issue." Over half of the products belong to category (4) reflecting the primary objective of NEDO's establishment. After careful examination of these technologies, we found that it would make more sense if we divided (4) into social demands and everyday life issues. Having consulted with external experts, we re-categorized the item (4) as (4) solutions to resources and energy issues, and (5) providers of safety, security, and comfort. As a result, we have five categories. This process is explained in detail in subchapter 2.6.

For the inter-industry relations analysis, we eventually added the reference detailing relevant information in subchapter 4.3 due to the word count of this article. As you pointed out, it is a method frequently used in LCA and other analyses, but to calculate the effects NEDO Inside Products induced using the inter-industry relations table, we made investigation from different perspectives focusing on these two points: (1) Distinction must be made between the products amenable for the calculation of induced effects and those that are not, and (2) the threshold values need careful examination. As a result, B-to-B products were chosen subject to estimation as they have no problem calculating the induced effects using the inter-industry relations table, and for B-to-C products, calculations were performed on the assumption that there were hardly any induced effects among the industries and the only contribution being made was the sales revenue of NEDO Inside Products. In future, we are willing to utilize the inter-industry relations table to calculate the benefits and induced effects for environmental effects and CO_2 ripple effects analyses as well as sales figures.

4 Industry-academia-government collaboration and contribution rate to the NEDO projects

Question and comment (Akira Kageyama, Naoto Kobayashi, and Ayu Washizu)

On top of the funding awarded by a NEDO project, there must be an amount of expense given from participating enterprises. How did you handle this burden on participant companies when looking at investment efficiency? You posited the contribution rate of NEDO's R&D outcome to be 100 %, and your initial explanation for this was: 1) practical application would have been seriously delayed or could not have been achieved without given project outcome; 2) many of the products underwent development phases from basic/generic to demonstration, and 3) the project's contribution rate to practical application differs depending on the product and cannot be specified due to the difficulty associated with verification. As the Great East Japan Earthquake devastated a semiconductor plant and it affected the operation of automobile manufacturers around the world, the product's whole supply-chain goes dysfunctional however tiny the missing part may be. Assuming a 100 % contribution rate is a way to represent certain viewpoint. However, it is seemingly inevitable for you to face criticism for overestimating the rate.

In the theory of R&D management, there is a widespread saying: Surviving "Valley of Death" to confront "Darwinian Sea." The manufacturers, in particular, are aware that they will never arrive at a new product or business without crossing Darwinian Sea. Furthermore, "practical application would have been seriously delayed or could not have been achieved without given project outcome" holds true (necessary condition) and is critical. But, considering the additional investment[Note*] of substantial amount necessary to record sales from a new business or a new product (sufficient condition), it is essential to examine and account for the basis of the 100 % contribution rate.

Note*) (1) Reproducibility of the technology, (2) investigation on yield increase, (3) investigation on scalability and subsequent optimization, (4) marketing, (5) close cooperation including joint research with user companies, (6) establishment of quality-assurance system, and etc.

Answer (Masaru Yamashita)

Thank you for such pertinent advice. We have received the same question from a number of researchers regarding the point you mentioned. For the products taken up as NEDO Inside Products, their sales figures are presented after obtaining approval from the developers, relevant bodies, and the researchers involved. Moreover, the contribution rate was set at 100 % because two or more of the following conditions would apply to almost all the products:

> (1) were developed through multiple mid-to long term projects; (2) addressed topics the companies would seldom consider and had difficulty obtaining funding for the purpose; (3) were in need for support from external experts, which was difficult to obtain in corporate research, (4) would never be put to practical application if it were not for the NEDO project outcome; (5) must be realized as corporate obligation owing to the funding support from the tax during the critical phase of development; (6) may differ in contribution rate and the companies are unable to grasp; and (7) were realized following the completion of the project and their subsequent commercialization was more likely due to the know-how and the companies' manufacturing effort rather than the funded research opportunity.

The maximum (sales) effect was calculated accordingly. We have added the above text and revised the items for subchapter 2.2 "Scope of NEDO Inside Products." In chapter 7, we have also inserted, "For the realization and commercialization of R&D outcomes, the companies are known to make investment an order of magnitude larger than the funding awarded by NEDO".

5 Understanding of R&D expenditure for NEDO projects

Question and Comment (Ayu Washizu)

It is always an issue when considering R&D expenses how to evaluate the expenditure on failed R&D projects. Since the scope of this research is the development projects that were successful, it is most unlikely that you have included the R&D expenditure on failures. Nonetheless, even a failed development project may have technological ripple effects as shown in Fig. 5, and it could be valuable because it establishes the fact that "this doesn't work." This may eventually be a factor leading a project to success. Therefore, the expenses on failures have supposedly contributed to successful results. In the cost-effectiveness calculations, you figured out the maximum effect assuming a 100 % contribution rate. Taking those expenditures into account, you might have to consider slightly exaggerating the figures when conducting sensitivity analyses.

Answer (Masaru Yamashita)

I totally agree with your point. NEDO has invested approximately 3 trillion yen as R&D expenditure over 30 years. It is only 70 out of it which have come into our focus as NEDO Inside Products. As demonstrated in subchapter 3.2, the investment of some 640 billion yen has actually generated practical application and sales, and the remaining 2.34 trillion yen resulted in failure. The follow-up survey by NEDO indicates that nearly 20 % of the project participants has successfully managed practical application and market launch, but those actually record sales are even less. However, in the answers to the questionnaire, almost all the researchers who took part in unsuccessful projects commented that they gained a degree of success in the form of papers, patents, know-how, training, and networking. About 80-90 % of them in fact admitted that they were reasonably satisfied despite the hardship during the project. Nevertheless, it seemed more appropriate to present as much quantifiable data as possible instead of showcasing such positive responses, in order to avoid subjectivity and self-satisfaction in evaluation. We considered it crucial to focus on such data as employment, CO_2 reduction, secondary social effects, and gross social benefit (resource circulation by recycling, CO_2 reduction, environmental measures, etc.) which can be presented in figure.

6 Technological ripple effects

Comment (Ayu Washizu)

I found Figs. 5 and 6 interesting as it gives a picture of technological development. In my view, the ripple effects of technologies that are not apparent in particular need more attention. These must be clearly illustrated, and the description in chapter 5 needs to be more precise.

Answer (Masaru Yamashita)

Due to the word limit, we mention only the essence of technological ripple effects; however, we have changed the description in chapter 5 to a more specific expression to make it clearer. Particularly, not only did we discuss the technology but also the effects on the human resource and the environment in the last paragraph. As for the complexity of Fig.6, we have revised it and simplified the diagram.

7 Success factors and their evolvement in future project management

Question and comment (Naoto Kobayashi and Akira Kageyama)

In the classification and selection of NEDO Inside Products, you might have explored the effective measures the companies and NEDO take or the positive effects the market environment caused that create such ‘stellar’ products. It is worth including the points above in brief at, for example, the end of chapter 2.

I would also recommend you analyze the successes and the failures whereby you can develop a simple and useful evaluation method to measure the investment effects; which can be utilized in the management and evaluation of future R&D projects.

Answer (Masaru Yamashita)

For almost all the NEDO Inside Products under investigation, we conducted interviews as well as questionnaire surveys. The successful projects, by and large, manage to materialize the seeds of technology in the way that satisfy the needs and the market demand. At the same time, we recognized the major factors of success below:

(1) The participants gained significantly larger amount of data, compared to their usual research situation; (2) the companies explored a mechanism which brought about improved reliability and problem-solving strategies, and development, modification, and extension of research policies through joint research opportunity with universities; (3) the participants were reasonably confident with the technology from the start for its practical feasibility and commercial viability; (4) the participants kept the idea for long before the project launch; (5) the participants had already had unrivaled know-how and capabilities, which saw further improvement and were exploited in the course of the project; (6) the participants were skeptical about the market information and proactive in exchanging information within the team; and (7) the participants carried out prototype demonstrations and repeatedly verified and modified the technology to the point where it was elaborate enough to ensure its proximity to commercialization.

These were discussed in newly added subchapter 2.8 “Success factors of NEDO Inside Products.”

We conduct interviews and questionnaire surveys on a project for up to five years after the completion, asking (almost all) the companies involved to participate. Using methods such as regression analysis, we work out the possible behavior patterns of successes and failures. As a result, we found out that unsuccessful projects and successful projects are somewhat different in the way they treat failures. The quality we have achieved in this paper is attributed to the discussion with the reviewers; which enabled us to extract and present the success factors of NEDO Inside Products. By sharing the results from these analyses, we hope to give NEDO’s project management food for thought. An article specifically on these analyses will be submitted in due course.

8 Intellectual property of NEDO Inside Products

Comment (Akira Kageyama)

It is presumably due to the limitation of space, but you spared no effort to mention patents in this paper. Patents are incredibly important as the means to protect R&D achievements. If you managed to describe the level of patent protection the 70 themes of NEDO Inside Products are offered, that would illustrate a part of the technological effects and serve as an index of the international competitiveness of made-in-Japan technologies. A few lines of description should be sufficient enough to show that you are aware of the significance of intellectual property.

Answer (Masaru Yamashita)

As you pointed out, the patents represent remarkable achievement. There is a study underway confirming the patents’ relevance to NEDO project outcomes, and so far, only around 30,000 are being investigated. A team of researchers will have opportunities to publish the findings in the form of oral presentation in an academic society meeting or a journal article. For this reason, I added a line “another research on the intellectual property of NEDO Inside Products is underway, and a paper is forthcoming.” in chapter 7 “Summary.”

Application of laser Compton photon beam to nondestructive tests

— A spin-off technology from nuclear physics —

Hiroyuki TOYOKAWA

[Translation from *Synthesiology*, Vol.8, No.2, p.89-96 (2015)]

Laser Compton photon beams generated by a high-energy electron storage ring have energy in the gamma-ray range. X-ray radiography for industrial products using the laser Compton photon beam is expected to show good spatial and density resolutions, because of its monochromaticity and good beam property. A radiography and computerized tomography system was built using AIST's TERAS electron storage ring. The performance of the system was examined. A summary of the development process is outlined to figure out the general methodology for translational research.

Keywords **:** Electron accelerator, laser, radiation, radiography, nondestructive inspection

1 Introduction

Translational research is a process in which scientific knowledge for basic research is translated into practical application for the benefit of society. While we attain the objectives of research, we take several issues into account, such as schedule, quality of research output, funding, cost efficiency for investment, objectives of the organization, and the voice of society. Technical level might be lowered if we easily compromised to produce outcomes in a short time, or we may become isolated from society if we keep pursuing our own way.

The objective of this paper is to show how a basic research study in an electron accelerator translated into industrial technology. The translation process is not to improve the device performance or produce champion data, but is to bridge research results to industry in an appropriate form.

The present research consists of the following scenario:
(1) Development and compilation of elemental technologies.
(2) Open to users: Device open to users to estimate potential users by listening to the users' voices.
(3) Investigation of plan: To investigate the research plan by objectively understanding the users' voices on whether the obtained results were as expected initially, what was overlooked if the results were not as expected, or whether there were better ways.
(4) Modification of plan: To organize the main points of future devices and technologies. To determine whether the research will be continued by considering the cost-effectiveness and the situation of the organization. To act quickly according to the decision made.

This paper consists of four chapters. In chapter 2, technical issues will be discussed. Chapter 3 discusses the process of selection and integration of technologies for bridging, in correspondence to (1) ~ (3) listed above. Chapter 4 reflects on the process of selection and integration of the elemental technologies in correspondence to (4), and discusses the efforts spent to achieve the goals and results.

2 Technical issues about laser Compton scattering

There are attractive technologies in nuclear physics and elementary particle physics especially in radiation measurement technologies. They are highly sophisticated, and can be applied to industrial technology with some modifications. We applied a method for measuring cross-sections of atoms and nuclear reactions to nondestructive testing via industrial radiography.

Industrial radiography is an important technique in improving reliability of industrial products such as automobiles, aircraft, rockets, sintered materials, cast products, and electronic substrates.[1] A high-energy X-ray computerized tomography (CT) system using an electron accelerator that is capable of radiographing a whole engine block at spatial resolution of 2~3 mm has been developed. In infrastructure diagnosis, the technology to inspect roadbeds and bridges on site using a portable electron accelerator has been developed recently.[2] A nondestructive and highly precise method for visualizing reinforcing steel-bars and cracks in concrete structure is strongly demanded in our society.

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The word “photon” is the name for quantized electromagnetic waves, and in this paper, it is used to mean X-rays or gamma rays. Radiography is a photographic method using ionizing radiations, and this includes so-called roentgen photography and cross-sectional photography using X-ray CT.

In this research, laser Compton scattering (LCS)[3] technology using an electron storage ring is used. An electron storage ring is a circular electron accelerator, in which electrons are enclosed in a donut-shaped ultra-high vacuum chamber by magnetic fields, and are accelerated using electric fields. We used an electron storage ring with a diameter of 10 m and a circumference of about 30 m, which is a medium- to small-scale device.

LCS is one of the methods to generate high-energy photons using an electron accelerator. When laser beams are irradiated onto high-energy electron beams, laser photons are scattered with the electrons, receiving part of the electron energy through Compton scattering, and become X-rays and gamma-rays. Compton scattering is the collision of photons and electrons, and the photon energy before and after scattering, scattering angle in the laboratory frame, and relationship with electron energy in LCS are expressed in Equation 1.

$$E_\gamma = \frac{E_0(1-\beta\cos\theta_1)}{1-\beta\cos\theta_2 + E_0\dfrac{1-\cos(\theta_2-\theta_1)}{E_e}}$$

The kinematics is shown in Fig. 1. The LCS photon research started in 1985 at the Electrotechnical Laboratory (later became part of AIST), and the photon beam source at the photon range of 1~40 MeV was available for scientific studies since 1990s.[4][5] Since high-energy and highly-oriented photon beams can be obtained, it has been used in much research such as nuclear physics studies, measurement of response function for radiation detectors, measurement of cross sections of photonuclear reactions, and measurement of absorption cross sections of atoms.

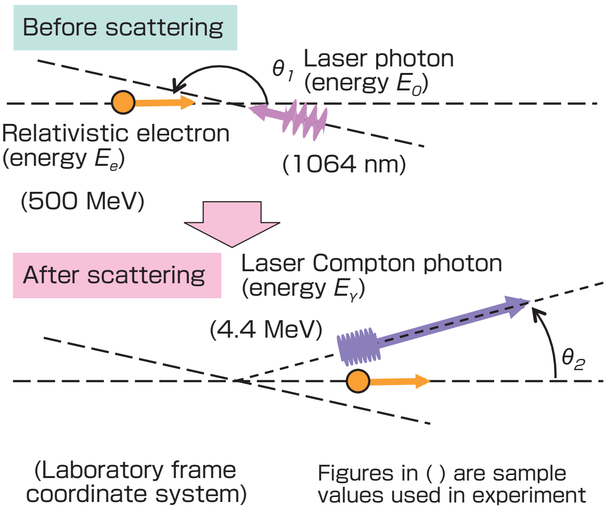

Fig. 1 Kinematics of laser Compton scattering

3 Process of the selection and integration of technologies

(1) Development and sophistication of the elemental technologies

For industrial radiography, a spatial resolution of 1 mm or less is necessary to detect foreign materials. To detect and evaluate the air bubbles in resin, the resolution of approximately 10^{-2} cm^{-1} is necessary as the absolute value of linear attenuation coefficient.[6] A photon flux that passes through a substance exponentially attenuates against the distance travelled, which is characterized by the linear attenuation coefficient that has the dimension of inverse length.

In X-ray CT systems, the attenuation of photon intensity as a function of the penetration depth is assumed to be exponential. However, as shown in Fig.2, the linear attenuation coefficient is a function of the substance and the photon energy. Because the conventional X-ray CT system uses white-colored X-rays that contain various wavelengths (energy), the CT image is the result of the convolution of various X-rays with different linear attenuation coefficients. As a result, many artifacts appear in the CT images. In medical CT, all substances can be considered more or less equivalent to water since the subject measured is mainly living bodies. So, it is possible to correct the artifacts by using a water phantom in medical CT.

Because various substances of wide dynamic range of linear attenuation coefficients will be considered for industrial CT, it is difficult to correct artifacts and to evaluate precisely the density and material distribution. A CT system using monochromatic photons with sufficient transmissivity can

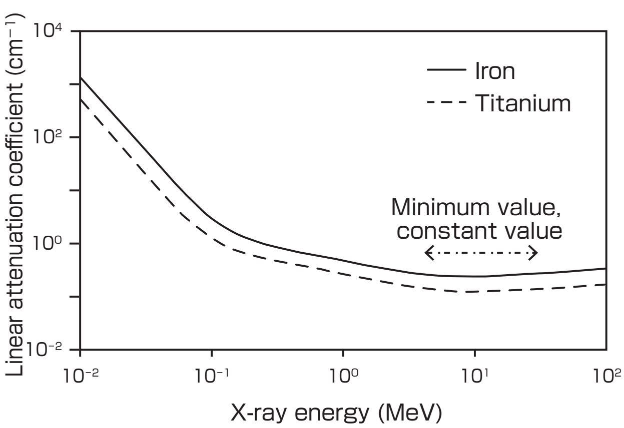

Fig. 2 Linear attenuation coefficients of iron and titanium at 10 keV ~ 100 MeV[6]

overcome this difficulty.

As shown in Fig. 2, the linear attenuation coefficients for industrial materials remain almost constant for photon energy of 5~20 MeV. For example, the linear attenuation coefficient for iron shows a shift of 0.6 % at photon energy of 10 ± 3 MeV. This value is equivalent to the energy spread of several eV per 1 keV of photons. That is, the CT measurement using photons at MeV range of little over 10 % becomes equivalent to the photon CT measurement with energy spread of 1 % or less at keV range, and therefore it can be regarded as using monochromatic photons. The linear attenuation coefficient becomes the minimum in the MeV range for many substances. Therefore, photons readily pass through substances in the MeV range. That is, the photon beams at MeV range are the optimal tool for testing thick samples at high density resolution.

High spatial resolution, high density resolution, and high time resolution (short measurement time) are required for a good industrial radiography system. To achieve these concurrently, it is necessary to scan samples with a pencil-like thin beam at a small pitch, or with a cone-like beam and an X-ray camera with a small pixel with high detection efficiency.

Models that realize these properties are shown in Fig. 3. The diagram in (A) is the CT method where scanning is done using a thin beam, which is called the first-generation CT. The sample is moved perpendicularly to the beam axis, moved up and down, and rotated 360 degrees to measure the transmission image. The diagram in (B) shows the third-generation CT method where the transmission image is obtained without moving the sample by using the cone-beam and the X-ray camera placed behind the sample. While the third-generation CT system has an excellent time resolution, the spatial resolution cannot be improved better than a few mm, because of the scattered X-rays within the camera.

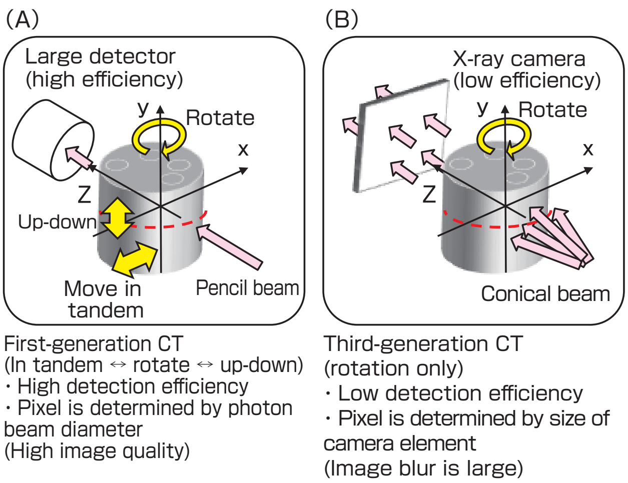

Fig. 3 Explanation of CT generations. (A) First-generation and (B) third-generation.

Because the technical goal of the present research is to develop a prototype industrial CT system using MeV photons, and to demonstrate high numerical performance for density and spatial resolutions with fine CT images, we built a first-generation CT system in this study. The outline of the first-generation CT system developed in this research is shown in Fig. 4.

(2) Open user research

We have successfully developed the elemental technologies and the CT system. The next step was to enhance the utility of the system by supplying the CT system for open use, and to continue discussions with the users on improvement points and requirements. The system was actually released to open user experiments to hear their voices.

We conducted joint research with companies in the automobile and electricity industries in this research phase, and found their demands were to have spatial resolution of at least 1 mm or less, and to detect inhomogeneity in density distribution of 1 % or less. The measurement results of transmission images of industrial products using the present radiography system are shown in Fig. 5 (left). We succeeded in demonstrating the principles but failed to obtain satisfactory images in the photography tests for metal bolts that were conducted in the early stages of this R&D.

Various improvements were conducted to enhance the performance.[7] For example, we improved the alignment precision of the collimator, the spatial-and-temporal collision precision of the laser and electron beams, intensity and stability of the LCS photons, and so on. We made an electron

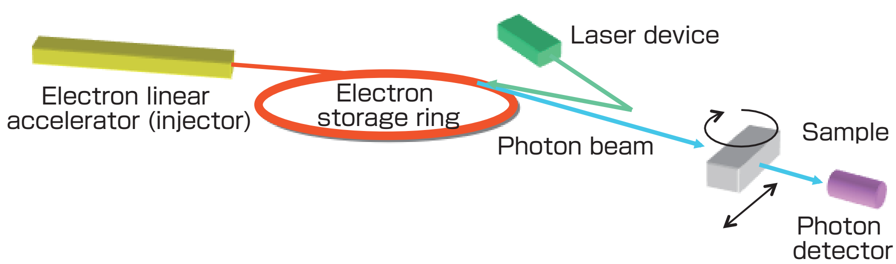

Fig. 4 LCS photon CT system using the electron accelerator

accelerator system that could be operated by one person, so that users could tune the LCS photon energy and intensity online.

The image quality improved, and the CT image of spatial resolution of 1 mm or less was obtained.[8] We also obtained highly precise CT images (Fig. 6).[9] The CT numbers were accurately measured for various substances, and they were proportional to the linear attenuation coefficients in a wide dynamic range. We succeeded in achieving density resolution of 1 % or less (Fig. 7).[10] We were able to demonstrate its effectiveness as a measurement technology for infrastructure diagnosis such as for cracks of 0.2 mm width in concrete and CT of cross sections of reinforced steel concrete with 50 cm thickness.[11] Figure 8 shows how the elements are integrated to make a system.

(3) Verification of the research results

As the automation of the device progressed, it became possible for the users themselves to conduct adjustment operation of the accelerator and to generate the LCS photon beam. This started to produce results in the CT research for open use. Joint research was conducted with companies and universities for many years. In this period, evaluations and improvements of the spatial and density resolutions were conducted, and we were able to achieve the performance that was initially set as our goal.

The users gradually voiced requests for the development of small devices that can be installed in their own factories. To accomplish this, downsizing and cost reduction of the accelerator are mandatory.

We need an electron storage ring or a continuous-beam electron accelerator of a few hundred MeV for the present method. Downsizing the CT system is almost equivalent to downsizing the electron accelerator. However, since the accelerator energy is proportional to the system size, it is difficult simply to decrease the size of each device. More development is needed such as the development of materials and a surface treatment technology that can resist high electric fields of several 100 MV/m or more; a machining technology of nanometer precision and technology; a

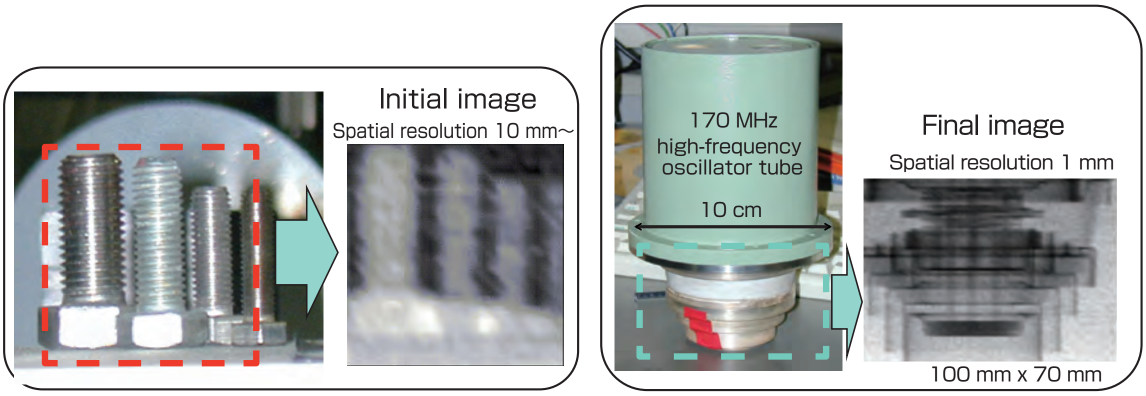

Fig. 5 Transmission radiography using LCS photons
Left: Stainless bolts were photographed using 10 MeV LCS photons (black-white are reversed). Right: Electrode part of high-frequency oscillator tube was photographed using 10 MeV LCS photons (spatial resolution 1 mm; part of the diagram was cited from Reference [8]).

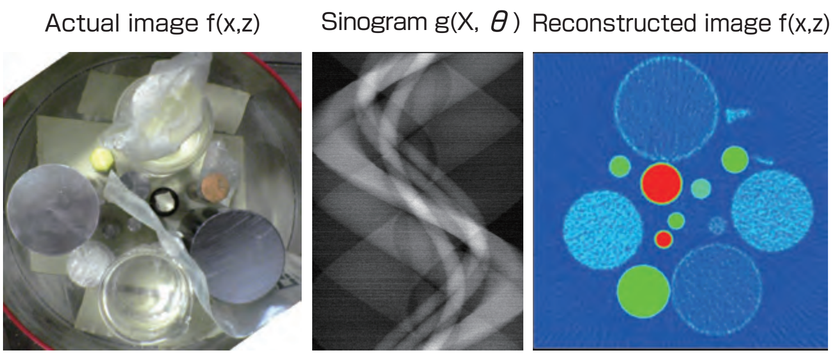

Fig. 6 (Left) Sample photograph, (center) sinogram, and (right) CT image[9]
The samples include water in a beaker and rods of various metals such as silicon, aluminum, and tungsten. Blue to green represent the low density ranges, while yellow to red show the high density ranges.

magnet that can achieve highly precise magnetic field; and improvement in bunch charge density and management of severe space charge effect. Downsizing and weight reduction are also necessary for all parts being used. It is difficult to achieve full performance equivalent to that of a large accelerator system with a small accelerator system. The best way is to develop an electron accelerator of specific performance for specific usage, with a moderate cost.

Now, the usefulness and the problem of an industrial high-energy photon CT system became clear. Unlike the medical X-ray CT system, various materials are the subjects of measurement in industrial radiography. So, it is important to accurately measure the shape, outer and inner sizes, and the density distribution of industrial products using a high-energy X-ray CT system. A research project to evaluate the precision and reliability of the measurement of the inner structure of industrial products obtained with CT images compared with other methods, such as a three-dimensional coordinate measuring machine, is being conducted, as one of the important translational research projects for industry.[12]

4 Future developments

At present, the present research has entered the phase of investigating downsizing and weight reduction of the electron accelerator for a specific purpose. A 0.9 MeV portable electron accelerator system for infrastructure measurement is being developed. We use a coniferous carbon nanostructure (CCNS) material[13] as an electron emitter for the electron gun to minimize the system size and weight. We started up a project to build a radiography system that observes the internal part using backward scattering of X-rays, and to apply this system to nondestructive tests for infrastructures.[14]

Although it may be a repetition of the first chapter, the scenario of the present research is as follows.

(1) Development and compilation of elemental technologies

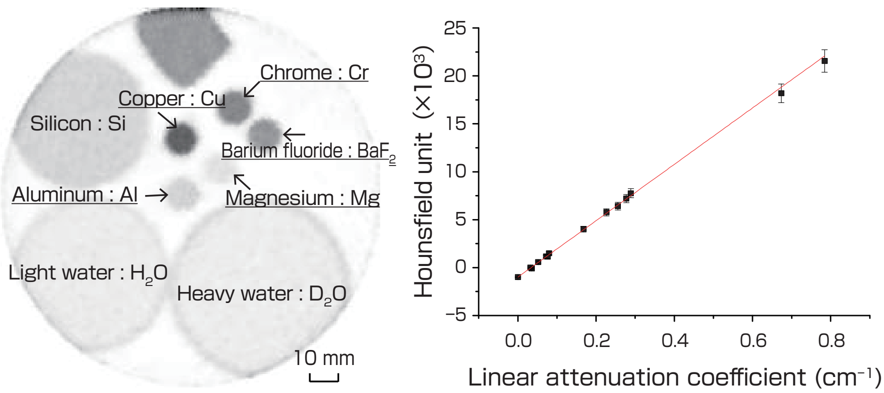

Fig. 7 (Left) Plot of the linear attenuation coefficients of various materials and the CT values expressed by HU.[10] The symbols in the diagram represent the substances, e.g. D_2O = heavy water.

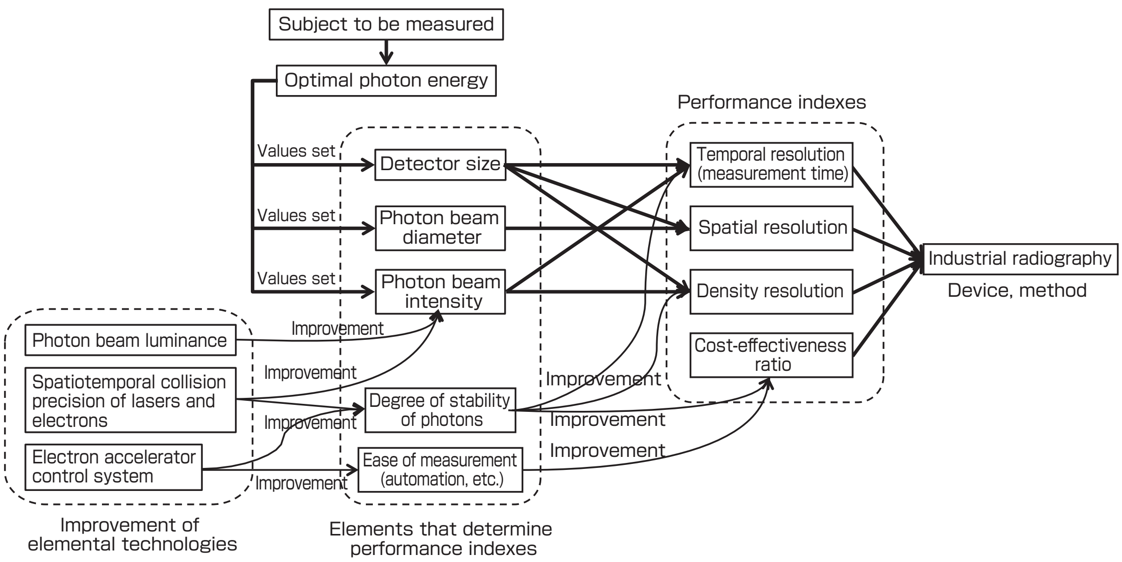

Fig. 8 Improvement of elemental technologies, elements that determine the performance index, and relationship of the sophistication of devices and methods

(2) Open to users
(3) Investigation of plan
(4) Modification of plan

By conducting the research according to the above flow, we believe translational research can be conducted efficiently. Particularly, the user response of (2) is a job that requires concentration and physical energy, and if one stays too long at this phase or concentrate research resources here, the main objective turns into providing stable supply of devices, and we may miss the timing to move on to (3). Phase (2) is a passing point, and it is necessary to make a managerial decision to move forcibly to (3). Since the bridging research involves the researchers listening directly to the social demands, strong consciousness and motivation are generated among the researchers. If translational research is conducted in a bottom-up style, there is danger that the research resource of the organization becomes fragmented and the governance may decline. To promote this research, it is necessary to also conduct revisions to strengthen the organization.

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Discussions with Reviewers

1 Overall

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

This paper describes the application of the laser Compton scattering technology to radiography. It organizes the abundant research results that the author has achieved over the years, and describes the process by which the technologies were selected and integrated to achieve the goal. This paper has solid content that is appropriate for *Synthesiology*.

However, the part on the LCS application in the first half of the paper is a review of the contents that were published in other papers, and does not necessarily address the synthesiological research that is particular to *Synthesiology*. As a paper of synthesiology, I think you should describe in order, what kind of R&D scenario was created to realize the specific goal (application of LCS to radiography), how the elemental technologies were selected, and how they were integrated to realize the scenario. Also, I think you need to add a descriptive diagram to clarify your arguments.

2 Main focus of the paper

Comment (Shingo Ichimura, Strategic Innovation Office, Nagoya University)

As you described in the discussion, why don’t you set the main focus of the paper on the following point: “Basic research results of science and technology conducted by the research institutes are required to be closely bound to corporate activities in many cases. This type of research is “bridging research” or translational research. Bridging research is work whereby one’s concerns and thinking are organized and gradually shaped into a form that can be readily accepted by society.” In other words, I think you should make the “methodology of bridging research” as the main focus of the paper.

By applying this methodology to the case of “high-energy photon beam generation technology and its application to nondestructive testing,” you would be able to organize the contents described in the first half of the paper to show how specifically you sought the landing points of the following issues.

Technical level might be lowered if we easily compromised to produce the outcomes in a short time, or we may become isolated from society if we keep pursuing our own way.By applying this methodology to the case of “high-energy photon beam generation technology and its application to nondestructive testing,” why don’t you organize the contents described in the first half of the paper to show how specifically you sought the landing points of the following issues?

Technical level might be lowered if we easily compromised to produce the outcomes in a short time, or we may become isolated from society if we keep pursuing our own way.

Comment (Naoto Kobayashi)

In the abstract it is written “a summary of the development process (by which a technology takes one form) is outlined,” and thinking that the “form” is “contribution to society” that is valuable for a *Synthesiology* paper, I think it is better to reorganize the paper with focus on “process” and “discussion.” In that sense, if the “bridging research” is set as a goal, I suggest you structure the paper as follows: the contents in chapters 6 and 7 should be presented as a scenario to achieve the goal; the “process” of selection and integration of individual LCS technologies should be described as the elemental technologies that comprise the scenario; and the discussion should be provided in the final chapter.

Answer (Hiroyuki Toyokawa)

Taking your advice into consideration, I totally changed the structure of the paper. The review of technology was kept to a minimum, and the number of chapters was reduced to four.

Chapter 1 describes the background of research and the research disciplines that will be discussed in the paper. Chapter 2 explains the academic background and the process of research along with technological reviews. Chapter 3 presents the specific example of the process of selection and integration of technology. Also, I added Fig. 8 “Improvement of elemental technologies, elements that determine the performance index, and relationship of sophistication of devices and methods” that shows the overall goal and the structure of the technology to achieve the goal. Chapter 4 provides supplementary explanation to the facts presented in the previous chapter, and discusses the significance and positioning of the results. In this way, I attempted to expand this paper to the methodology of bridging research.

However, the task of raising the paper to the level of methodology of bridging research is quite difficult. If I try to universalize the research to a methodology, it tends to get summarized into general terms. The essence of the problem is that the granularity of various information shifts when moving from a specific case to a general discussion, and I think this is exactly the difficulty of this paper.

3 Reorganization of the paper

Comment (Shingo Ichimura)

In the revised paper, chapters 3 and 4 describe the contents according to the topics numbered as follows:

(1) Elemental technologies are developed (in this case five years; outside funds that allow basic research were used).
(2) After demonstrating the principle, use research is started. At the same time, the device utility is sophisticated.
(3) Use research is conducted smoothly.
(4) Points of future developments for devices and technologies are organized.
(5) Whether the research will be continued is determined considering the cost-effectiveness ratio and situations of the organization.
(6) Technological development is started at once after the decision to continue is made.

In the revised paper, overall (1) ~ (2) became chapter 3, while (3) ~ (6) became chapter 4. However, in terms of content, isn’t (1) ~ (4) the first phase of development, and (5) and (6) the following phase built upon the first phase? If this perspective is correct, I think you should reorganize chapters 3 and 4, and divide the topics to a chapter for (1) ~ (4) (title for chapter 3 can be left as is) and a chapter for (5) and (6). I think it will be easier to understand if you add subtitles corresponding to (1) ~ (6). Also, I think the readers will better understand if you provide some detailed explanation for the following points:

A) Even if you select the method called the first-generation CT as “development of elemental technology,” there must have been some developed item that was highly original of the author. One will understand better if there is a specific description on such an item. It can be presented in a simple diagram.
B) In the places that correspond to “sophistication of utility,” what was the subject of investigation, what was lacking, and what advancement did you make to solve the issue? I think you should give a more detailed explanation.
C) In the essence part of the description for (5), I think you should add a bit more description on what decisions you made under what requirements (considerations), and how that led to the conclusion described. This will be useful in understanding the methodology of bridging research.

Answer (Hiroyuki Toyokawa)

I adjusted the whole structure of the paper based on your comments. Also, I have added, deleted, and moved explanations where appropriate. The details are provided in (1), (2), and (3) of chapter 3.

Detection of influenza viruses with the waveguide mode sensor

— Development of a palmtop sized sensor —

Koichi AWAZU*, Makoto FUJIMAKI, Subash C. B. GOPINATH and Xiaomin WANG

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We developed a highly sensitive sensor, based on optical waveguide modes, which was reported in the journal, *Synthesiology*.[1] The first part of the present paper reports the method for reducing sensor size. Applications include identification of influenza virus A H3N2 and other subtypes of influenza viruses. We also found that sialic acid based detection using the waveguide mode sensor system analysis was very useful in distinguishing between H3N2 and H5N1 viruses. Using these techniques, H3N2 and H5N1 strains of influenza viruses have been successfully identified with the waveguide-mode sensor. Sensitivity comparison was also conducted for waveguide-mode sensor, immuno-chromatography, enzyme-linked immunosorbent assay (ELISA), and surface plasmon resonance (SPR). Of these techniques, waveguide mode sensor showed the greatest sensitivity for the H3N2 Udorn strain. The palmtop sized, high sensitive sensor will be useful in border control against intrusion of infections, for example, in aircraft, at airports, and arenas.

Keywords : Bio sensor, waveguide mode, influenza virus, palmtop sensor

1 Introduction

Humankind faced three influenza pandemics in the 20th Century and has already experienced the first one in the 21st Century. The pandemics of the 20th Century include the Spanish flu of 1918, the Asian flu of 1957, and the Hong Kong flu of 1968. The 2009 flu pandemic is still fresh in our minds. Influenza is a communicative disease that must be reported to the authorities.[Note 1)] The Spanish flu developed into a pandemic in seven months, and although estimates of the number of those infected and those who died vary widely, of the affected world population of 1.8 billion people, 1 billion people were infected and 80 million died. In Japan, after the first patient was reported, the disease spread throughout the nation in three weeks, and 42 % of the Japanese citizens were infected and 450 thousand people died. The Spanish flu came to a close in 1920, and economists consider it as the remote cause of the Great Depression that started in 1929.[2] Regarding the 2009 flu that started in the spring of 2009, according to the Center for Disease Control and Prevention (CDC), about 270 thousand people were admitted to the hospital by October 2010 throughout the United States, and 12,000 people died.[3] The reason there were fewer deaths compared to the past pandemics was because the virus was hypovirulent.[Note 2)] It is reported that in total, 20.68 million people were infected in Japan.[4]

Why does such pandemic influenza appear periodically? First, there are three types of influenza: types A, B, and C. Type A has 144 subtypes according to the combinations of 16 types of hemagglutinin (HA) and nine types of neuraminidase (NA) with different antigenicity. In a new strains of influenza, mutation occurs in the HA and/or NA. Names such as type H1N1 influenza are given according to the type of HA and NA. In a new strain of influenza, new types of HA or NA appear among humans, and the antigenic drift and antigenic shift occur, or the influenza genes pass on from birds to humans. In past fact of research, it was found that the Spanish flu was caused by a hypovirulent H1N1 type derived from the avian flu.

There are three reasons why a new strain of influenza is serious. (1) Since a new strain never existed before, no one has immunity. (2) It is highly infectious. It is thought that only an influenza virus that developed the ability for airborne infection causes a pandemic. (3) Since it is an unknown virus, vaccines cannot be made beforehand. Also, as an outstanding characteristic of the Spanish flu, young people developed serious conditions such as systemic infection, multiple organ failure, or a cytokine storm, which is an excessive vital reaction to viral infection. For example, the peak deaths of the Spanish flu occurred in people of ages 24-29. In Japan, there were newspaper headlines that said, “Most productive people were first to fall victims.” The patients spread amongst the most productive people that supported society, and they died and paralyzed the social functions. According to the estimates by the Ministry of Health, Labour and Welfare,[5] if a pandemic equivalent to the strength of the Spanish flu (2.0 % fatality) occurred, 640 thousand people may die. However, since a mutant virus of subtype H5N1 has 60 % fatality rate, there are estimates that greater damage

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Table 1. Number of deaths by avian flu virus
As of June 27, 2014[7][8]

	Number of deaths / Number of infected people
H5N1	393/667
H7N9	118/393

may occur.[6]-[8]

Influenza is a serious problem for animals as well as humans. When infection of poultry or cattle by avian flu virus is confirmed, the current measure is to conduct extensive culling and disposal of farm animals according to the Animal Infectious Diseases Control Law. For example, in 2010, a subtype H5N1 was detected in a poultry farm of Shimane Prefecture, and 21,549 birds were culled.[9] In addition to culling, inspection of the poultry farms in the 10-kilometer radius range, epidemic prevention work, and traffic blocks of the roads to poultry houses are needed, hence generating enormous economic damage. Therefore, if the source of the avian flu is found immediately, and the disease can be contained with minimum culling, wide-range measures do not have to be taken. It also becomes possible to prevent the development of a pandemic, and the economic effect is large. With this lesson in mind, when a highly pathogenic avian flu broke out in a poultry farm of Kumamoto Prefecture on April 13, 2014 (later this flu was determined to be H5N8), the spread of damage was kept to a minimum due to prompt early response.

The issues for types H5N1 and H7N9 are totally different even if they are similar avian flus that are currently at issue. Type H5N1 is hypervirulent and causes fatal infections to many birds including chickens, but the infection from birds to human is thought to be rare. In contrast, H7N9 is hypovirulent, and no symptoms occur in infected birds, and therefore, monitoring of birds' temperature is meaningless. However, although hypovirulent, infection from birds to humans does occur, and people develop serious conditions because humans have no immunity.

Type H5N1 and H7N9 avian flus are no longer problems of animals only. Both viruses can be transmitted from animals to humans. Moreover, as shown in Table 1, the fatality is extremely high. There is also concern for a complication of the problem. By frequent infection of humans, there is the possibility that the flu virus undergoes better adaptive mutations and the infection may spread from human to human efficiently. At this point, both viruses are thought to be transmitted from chickens to humans, and then the humans develop symptoms. However, no one can predict when the situation may change and an epidemic may occur among humans.

2 Benchmark

Normally, for the identification of pathogenic microorganisms, the identification of genes or antigenic proteins is necessary. When the polymerase chain reaction (PCR) or reverse transcription PCR (RT-PCR) are used for gene identification, there is a high possibility of producing false positive results due to the aerosol contamination that may be caused by a leakage of just one positive sample. Although dramatic progresses have been made in the last few years in the digital PCR and the real-time PCR such as qRT-PCR and qPCR that are gene amplification methods in sealed tubes, the possibility of aerosol contamination of the PCR products cannot be denied. Once this occurs, PCR false positive response becomes normal. The manufacturers' guidebooks spend several pages on the methods to avoid contamination, and recommend the preliminary and post treatments to be done in separate rooms, and to prepare exclusive reagent sets, pipettes, and disposable equipment for each room.[10] The PCR analysis method works well only when done by skilled personnel in a well-equipped research facility, but is not suitable for detection and identification in ordinary facilities such as general clinics, airport quarantine stations, meeting halls, or schools. In case of the avian flu virus, detection must be done in the field such as poultry houses, poultry markets, or slaughtering facilities, but PCR is not effective in such environments. If PCR is conducted in the field, even if the negative control is negative in the first test, the possibility of contamination by PCR products increases dramatically in the second measurement at the same place. Another disadvantage is that time is needed for detection and the procedure is complicated. In contrast, the detection by antibodies is a simple method with short detection time and does not require special procedures or gene amplification, although the detection sensitivity does not come close to the genetic test. There is almost no possibility of contamination of the antigenic proteins, because there is no process of amplification of the antigenic proteins.

The immuno-chromatography is the most common method for testing using antibodies. Because it has high National Health Insurance (NHI) points, the immuno-chromatography is widely used for diagnosing types A and B influenza. However, in a recent study in 2009, Hurt *et al.* conducted a sensitivity test using three types of immuno-chromatography and five types of influenza A H1N1 and H3N2.[11] As a result, it was found that the detection limits differed by test kits and target viruses, and the sensitivity was 10^3~10^5 TCID 50/mL. Yamaguchi *et al.* conducted sensitivity comparison using the virus positive control attached to the immuno-chromatography.[12] As a result, in the case of high infectivity titer of 0.7-1.4 × 10^3 TCID 50/mL, the hit rate was relatively high at 98.8 % for skilled clinical lab technicians and 85.4 % for lab personnel (assistant, nurse, or nursing school faculty). However, in the case of low infectivity titer 3.5-7.0 × 10^2 TCID 50/mL, the hit rate was extremely low at 60.7 % for skilled clinical lab technicians and 43.8 % for lab personnel. Baccam *et al*. reported that the A/Hong Kong/123/77H1N1 strain sampled by nose smear reached the maximum value in two to three days after infection, and the value was about 5 × 10^2-1 × 10^3 TCID 50/mL nasal wash.[13] Considering the above three studies, it can be seen that the detection with good precision cannot be obtained by immuno-chromatography unless the virus count reached the maximum after infection.

According to the National Institute of Infectious Diseases, the false positive (true negative) by immuno-chromatography method is seen most frequently in the early stages of an outbreak when the influenza is not yet common in the community, as well as in the final stages.[14] Also, the false negative (true positive) by immuno-chromatography is seen commonly during an outbreak when the influenza is rampant in the community.

The situation is similar for avian flu, and the Ministry of Environment reported that the problem of immuno-chromatography was that infected birds might show negative.[15] For example, the manual presents a case where of the 60 birds that were positive in the definitive test, only 27 were tested positive in the simplified test. Conversely, there were cases where the birds were positive in the simplified test but negative in the definitive test. As a reason, it is explained that the virus in the sample became inactive due to drying or not being kept in low temperature during the period when the virus was taken to the lab and became subject to the definitive test of virus isolation. This means a technology for highly sensitive and quick detection at several digits higher than the current method is needed.

3 Developed content

3.1 Development of portable waveguide mode sensor

We have been developing our original waveguide mode sensors.[16][17] As reported in *Synthesiology*,[1] in the earliest waveguide mode sensor, the waveguide modes were formed in the reflective film layer and the waveguide layer at a certain angle of incidence. When the angle sweep is done using the He-Ne laser at a wavelength of 632.8 nm as the light source, the reflection intensity declines at a certain angle. When the surface condition changes such as by the adsorption of molecules on the surface, it is possible to measure the accompanying changes in the refraction index of the surface. However, in this case, it was necessary to conduct the sweep by synchronizing the two goniometers on the light source and detector sides as shown in the optical system in Fig. 1, and there was a problem that the optical system itself became large and complex. Therefore, we thought perhaps we could not satisfy the user demand for a potable sensor using the angle sweep type. Rather than sweeping the angle, we devised a method for sweeping the wavelength. If a spectrum is obtained by sweeping the wavelength, it would be possible to discard the two goniometers that were barriers to size reduction.[18] Figure 2 shows the simulation results of reflectivity changes before and after adsorption, assuming the adsorption of protein with 5 nm diameter (refractive index 1.45). The calculation was done with monocrystalline silicon layer thickness of 220 nm, silica waveguide layer thickness of 360 nm, prism material of silica, and at s-polarization. Several peaks were observed. For example, there was a peak in the range where the reflectivity change reached maximum at around 500 nm and 68º. From this calculation result, it was found that the target substance could be detected by fixing the angle of incidence and observing the reflection spectrum of the incoming light.

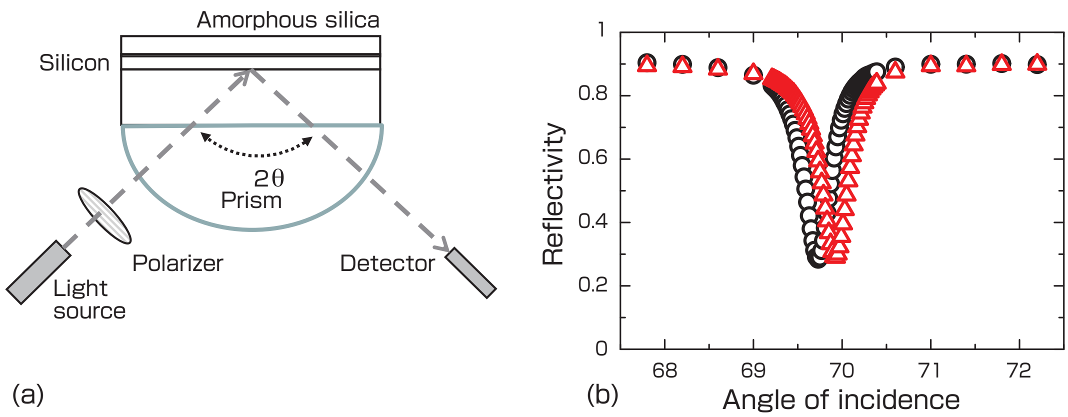

Fig. 1 (a) Optical arrangement of the angle sweeping waveguide mode sensor. Monocrystalline silicon (c-Si) film was laminated onto a SiO_2 glass substrate beneath the prism. The c-Si was thermally oxidized to form an amorphous SiO_2 (a-Si) film, and waveguide modes were formed inside this SiO_2 film. The reflection intensity was observed to change rapidly at a certain angle 2θ. When the molecule adhered to the amorphous silica surface, the value of 2θ changed. The angle 2θ synchronized the two goniometers.
(b) Conceptual image of the molecules adsorbing onto the amorphous silica surface in the optical system (a). The horizontal axis became 2θ. ○ is before the molecules were adsorbed and △ is after they were adsorbed.

Since it was possible to measure using the waveguide modes by sweeping the wavelength, we designed an optical system as shown in Fig. 3. The excitation light reached the back of the measuring site as white light, and the reflected light passed through the collimator lens and optical fiber and reached the spectrometer. The four-point measurement was possible at the measuring site using four light sources. The two goniometers for sweeping while synchronizing became unnecessary in this optical system, and this enabled size reduction.

Figure 4 is a detailed diagram of the measuring site of Fig. 3 during measurement. The detection plate that detected the surface reaction was a SiO_2 glass substrate on which monocrystalline silicon (c-Si) film was formed, and it was obtained by thermally oxidizing silicon to obtain amorphous silica (a-SiO_2). The mechanism was to sensitively detect the surface reaction by designing the thicknesses of c-Si film and a-SiO_2 film so it would be possible to obtain the maximum reflectivity change against the refraction index change on this a-SiO_2 layer surface. Figure 5 is the calculation of electric field intensity distribution near the detection plate surface at a wavelength of 512 nm, silica waveguide layer thickness of 284 nm, and monocrystalline silicon layer thickness of 220 nm. It can be seen that a strong electric field was formed on the waveguide layer surface, and this enabled highly sensitive detection. Therefore, it was possible to capture the refraction index change of the surface upon which the antibodies were fixed and then were made to react with the virus. Also, it was possible to amplify the signal with gold nanoparticles, as explained later.

The process of size reduction is shown in Fig. 6. First, it was an angle-sweeping type where the optical system was set on a two stage plate at 1 m × 50 cm as shown in (a). Later, since it was possible to conduct measurement at waveguide mode by sweeping the wavelength as shown in Figs. 2 and 3, the optical system as shown in Fig. 3 was designed. The excitation light reached the back of the measuring site as white light, and the reflected light passed

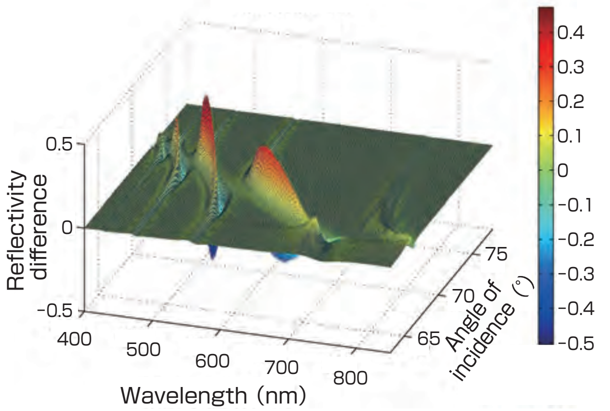

Fig. 2 Calculation results of the dependence of reflectivity change on angle and wavelength

The quantity of reflectivity change is shown in color. The peak of reflectivity change was observed when the wavelength was fixed and the angle was swept, but it can also be seen that the peak of reflectivity change was observed when the angle was fixed and the wavelength was swept.

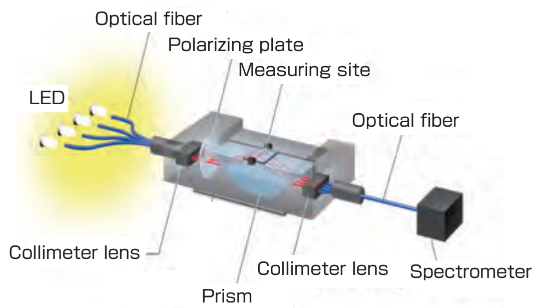

Fig. 3 Wavelength sweeping waveguide mode sensor

White LED was used as the light source. The measuring plate was installed in the measurement site, and the reaction on the measuring plate was detected by reflected light. The reflected light could be led to the spectrometer by installing the optical fiber optical axis.

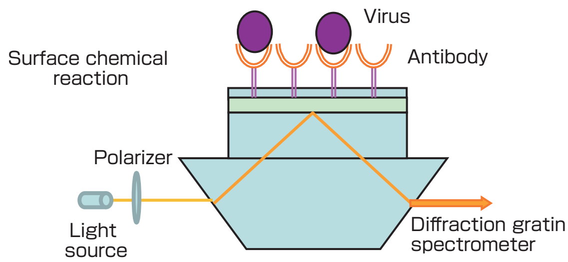

Fig. 4 Optical arrangement of the waveguide mode sensor

Configuration of the SiO_2 glass substrate on a prism and the detection plate was the same as Fig. 1. The outgoing light was dispersed by the spectrometer.

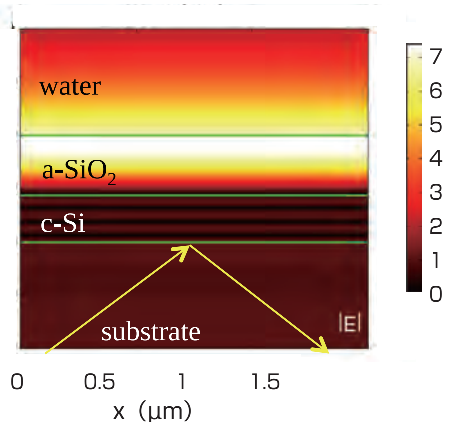

Fig. 5 Electric field intensity distribution of waveguide modes at 220 nm c-Si layer, 284 nm SiO_2 layer, and 512 nm excitation wavelength

Similarly to Fig. 1, the yellow arrow is the direction of incoming and outgoing light. The film thickness and others were designed so the electric field intensity reached the maximum at the SiO_2 layer surface. The scale bar on the side indicates electric field intensity.

through the collimator lens and optical fiber and reached the spectrometer. The two goniometers for sweeping while synchronizing became unnecessary in this optical system, and size reduction (30 cm × 15 cm × 20 cm) as shown in Fig. 6(b) was attained. This device was realized as a product by a company to which the technology was transferred. This device was equipped with a PC, Bluetooth communication, and a battery. We worked on further size reduction of the optical system, and achieved a 7 cm × 5 cm × 15 cm device as shown in (c).

3.2 Identification of influenza subtypes

The identification of influenza subtypes was attempted using the waveguide mode sensor.[20] The polyclonal antibodies were obtained by immunizing healthy rabbits with H3N2 A/Udorn/307/197. These polyclonal antibodies were fixed onto the detection plate surface. After decomposing the four types of H3N2 influenza virus with surfactant Triton X-100, these were reacted with the polyclonal antibodies fixed on the detection plate surface. Then, it was highly sensitized using a label in which the polyclonal antibodies were fixed around the gold nanoparticles. The virus used in measurement was 1 μg. Figure 7 shows the results, and the dashed line shows the reaction with the virus alone, while the solid line shows the reaction of antibodies highly sensitized with gold nanoparticles. The virus types were: (a) A/Shandong/9/1993, (b) A/Brisbane/10/2007, (c) A/Panama/2007/1999, and (d) A/Wisconsin/67/2005. Changes in spectrum reflectivity were confirmed in all types, and although there were differences in reactivity, it was found that H3N2 bonded with the antibodies of the same H3N2. The error was within 20 % for reflectivity changes.

Next, the anti-H3 antibodies were fixed on the surface and

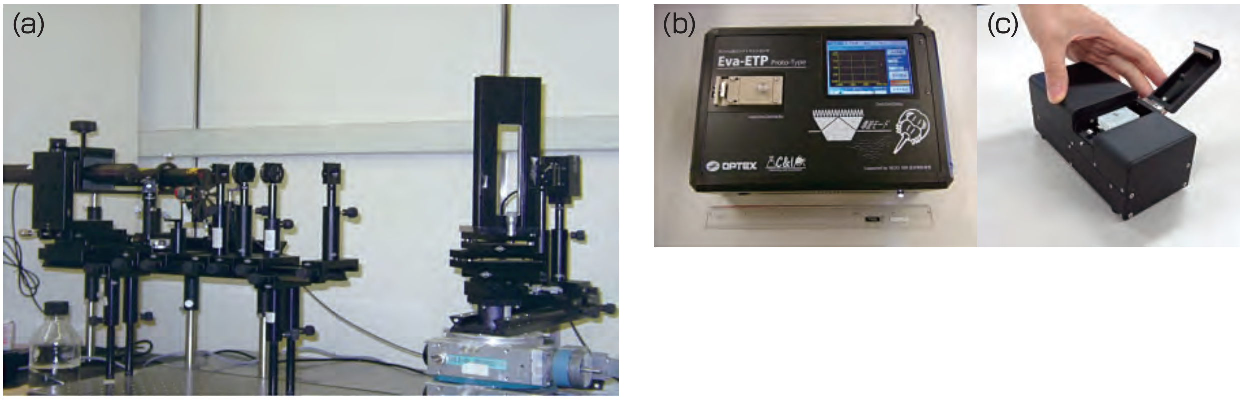

Fig. 6 Process of size reduction of the wavelength mode sensor
(a) Device number one. The optical system was set on a two-stage plate of 1 m × 50 cm. (b) A small device (30 cm × 15 cm × 20 cm) was commercialized as a product from a company to which the technology was transferred. This device was equipped with a PC, Bluetooth communication, and a battery. Further size reduction was conducted, and as shown in (c), device size of 7 cm × 5 cm × 15 cm was achieved.[19]

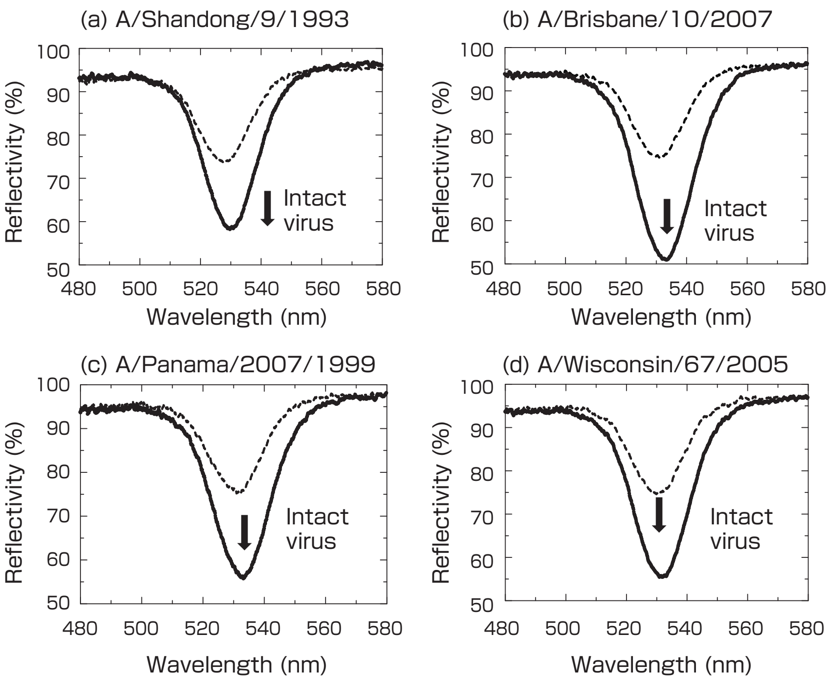

Fig. 7 Results of detection for various types of H3N2 virus using the detection plate to which the H3N2 antibodies were fixed
The subtypes were (a) A/Shandong/9/1993, (b) A/Brisbane/10/2007, (c) A/Panama/2007/1999, and (d) A/Wisconsin/67/2005.

the virus subtypes other than H3N2 were used as detection targets. Since the handling of the H5N1 virus was difficult in Japan, HA proteins were used for all samples. The results are shown in Fig. 8. The dashed line shows the reaction with the virus alone, while the solid line shows the reaction of antibodies highly sensitized with gold nanoparticles. The virus used in the measurement was 1 μg. Figures 8 (a), (b), (c), and (d) show the results of the HA detection test for A/Wisconsin/67/2005(H3N2), A/chicken/India/NIV33487/2006(H5N1), A/California/07/2009(H1N1), and A/Japan/305/1957, respectively. For H3N2, as shown in (a), spectrum change was seen just for the HA. However, no spectrum change was detected in the HAs of other sub-species. This means that the HAs of different sub-species did not bond with the fixed antibodies. Therefore, when the detection plate onto which the H3N2 antibodies were fixed was used, the H3N2 virus could be detected while other sub-species could not be detected, and it was possible to identify the sub-species using the waveguide mode sensor.

We shall introduce another identification method for the influenza virus subtypes.[21] The schematic diagram of the various reactions and the experiment results are shown in Figs. 9 and 10. The detection targets were the virus particles of human influenza type A H3N2, and the HA of avian influenza H5N1. To identify each virus, two types of gold nanoparticles coated with 2,6-sialic acid and 2,3-sialic acid were used as labels. High sensitivity was achieved by using such gold nanoparticles as labels. The HA protein of the human influenza H3N2 virus reacted with the 2,6-sialic acid on the surface of gold nanoparticles, and the spectrum changed [Fig. 9(a) and (c)], while there was no spectrum change since it did not react with the 2,3-sialic acid on the gold nanoparticle surface [Fig. 9(b) and (d)]. In contrast, the HA protein of avian influenza H5N1 did not react with the 2,6-sialic acid on the gold nanoparticle surface and the spectrum did not change [Fig. 10(a) and (c)], while it reacted with the 2,3-sialic acid on the gold nanoparticle surface and the spectrum changed [Fig. 10(b) and (d)]. Hence, simple identification of the HAs of human influenza H3N2 and avian influenza H5N1 viruses became possible.

Table 2. Comparison of the detection limit concentration of the waveguide mode sensor, immuno-chromatography, and ELISA, using the H3N2 Udorn strain

Method	H3N2 pfu/ml
Waveguide mode sensor	800
Immuno-chromatography	8 x 10^4
ELISA	2 x 10^3

Next, type A influenza virus H3N2 Udorn was used for the detection sensitivity test using viruses. Here, comparison was conducted using the plaque forming unit (pfu), which is the index of infectivity, and the results are summarized in Table 2. In the detection test using the waveguide mode sensor, the virus and the antibodies labeled with gold nanoparticles were mixed, and left for 10 min. The mixture was dropped onto the sensor, and signals 30 min later were measured. The data indicated that the detection limit of the waveguide mode sensor would be 8 × 10^2 pfu/ml. For immuno-chromatography, the detection limit was 8 × 10^4 pfu/ml using the same sample. The H3N2 virus detection limit using the Sandwich ELISA method was 2 × 10^3 pfu/ml.

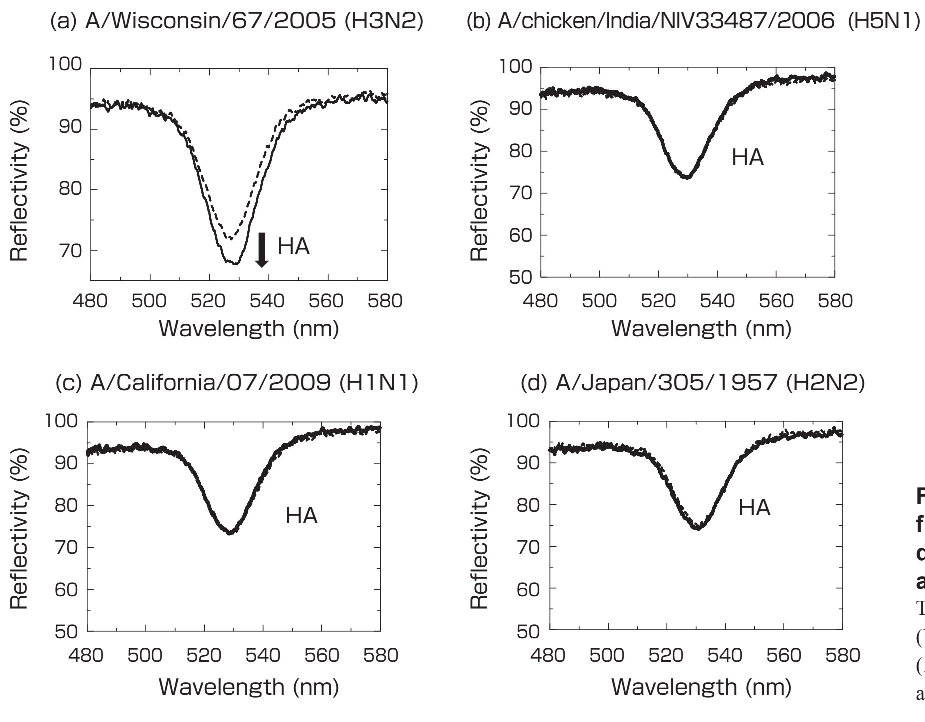

Fig. 8 Results of the HA detection for various subtypes using the detection plate to which the H3N2 antibodies were fixed
The subtypes were (a) A/Wisconsin/67/2005 (H3N2), (b) A/chicken/India/NIV33487/2006 (H5N1), (c) A/California/07/2009 (H1N1), and (d) A/Japan/305/1957 (H2N2).

From the results of the above quantitative tests, it was found that the waveguide mode sensor was one to two digits higher in sensitivity compared to the immuno-chromatography and direct adsorption ELISA methods. The Sandwich ELISA method was troublesome to conduct since the preliminary treatment was complicated and the procedure took several hours to a day until detection, and also it depended on the skill of the testing personnel. Therefore, the waveguide mode sensor technology is thought to have overwhelming superiority over other methods in terms of simplicity of preliminary treatment and time required.

3.3 Nonspecific adsorption inhibiting surface

The important point in the detection by antigen-antibody reaction is to prevent nonspecific adsorption. Surface formation as shown in Fig. 11 was created in a joint research with the Biomedical Research Institute, AIST.[22] Methoxyoligoethyleneglycol-triethoxysilane was used as the modifying material for the silane surface to inhibit nonspecific adsorption of protein. This is an oligoethyleneglycol group where the terminal has been methylated, and it is capable of almost completely inhibiting nonspecific adsorption. Succinimide ester-triethoxysilane was used as the silane surface modifying material to fix the antibodies. The succinimide group was present on the surface terminal to which the antibodies were fixed. By soaking the detection plates with these silica surfaces in two types of hybrid solutions, a high level blocking property and an antibody fixing property were achieved. Currently, it has been confirmed that nonspecific adsorption could be efficiently inhibited in the detection of viruses in serum and plasma. It is expected to specifically detect influenza viruses in nose smear samples.

3.4 Synthesiological discussion

Figure 12 shows the synthesiological description of the above process. The “realization of a simple and highly sensitive influenza virus detector” is the demand and the goal. On the other hand, we already have significant accumulation of elemental technologies of silicon technology, optics, and electromagnetics. To achieve an integrated technology, the fusion of the four fields of elemental technologies, where there were hardly any overlaps, was necessary. By conducting

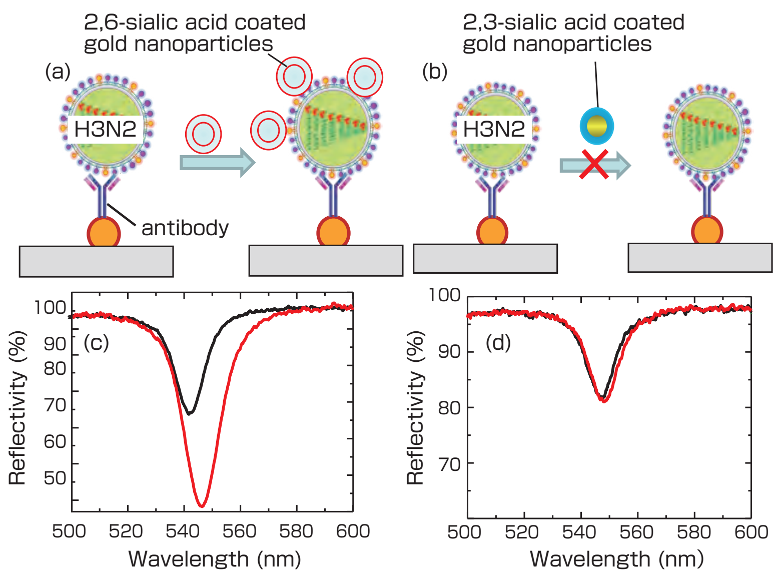

Fig. 9 The H3N2 virus was fixed on the waveguide mode detection plate using antibodies. The gold nanoparticles with diameter of 5 nm were coated with 2,6-sialic acid and 2,3-sialic acid, and were used as labels. High sensitivity was achieved by using such gold nanoparticles. (a) The 2,6-sialic acid on gold nanoparticle surface bonded with the HA protein of H3N2. (b) The 2,3-sialic acid on gold nanoparticle surface did not bond with the HA protein of H3N2. When the reactions of (a) and (b) were actually observed using the waveguide mode sensor, (c) the 2,6-sialic acid on gold nanoparticle surface bonded with the HA protein of H3N2 and the spectrum changed (from black line to red line). (d) The 2,3-sialic acid on gold nanoparticle surface did not bond with the HA protein of H3N2 and the spectrum did not change.

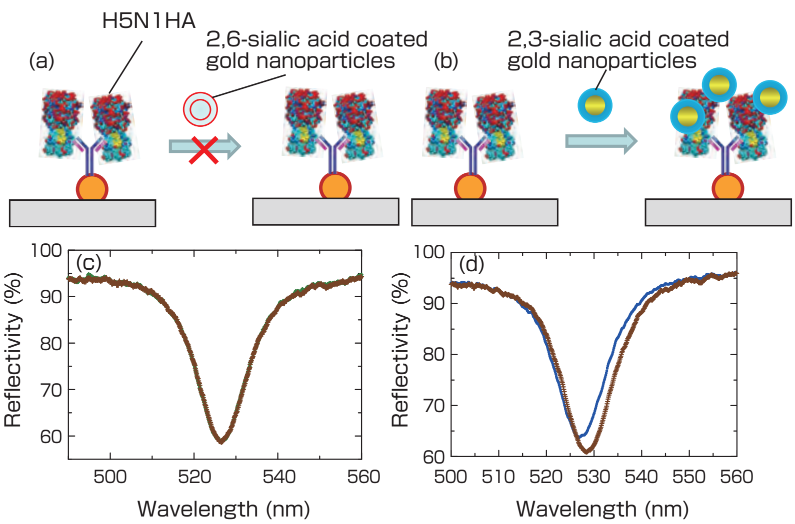

Fig. 10 The H5N1 HA was fixed using antibodies. The gold nanoparticles with diameter of 5 nm were coated with 2,6-sialic acid and 2,3-sialic acid, and were used as labels. (a) The 2,6-sialic acid on gold nanoparticle surface did not bond with the H5N1. (b) The 2,3-sialic acid on gold nanoparticle surface bonded with the H5N1. When the reactions of (a) and (b) were actually observed using the waveguide mode sensor, (c) the 2,6-sialic acid on gold nanoparticle surface did not bond with the H5N1 and the spectrum did not change. (d) The 2,3-sialic acid on gold nanoparticle surface bonded with the H5N1 and the spectrum changed (from red line to brown line).

joint research with the experts of surface chemistry and virology, we succeeded in developing an intermediate integrated technology. Toward our goal, we returned to the elemental technologies several times, optimized the intermediate integrated technologies, and constructed the integrated technology.

4 Process of the fusion of different fields

In this research, the cooperation of the researchers of optical experiment and calculation was necessary to design and fabricate the palmtop sensor. Moreover, we needed cooperation of the companies to realize the design. As the social issue for which the sensor that we fabricated could be used, we received suggestions from an internist for a quick testing method for new strains of influenza. In 2008, the internist commented that if a pandemic of a new strain of influenza occurred, they would be helpless as physicians because the PCR technology at the time took too long and the immuno-chromatography could not determine whether a virus was a new strain. This was one year before the spring of 2009 when a new strain of influenza broke out in Mexico and developed into a pandemic. We believe we can respond to the urgent social demand for quick, on-site identification of new strains of influenza using this sensor. The most important point in observing the surface reaction was the inhibition of nonspecific adsorption. Although there were no descriptions about inhibiting nonspecific adsorption in most papers, it was an important issue in measuring viruses in samples. This was solved through joint research with the Biomedical Research Institute within AIST. This research was achieved through the collaboration of information and technical elements of the researchers in different fields.

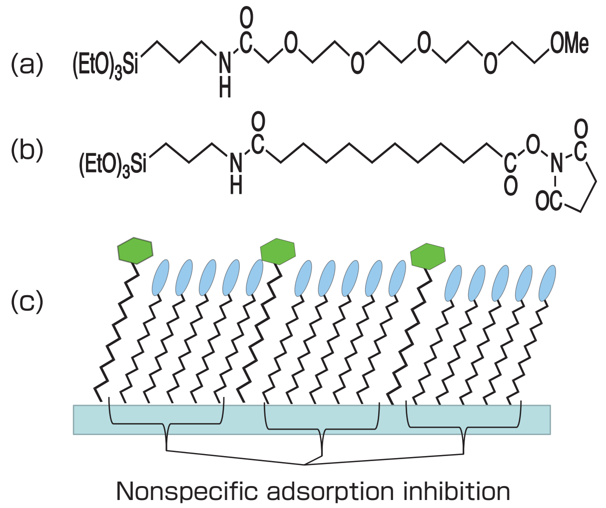

Fig. 11 Nonspecific adsorption inhibiting surface
Triethoxysilane was bonded with (a) methoxy oligoethyleneglycol and (b) succinimide ester. The (a) inhibited nonspecific adsorption, and (b) of the succinimide group bonded with the carbonyl group of antibodies.

5 Conclusion

To achieve a safe and secure society in the future, we think it is necessary to be able to detect various viruses, not just of influenza. Since there is no boundary for viral infection, it is necessary for each country to regularly and carefully monitor the viruses and stop the virus spread at the border. Although it is said that virus infection and temperature, humidity, and bacteria are related, the whole picture is not yet clear. By managing all data with geographical information, it can be developed into a new business such as IT medicine or IT agriculture. In such a case, rather than selling a sensor as a product, there is a possibility for business of packaging the product with service, information, and maintenance.

In this paper, the content was specifically on the detection of influenza viruses. Currently, we are developing a simplified blood testing device using waveguide mode sensors, and we aim to determine the presence of infectious diseases such as B or C type hepatitis as well as blood types. If this can be achieved, it may be possible to provide blood transfusion at refugee shelters in disaster areas or conduct blood tests in ambulances. Also, since it is a system to observe surface reaction, it can be used in the management of production lines such as in the continuous monitoring for deterioration of plating solutions. Several companies that operate plating plants have already shown interest in this application.

Acknowledgement

In this R&D, the students of Professor Yoshimichi Ohki's Laboratory, Faculty of Science and Engineering, Waseda

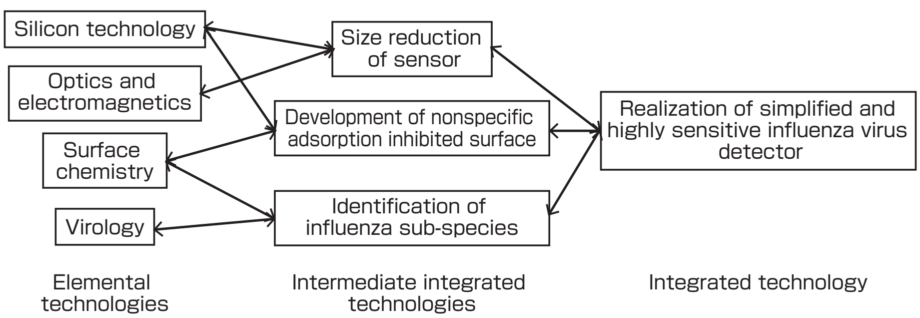

Fig. 12 Synthesiological description

University helped us with the experiments. We received advice on biochemistry and virology from: Associate Professor Kazumichi Kuroda, School of Medicine, Nihon University; and Special Appointment Professor Kazufumi Shimizu, Center for Infectious Disease, School of Medicine, Kobe University.

Notes

Note 1) In Japanese, words for cold and influenza are used interchangeably, but the two are totally different. Influenza is a communicable disease that must be reported to the authority. There are some infectious diseases that must be reported and others that must be reported only at certain designated hospitals. The seasonal influenza falls in the latter category.

Note 2) A clear definition of hypervirulent influenza is difficult. Normally, it is used for avian flu, and one of the conditions is that the protease cleavage site of HA is hypervirulent. In that sense, the Spanish flu is a hypovirulent type.

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Completed the doctorate course at University of Madras, India in 1999. Joined the Academia Sinica, Taiwan in 1999; post-doctoral researcher and technical staff, AIST in 2003-2013; and Associate Professor, Institute of Nano Electronic Engineering, University Malaysia Perlis in 2013 to present. Engages in research of fused disciplines of bioscience and nanotechnology. In this paper, was in charge of overall virus detection.

Xiaomin WANG

Withdrew from the doctorate course at the Department of Electronic Engineering, Graduate School of Engineering, The University of Tokyo in 1999. After working as Visiting Researcher, Telecommunications Advancement Organization of Japan, participated in Femtosecond Technology Research Association in 2000 and engaged in the research for ultra high-speed optical transmission. Engaged in the development of new optical device at the Center for Applied Near-Field Optics Research, AIST in 2003-2010. Transferred to the Nanoelectronics Research Institute, AIST and engaged in the research of new phase-change functional devices. Doctor of Engineering, Waseda University in 2011. In this paper, conducted the numerical calculation of magnetic wave and the optical design for achieving high sensitivity.

Discussions with Reviewers

1 Overall

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

This paper is a report on the R&D of a device that enables simple and quick identification of the influenza virus by detecting the changes in light reflection spectrum using the waveguide mode sensor. It is a detailed description of a process by which an extremely useful method for solving an urgent health and medical issue of society was created. It is an excellent case of innovative creation, and the content is appropriate for *Synthesiology.*

However, since the first draft was a review of the authors' published papers shown in the references, and I suggested restructuring the paper as a description of innovation methodology. As a result, the objective, scenario, elemental technologies, and their syntheses were described in an organized manner, and the paper became appropriate for *Synthesiology.*

Comment (Yasushi Mitsuishi, AIST)

This paper is about the size reduction of a virus detector using the waveguide mode sensor that can sensitively detect the adsorption of nanoparticles, and the company to which the technology was transferred has developed a palmtop device for practical use. This is a paper befitting *Synthesiology.* However, the first draft of the paper spent much space on the presentation of detection data based on the antigen-antibody reaction, and there was very little description about what kind of work was done to reduce the device size or how it was made usable for on-site use. I felt that the goals of the paper were not sufficiently explained.

2 Synthesiological discussion

Comment (Naoto Kobayashi)

In *Synthesiology*, you are required to describe the goal of research, the scenario to achieve the goal, the selection and integration of elements (elemental technologies) to achieve the goal, and the evaluation of the results. Please present a figure that enables ready understanding of the relationship of the above, and describe the relationships of the elemental technologies, intermediate integrated technologies, and the integrated technology (goal) of this research. Also, please describe the general evaluation and future prospects for the R&D method for simplified and quick influenza virus detection.

Answer (Koichi Awazu)

I added Fig. 12 as a synthesiological diagram. The "realization of simple and highly sensitive influenza virus detector" is the demand and the goal. On the other hand, we already have significant accumulation of elemental technologies of silicon technology, optics, and electromagnetics. To achieve an integrated technology, the fusion of the four fields of elemental technologies, where there were hardly any overlaps, was necessary. By conducting joint research with the experts of surface chemistry and virology, we succeeded in developing the intermediate integrated technologies. Toward our goal, we returned to the elemental technologies several times, optimized the intermediate integrated technologies, and constructed the integrated technology. I added such a description to subchapter 3.4 "Synthesiological discussion." I also added chapter 4 "Process for the fusion of different fields" for the general evaluation and future prospects, to match the objective of *Synthesiology.*

3 Superiority of the performance

Comment (Yasushi Mitsuishi)

Since it is already widely known that the specificity of antigen-antibody reaction is extremely high, in this paper, I think the objective will be achieved if you thoroughly describe the work on sensor design to introduce the wavelength sweeping property without sacrificing the sensitivity of the angle sweeping detector, as well as the implementations done to the palmtop device that will make it appropriate for on-site use. Also, please organize the descriptions so you can clearly convey the superiority of the device that can detect influenza virus subtypes precisely, quickly, with high sensitivity compared to the detection methods using the conventional antigen-antibody reaction.

Answer (Koichi Awazu)

Since the concept of shifting from angle sweep to wavelength sweep is difficult to communicate to the readers, I added Fig. 2 that shows the results of the new calculation. I think this figure will help three-dimensional understanding of waveguide modes that appear in the respective sweeping method. The superiority of this method against the conventional ones is shown in Table 2, with the description of sensitivity and measurement time.

4 Response to the result of this research

Comment (Naoto Kobayashi)

In this research, you have developed an innovative method from the perspective of simplification and quickness, compared to the conventional methods that require a long period of time for preliminary treatment and measurement and yet have low sensitivity. I believe the research results have attracted much attention of persons concerned, but how are their responses? If you have any comments or evaluations from such parties, please mention them.

Answer (Koichi Awazu)

As the social issue for which the sensor that we fabricated would be used, we received suggestions from an internist for a quick testing device for new strains of influenza. In 2008, the internist commented that if a pandemic of a new strain of influenza occurred, they would be helpless as physicians because the PCR technology at the time took too long and the immuno-chromatography could not determine whether the virus was a new strain. I think we can respond to the urgent social demands for quick, on-site identification of new strains of influenza using this sensor. I added this point in chapter 4 "Process of the fusion of different fields."

Editorial Policy

Synthesiology Editorial Board

Objective of the journal

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

Content of paper

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

Subject of research and development

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

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

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

Peer review

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

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

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

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

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

References

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

Types of articles published

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

Required items and peer review criteria (January 2008)

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

Instructions for Authors

"Synthesiology" Editorial Board
Established December 26, 2007
Revised June 18, 2008
Revised October 24, 2008
Revised March 23, 2009
Revised August 5, 2010
Revised February 16, 2012
Revised April 17, 2013
Revised May 9, 2014
Revised April 1, 2015

1 Types of articles submitted and their explanations

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

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

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

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

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

2 Qualification of contributors

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

3 Manuscripts

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

research ethics

3.2 Structure

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

3.3 Format

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

Website – [No.] Author(s) name (updating year): Title of a web page, Name of a website (The name of a website is possible to be omitted when it is the same as an author name), URL, Access date.

4 Submission

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

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The submitted article will not be returned.

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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.

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Letter from the editor

The National Institute of Advanced Industrial Science and Technology (AIST) has played a major role in utilizing the results of basic research in society, and has engaged continuously and integrally in basic research to practical application research, ever since its establishment in April 2001. The role of this journal is, as explained in the “objective” at the end of the journal, to accumulate the knowledge to utilize the research results in society. Starting in April 2015, AIST has transformed from *dokuritsu gyosei hojin* or incorporated administrative agency to *kokuritsu kenkyu kaihatsu hojin* or national research and development agency. The fourth medium to long-term period has started. In the goal set for this medium to long-term, there is particular emphasis on strengthening the “bridging (translational)” function to quickly bring innovative technological potentials to commercialization.

Needless to say, the accumulation of the results of synthetic and integrating research activities that is the aim of this journal is also essential for “bridging.” Together with Executive Editor Naoto Kobayashi of the Editorial Board, the author has conducted an analysis of the synthetic methods of 70 papers published in this journal [*Synthesiology English edition*, 5 (1), 37-55 (2012)]. As a result, while there are characteristic synthetic methods for each individual research discipline, it became clear that it is necessary to turn the feedback process several times through social trials for a result to be introduced into society. The paper “Application of laser Compton photon beam to nondestructive tests” describes the process by which the direction of research was adjusted by listening to multiple users’ voices.

Recently, the *Synthesiology* Editorial Board conducted a questionnaire survey to the authors who published in this journal, and obtained 136 responses. 18 % of the authors responded that publishing their paper in *Synthesiology* was highly beneficial, and 69 % responded that it was beneficial. In total, nearly 90 % of the authors responded that publication was beneficial, and I am happy about this result. On the other hand, in recommending others to write for this journal, 58 % responded that the low awareness of this journal was a barrier. The Editorial Board has taken various measures in raising the awareness for the journal, but I think more measures are needed in the future, and I shall appreciate it if you could give us some suggestions.

According to the aforementioned authors’ questionnaire survey, many people responded that it was beneficial to organize their research from a synthesiological standpoint. I feel that the knowledge is being accumulated on the direction of analyzing the synthetic methods, but on the direction of how to synthesize the elemental technologies and how to accelerate the commercialization of innovative potentials using such knowledge still needs investigation. If this direction becomes clear as the journal advances into future, I think the value of *Synthesiology* will rise dramatically.

(Noboru YUMOTO, Senior Executive Editor)

Aim of *Synthesiology*

— Utilizing the fruits of research for social prosperity —

There is a wide gap between scientific achievement and its utilization by society. The history of modern science is replete with results that have taken life-times to reach fruition. This disparity has been called the *valley of death*, or the *nightmare stage*. Bridging this difference requires scientists and engineers who understand the potential value to society of their achievements. Despite many previous attempts, a systematic dissemination of the links between scientific achievement and social wealth has not yet been realized.

The unique aim of the journal *Synthesiology* is its focus on the utilization of knowledge for the creation of social wealth, as distinct from the accumulated facts on which that wealth is engendered. Each published paper identifies and integrates component technologies that create value to society. The methods employed and the steps taken toward implementation are also presented.

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