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HITACHI
Inspire the Next

Innovative R&D Report 2014

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Preface

With people's attitudes and economic circumstances changing at unprecedented speed, modern society is seeking to transform itself as it faces various new challenges that are arising at different levels, including the corporate, community, city, and national levels. Along with the steps it is taking toward reforms based on its own perception of the issues, Hitachi is also focusing on developing its Social Innovation Business.

The Social Innovation Business is about more than the supply of equipment and systems. Rather, it involves working together with society and customers to identify the challenges they face and how these challenges can be overcome, and to offer solutions that combine infrastructure, information, and other technologies.

Possessing a depth of technical knowledge is a prerequisite for dialogue and collaboration with customers. When solving the identified problems, what is also essential is the accumulation of dependable technologies. It is on this basis that this issue of *Hitachi Review* presents articles about the various technologies that Hitachi has built up over time, and aspects of the research and development that underpins them. Along with the analysis and simulation techniques that support leading-edge developments, this includes the various technologies used to maximize energy efficiency and ensure security of supply, to maintain security and speed up information processing in the era of big data, and to improve the reliability and add value to devices and other products. In its leading-edge research, which it undertakes from both a medium to long-term perspective, Hitachi has also introduced initiatives in which scenarios for the future are identified based on trends in society and developed into research topics by debating and sharing visions for the future with customers.

All of these measures conform to Hitachi's key research and development (R&D) policies of adopting a customer-driven research approach, expanding service businesses, and strengthening "number one product" businesses. Hitachi believes that performing R&D on a wide range of business sectors brings numerous discoveries and opportunities for learning, leading to the development of applied technologies and ultimately to the achievement of global innovation.

I hope that you will enjoy the articles in this issue and that they prove useful to all readers.

Keiji Kojima

Vice President & Executive Officer
Chief Technology Officer
President & CEO, Research & Development Group
Hitachi, Ltd.

Innovative R&D Report 2014

Hitachi's Social Innovation Business operates on a global scale.
Research and development (R&D) provides the essential foundations for this endeavor.
Based around the key concepts of adopting a customer-driven research approach, expanding service businesses, and strengthening "number one product" businesses, Hitachi's innovative R&D will deliver a better future for the world by offering promising solutions to the problems faced by society.


HITACHI
$P = \rho T \sum Y_j R_j$
$C_8H_{18} + 12.5O_2 \rightarrow 8CO_2 + 9H_2O$
HITACHI
HITACHI

Frontier Topics Leading Technology Developments from Hitachi

Hitachi is developing technologies that provide the foundations for a diverse variety of solutions with the potential for solving society's problems and delivering innovation.
This article presents some major examples of this work undertaken in recent years.

Healthcare

MRI system with 3-T superconducting magnet

MRI Systems with 3-T Superconducting Magnet

The 3T magnetic resonance imaging (MRI) system* incorporates a superconducting magnet with a static field strength of 3 tesla (T) and features an oval-shaped gantry bore. Since the profile of a recumbent patient extends horizontally, the 74-cm-wide oval-shaped bore provides a less confining environment for large-bodied or claustrophobic patients. Similarly, because the system is able to scan over a wider horizontal range, off-center parts of the body that in the past were difficult to position in the center of the magnetic field for imaging can now be imaged at the field center where the best image quality is obtained. Since 3-T MRI systems are generally prone to non-uniform radio-frequency (RF) irradiation of the torso region, the system maps the RF irradiation level during scanning. The map is then used to perform four-channel/four-port independent control of RF irradiation to eliminate the non-uniformity. This produces a highly uniform image.

* As of November 2014, these MRI systems are only being sold in Japan; FDA and local registration is currently pending.

Proton Beam Therapy System

A proton beam therapy system jointly developed by Hokkaido University and Hitachi has been completed at Hokkaido University Hospital, commencing operation in March 2014. The proton beam therapy system is designed to significantly reduce the impact on healthy tissue, combining both real-time tumor tracking and spot scanning to target the beam accurately even on tumors that move about due to the patient's respiration, for example. The real-time tumor tracking technique developed by Hokkaido University involves implanting a gold marker near the tumor and tracking it using an X-ray machine. The beam is then only applied when the marker is within a few millimeters of the targeted position. Hitachi's spot scanning irradiation technique, meanwhile, uses a constant, narrow beam, repeatedly turning this beam on and off at high speed as it progressively changes location.

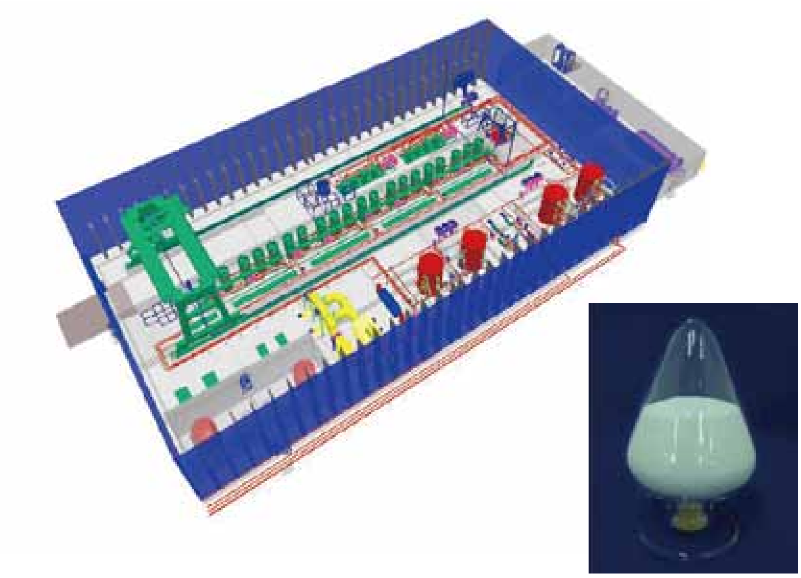
*1 Some of the technology described here was jointly developed by the Hokkaido University Graduate School of Medicine and Hitachi through the Funding Program for World-Leading Innovative R&D on Science and Technology under a scheme designed by the Council for Science, Technology and Innovation.
*2 Manufacturing and sales approval under the Pharmaceutical Affairs Law for the combination of real-time tumor tracking and spot scanning are currently pending.

Completed proton beam therapy system at Hokkaido University Hospital

Power Systems

Adsorbent for Radioactive Nuclide Removal System

There has been ongoing decontamination work at Fukushima Daiichi Nuclear Power Station involving the adsorption of radioactive materials and the desalination of seawater contained in the highly concentrated retained water that has collected at the plant since the accident. Since the concentrated brine produced by desalination contains radioactive cesium (Cs) and strontium (Sr), it is desirable to extract this radioactive material to eliminate the risk of its spreading due to leaks. The newly developed adsorbent uses special processing with titanates to adsorb both Cs and Sr, and to achieve a high removal ratio. A property of the adsorbent is that it selectively adsorbs Cs and Sr even in the presence of sodium, calcium, and other elements from seawater. Testing on samples with a similar composition to the retained water achieved a Cs and Sr removal rate of 99% or better from a volume of water 3,000 times that of the adsorbent.



Treatment plant for water contaminated with radioactive material (bird's-eye view) and adsorbent capable of simultaneously adsorbing two types of radioactive contaminants

5-MW Offshore Wind Turbine

With the installation of renewable energy taking place against a backdrop that includes a feed-in tariff scheme, the construction of a number of offshore wind farms is planned around the island nation of Japan. Since offshore wind farms have higher construction and operating costs than onshore sites, and are more difficult to maintain, they require systems with a high level of reliability and with a high output per turbine. Hitachi has decided to install the first 5-MW wind turbine, HTW5.0-126, at Kamisu in Ibaraki Prefecture. Compared to the previous model, the rated output is 2.5-times higher and the rotor diameter is approximately 1.5-times larger. It also uses Hitachi's own downwind configuration to reduce the wind load during high winds and electric power loss. The incorporation of a newly developed permanent magnet synchronous generator and a medium-speed gearbox make the overall system lighter, more compact, and more reliable.

HTW5.0-126 5-MW offshore downwind power generation system

Frontier Topics Leading Technology Developments from Hitachi

Infrastructure Systems

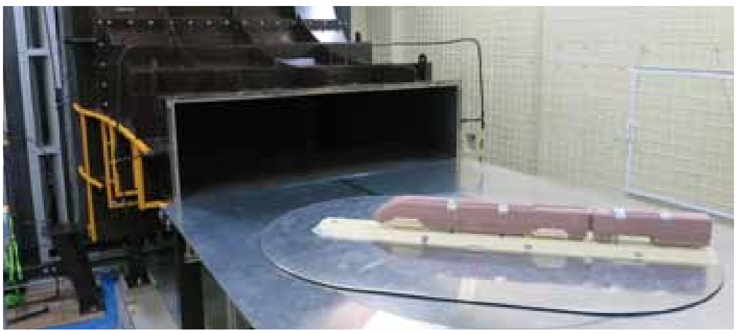
Hitachi ETCS-compliant signalling system

European Certification for Railway Signalling System

In December 2013, Hitachi released an on-board signalling system that is certified under the Technical Specification for Interoperability (TSI) as compliant with the European Train Control System (ETCS) standard. The on-board signalling system consists of a secure computer and wireless communications unit, this can automatically actuate the vehicle braking system based on safety signals transmitted to the train wirelessly from the wayside. The system, which is installed in each train cab, is also intended for installation on rolling stock that Hitachi is supplying for the UK's Intercity Express Programme. The ETCS standard is a common European standard for railway signalling systems that allows trains to operate across borders within Europe. All signalling systems in Europe must become compliant with the ETCS standard. As the only standard for signalling systems intended for intercity services, the ETCS standard is also being adopted outside Europe in countries such as China and India. It has already been applied to more than 68,000 km of railway line around the world.

High-speed/Low-noise Wind Tunnel

The provision of railway services being planned around the world is accompanied by a trend toward higher speeds on inter-city trains, raising issues that include running safety against crosswind and aerodynamic noise generated by rolling stock. However, because of the difficulty of conducting preliminary operational testing using actual-size rolling stock, the common practice is to conduct wind tunnel testing using 1:30 (approx.) scale models of the actual rolling stock to assess its aerodynamic characteristics. Given that many of the next generation of high-speed trains will have maximum speeds in the range of 350 to 400 km/h, Hitachi has taken steps to increase the maximum wind speed of its wind tunnel from 180 km/h to 420 km/h. This was achieved by approximately doubling the length of the flow path from fan to measuring section, and by streamlining the shape of the flow nozzle. It allows the noise generated by high-speed trains to be predicted with high accuracy. The wind tunnel also incorporates functions that comply with the rolling stock safety testing requirements specified in European standard EN 14067-6.



New wind tunnel (measuring chamber) and rolling stock safety test rig

Information and Telecommunication Systems

Flash Module

Hitachi Accelerated Flash, a proprietary Hitachi flash module, provides high-speed data processing while keeping costs low. Hitachi has succeeded in reducing the cost per byte compared to conventional flash memory by giving the module a larger capacity. Hitachi has also developed software that roughly doubles the performance of data processing using flash memory to facilitate the timely analysis or other processing of data within a limited time frame. The online data refresh function, one of Hitachi's distinctive reliability functions, ensures a high level of data reliability by performing periodic data checking and recovery. The smart management function for flash memory cells optimizes the cell refresh interval based on the memory status, simultaneously enhancing data reliability and maximizing cell life. These functions add value to business activities by allowing the data analysis and other processing that occurs in the routine operation of a wide range of application systems to be conducted at high speed, thereby ensuring that analysis results can be incorporated into sales strategies.

Hitachi Accelerated Flash flash module

Hitachi's high-speed data access platform

High-speed Data Access Platform

Hitachi's high-speed data access platform is a data access platform for the high-speed analysis of petabyte-class big data. The ultrafast database engine*1 at the core of the platform achieves data search performance approximately 100 times that of a conventional database engine in storage environments configured using either hard disk drives (HDDs) or flash memory. In October 2013, the platform achieved excellent performance on TPC-H*2, an industry benchmark for search performance on database systems. The benchmarking was conducted for the largest database class (100-Tbyte class), and the system was the first to record results for this class on the public register of performance measurement. Through database products that allow data to be searched at very high speed, Hitachi is contributing to the use of big data analytics to achieve innovation.

*1 Utilizes the results of "Development of the Fastest Database Engine for the Era of Very Large Database and Experiment and Evaluation of Strategic Social Services Enabled by the Database Engine" (Principal Investigator: Prof. Masaru Kitsuregawa, The University of Tokyo/Director General, National Institute of Informatics), which was supported by the Japanese Cabinet Office's FIRST Program (Funding Program for World-Leading Innovative R&D on Science and Technology)
*2 TPC-H is a trademark of the Transaction Processing Performance Council.

Frontier Topics Leading Technology Developments from Hitachi

Construction Machinery

ZH200-5B hybrid excavator

Hybrid Excavator

A variety of background factors, including rising environmental awareness throughout society and a desire to reduce fuel consumption in response to resource price increases, have led to growing interest in hybrid machinery in recent years, including in the construction industry. In the case of construction machinery, however, the demand for products with features such as powerful operation and a high level of practicality means that it is not enough to think only in terms of energy efficiency, fuel economy, and other considerations of the sort that relate to cars. The ZH200-5B is a hybrid excavator that was developed by bringing together the technical capabilities of Hitachi. An upgraded model was released in December 2013. Further improvements were made to the energy-efficient hydraulics system and hybrid system to reduce fuel consumption and carbon dioxide (CO_2) emissions by 15%* compared to standard models. The excavator is also designed for ease of operation, with most of the controls being located next to the seat, and the monitor used to operate the excavator has multi-function screens that support energy efficiency.

* Compared to PWR mode on the ZX200-5B hydraulic excavator, measured using Hitachi Construction Machinery Co., Ltd. measurement procedures

High Functional Materials

Low Dy Sintered Nd Magnet

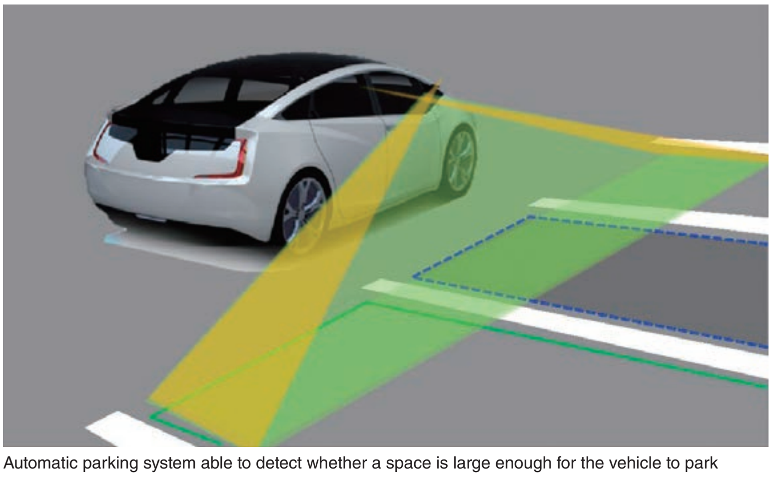
The neodymium (Nd), iron (Fe) and boron (B) rare earth sintered magnet shows better coercive force by replacing the main component (Nd) with dysprosium (Dy) since Dy has a higher anisotropic field than Nd. Increased coercive force improves demagnetization durability, and created huge demand of these magnets in applications requiring heat resistance such as factory automation, electric power steering (EPS), and hybrid electric vehicles (HEVs). But since the scale of the commercial production of Dy is very limited, there was supply and price risk. This technology is focusing on magnetic interaction to improve coercive force for Dy reduction. Coercive force can be obtained by separating the main phase (ferromagnetic phase) with a non-magnetic grain boundary phase. Hitachi succeeded in reducing the weight of Dy used in magnets by at least 2%, utilizing the new knowledge on the effect of the additive element to the phases other than the main phase, and the improvement of the magnetification process.


Nd-Fe-B rare earth sintered magnets

Automotive Systems

Technologies for Automatic Driving

Vehicle requirements in recent years have come to include further reducing the load on the environment, reducing traffic accidents, avoiding and mitigating traffic congestion, improving driving comfort, and facilitating travel by the elderly. In response, Hitachi is developing technology to support automotive manufacturers aiming to implement automatic driving. A technique for providing an all-round bird's-eye view uses four cameras located at the front, rear, and sides of the vehicle to identify nearby obstacles, road markings, and other features. Automatic parking, meanwhile, uses integrated control of the steering, brake, and motive power, and has features that include automatically braking in response to detection of a pedestrian or other vehicle, and detection of whether the space is large enough for the vehicle to park. Hitachi is also developing robotics technology that can anticipate and avoid dangers such as people emerging from corners or blind spots.



Automatic parking system able to detect whether a space is large enough for the vehicle to park

Customer-driven Research Approach

A film of future healthcare vision presented to the National Health Service England (Greater Manchester) in the UK

Social Science Approaches to Design

The Design Division of Hitachi, Ltd. has been developing and utilizing the human-centered design approach based on social science as the R&D for the Social Innovation Business. Ethnographic Research is to carry out the research by observing actual environment for identifying hidden needs and fundamental objectives. Hitachi's original Experience-oriented Approach is a process to collaboratively develop the ideal image of system by sharing challenges and potentials of focused operation among stakeholders in the phase of the upstream process of system development. Vision Design is a research methodology for developing disruptive technologies through illustrating a future vision of society in which the captured social issues are solved.

Overview

Hitachi R&D Strategy

Haruo Takeda, Dr. Eng.

R&D UNDERPINNING SOCIAL INNOVATION BUSINESS

THROUGH its 2015 Mid-term Management Plan, Hitachi is seeking to strengthen its Social Innovation Business, the role of which is to work alongside customers to achieve social innovation by jointly identifying the problems they face, and then mobilizing the technologies, products, services, personnel, and other business resources of Hitachi to deliver solutions to those problems. Since customers operate around the world, Hitachi seeks to bring about social innovation on a global scale. To achieve this, the group is embarking on a transformation that will allow it to fully mobilize its capabilities.

To drive this process, research and development (R&D) at Hitachi is pursuing the following four core strategies in accordance with the Mid-term Management Plan.

The first strategy is to expand its R&D facilities outside Japan. In particular, Hitachi is embarking on new R&D activities in emerging regions. It is also setting up new laboratories at existing overseas facilities to study those fields in which stronger capabilities are required to meet the needs of the Social Innovation Business in that region. Hitachi is also seeking to become more closely engaged with each region by increasing the proportion of research leaders who are recruited locally.

The second strategy is to shift R&D resources toward those research topics that are of most importance to Hitachi's Social Innovation Business. In keeping with the approach described above, Hitachi is focusing on research into products and services, as well as cloud computing and other forms of information technology (IT).

The third strategy is to pursue those R&D topics that are needed to transform the structure of Hitachi's business into a form that suits the Social Innovation Business. This means boosting R&D aimed at reforming product cost structures.

The final strategy is open innovation. Since interaction with customers is the basis of the Social Innovation Business, the R&D divisions are strengthening their dealings with customers around the world, including through Hitachi's growing network of overseas R&D facilities. Alongside this, they are also strengthening collaboration with technology partners in order to satisfy customers' diverse needs. Coordination at the national level, led from Japan, is essential to pursuing innovation on a global scale, and Hitachi's R&D divisions are striving to enhance their ability to achieve this.

The following sections provide an overview of R&D at Hitachi, and a description of the key policies for FY2014 based on these strategies. This is followed by a summary of the articles in this issue of *Hitachi Review* that describe innovative R&D and its role in implementing Hitachi's R&D strategy.

R&D AT HITACHI

Hitachi currently has seven core business groups, consisting of the Infrastructure Systems Group, Information & Telecommunication Systems Group, Power Systems Group, Construction Machinery Group, High Functional Material & Components Group, Automotive Systems Group, and the newly formed Healthcare Group. The groups are organized by market segment, with the Infrastructure Systems Group, for example, dealing primarily with markets and customers in the manufacturing, public sector, urban infrastructure, and transportation sectors, while the Information & Telecommunication Systems Group deals primarily with the finance, public sector, industrial, logistics, and telecommunications sectors. To help create a society in which people can enjoy a healthy and long life, the new Healthcare Group aims to utilize IT and medical technology to meet the diverse needs that arise at each stage of the care cycle, which encompasses prevention and examination, testing and diagnosis, treatment, and recuperation.

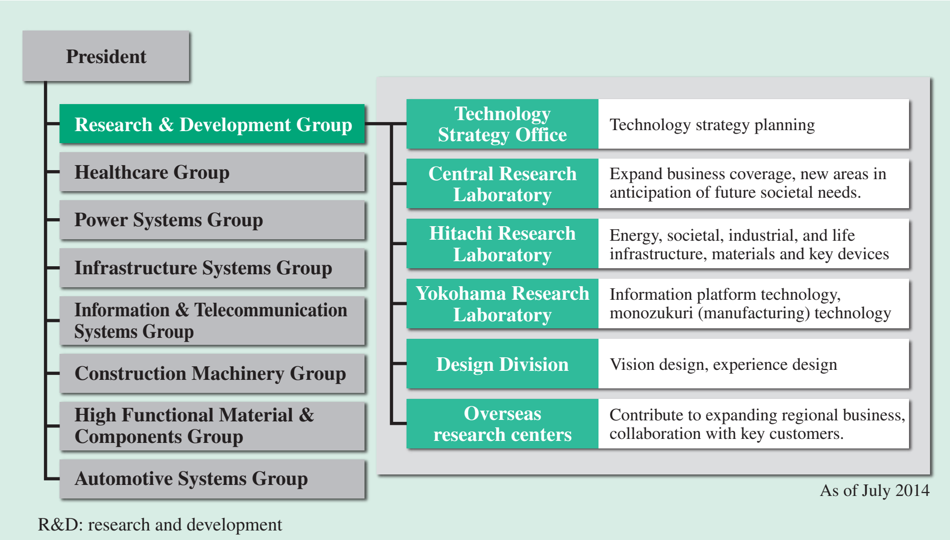


Fig. 1—Hitachi's Main Business Groups and R&D Organization.
The R&D Group engages in methodological and other research from a perspective that transcends the framework of the seven business groups, and that is aimed at the development of common core technologies and the creation of future markets.

Hitachi's annual investment in R&D totals approximately 350 billion yen. The vast majority of this is spent directly by the seven business groups on R&D aimed at meeting the requirements of the markets they serve and their customers in the short to medium term. Accompanying this, Hitachi also has a research and development organization that operates independently of the business groups. This organization operates under the Research & Development Group and consists of four facilities in Japan (the Central Research Laboratory, Hitachi Research Laboratory, Yokohama Research Laboratory, and Design Division) and six overseas (in the USA, Europe, China, Asia, India, and Brazil). It employs approximately 3,300 researchers. The Research & Development Group also includes a Technology Strategy Office to manage the overall R&D strategy for this organization (see Fig. 1).

The Research & Development Group has the following three primary roles:

Developing Technologies that are Difficult to Deal with within Individual Business Groups

Specializing in R&D allows an organization to establish business resources that suit R&D in humanistic/materialistic or tangible/intangible terms. It also makes it possible to establish methodologies for ensuring best practices as well as universal and standardized platform technologies by building on many years of experience in broad market and technology sectors that transcend the framework of business groups. Furthermore, it facilitates selectivity and consolidation through the flexible allocation of research resources based on the priority of each topic. The use of these leads to the solution of problems at a high level in accordance with the research topic requirements from the business groups, or from the market via a business group.

Developing Technologies that Span Multiple Business Groups

Because Hitachi's business groups are organized by market segment, as described above, care is needed to avoid developing the same technology separately in two or more different groups. Also, there are numerous cases in which a technology developed by one group can be used by another, either directly or after further development work. R&D aimed at establishing business infrastructure such as cost structure reform is also essential. Furthermore, beyond considerations of operational efficiency, the centralized development and aggregation of technologies applicable to a broad market segment, or to a number of different market segments, has in many cases led to this technology developing into something with unprecedented significance. Such technologies are not only an important future resource for the Research & Development Group described above, they also provide the impetus for pioneering new markets like those described below.

R&D Aimed at Entering New Markets not Served by Existing Operations, and Helping to Create Future Markets

R&D is being undertaken on the basis of the following core strategies in order to satisfy this proposition, which is of the utmost importance if dramatic progress is to be made by society, customers, and Hitachi.

(1) Acquiring detailed knowledge of the broad range of market information that can only be obtained by operating a diversified business.
(2) Acquiring detailed knowledge of the broad range of advanced scientific information that can only be obtained by undertaking R&D in the diverse technical fields that underpin these businesses.
(3) Researching the humanities, system science, and other methodologies that can identify indicators of social change from this information (big data).

Open innovation (described below) is the key to all three of these strategies.

These are managed for the medium to long term through the formulation of a long-term technology plan under the direction of the Technology Strategy Office.

HITACHI'S MEDIUM-TERM R&D PLAN

Expansion of Overseas R&D Facilities

To achieve a major expansion of its Social Innovation Business in overseas markets, Hitachi is expanding its overseas R&D facilities to strengthen its locally based R&D (see Fig. 2). This expansion is proceeding in terms of three aspects: geographical, quantitative, and qualitative.

Its geographical expansion includes a new facility established in June 2013 in Sao Paulo in the Federative Republic of Brazil. In addition to R&D that combines Hitachi's expertise in information and telecommunication technologies with leading markets such as agriculture and mining in which Brazil has a leading role internationally, the facility will also research and develop solutions that bring about social innovations by studying the nation's social infrastructure issues such as transportation and the supply of electric power. To identify new areas of business in Brazil, Hitachi launched the joint "Kizashi Project[(a)]" with the University of Campinas in FY2013 to predict future trends in that nation.

The quantitative aspect of the expansion involves a plan to increase the number of staff at overseas R&D facilities from approximately 150 in 2011 to approximately 400 in 2015. In particular, the framework of the expansion involves the establishment of four new laboratories beginning in FY2013. The first was the establishment of the Hitachi China Materials Technology Innovation Center at the Chinese R&D facility [Hitachi (China) Research & Development Corporation] in April 2013. This will provide manufacturing technology development and design support for the incorporation of Chinese-made materials into Hitachi products based on joint research into advanced analytical techniques for Chinese-made materials with the School of Materials Science and Engineering at Shanghai Jiao Tong

(a) Kizashi Project
This is a project to envisage the future state of a nation using the "kizashi" methodology of identifying new businesses by predicting social trends based on future changes in the values held by consumers. To envisage the future, desktop research is conducted based around looking at printed or web-based material from the perspectives of politics, economics, society, and technology, and considering how these will interact as they change over time.

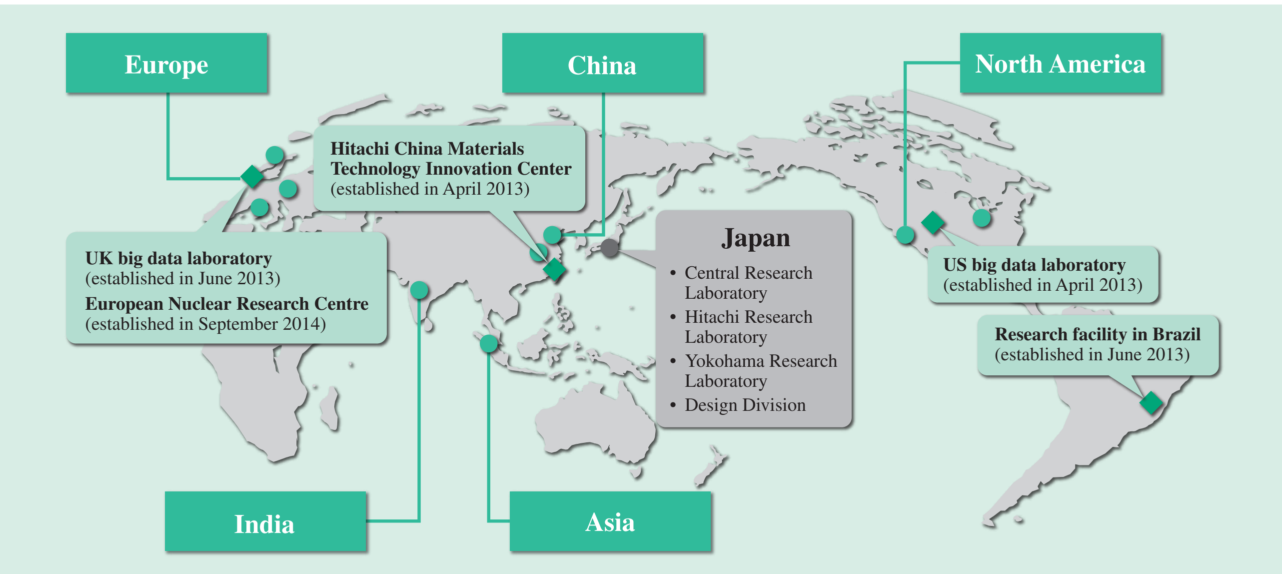


Fig. 2—Expansion of Global R&D Facilities.
Hitachi intends to strengthen locally based R&D by expanding its overseas facilities in terms of geographical, quantitative, and qualitative aspects.

University. The second and third are the establishment of a big data laboratory at the US R&D facility in April 2013 and another at the European R&D facility in June 2013. These laboratories will work closely with research teams in Japan and elsewhere to develop technology analyzing large quantities of data and supplying solutions based on the results of this analysis. The fourth is the establishment of the European Nuclear Research Centre at the European R&D facility in September 2014. This laboratory will work on the development of safe and highly efficient nuclear power technology including preventive maintenance technologies for advanced plants in Europe and proven reactor abolishment technology for nuclear power facilities.

The qualitative aspect of the expansion involves the appointment of more local staff in place of the practice in the past which has been for most overseas facility and laboratory leaders to have been seconded from Japan. The aim is to achieve a major expansion in the Social Innovation Business in global markets by more tightly aligning R&D activities at overseas facilities with their local environment. Local staff were appointed as facility leaders in April 2014. Also, strategy implementation was expedited across all aspects of global R&D, with numerous measures being adopted to achieve tighter coordination of technology strategies between overseas facilities and R&D groups.

Shift in R&D Topics

Hitachi is focusing on the following priorities to shift its R&D resources toward those topics that are most important to the Social Innovation Business.

For markets served by the Infrastructure Systems Group, Hitachi is focusing on innovative technical developments in such fields as transportation and water treatment. These are both examples of infrastructure that existed in ancient Rome, from where the term social infrastructure derives. In the transportation sector, for example, Hitachi is seeking to expand its railway business in Europe by working on technology developments primarily associated with achieving certification for its railway signal system, including obtaining SIL4[(b)], the highest safety rating under the Euro safety standard, and assessing the safety of rolling stock with respect to cross winds in accordance with the European standard.

(b) SIL4
An abbreviation of “safety integrity level,” SIL is a measure of safety level specified in the IEC 61508 international standard for functional safety based on the magnitude of risks posed by plants or other systems. SIL4 represents the highest of the four safety levels.

For markets served by the Information & Telecommunication Systems Group, Hitachi is focusing on the development of innovative technologies such as cloud computing, networks, and big data. In the case of cloud computing, in particular, this includes the research and development of advanced technologies for improving the reliability, boosting the speed, and reducing the cost of cloud systems, for example, among them the world’s fastest mid-range storage systems; flash memory control techniques; technologies for integrating servers, storage, networks, and operation management software to dramatically shorten the time taken to deploy virtual servers; and technologies for the distributed operation of data processing nodes at data centers. Research and development of big data includes an ultra-high-speed database engine and analysis and processing services for data on human behavior (human big data) to solve business problems faced by customers.

For markets served by the Power Systems Group, Hitachi is working on developing innovative technologies that include, for example, the detection of radioactive materials, absorbents for radioactive materials, and an underwater “shape deformation” robot for narrow part investigation for use in the cleanup at the Fukushima Daiichi Nuclear Power Station of the Tokyo Electric Power Co., Inc. They also include control techniques for ensuring stability on grids with a large installed capacity of renewable energy, large electrical storage systems for installation at power plants that use renewable energy, and high-capacity lithium-ion batteries and lead-acid batteries for use by such systems.

For markets served by the Healthcare Group, Hitachi is focusing on the development of innovative technologies to satisfy needs throughout the care cycle, including healthcare IT, medical equipment, and solutions for hospitals. In the fields of prevention and examination, Hitachi is working on researching and developing services that utilize big data analytics for preventing lifestyle diseases. For testing and diagnosis, examples include ultrasound diagnostic equipment and associated diagnostic applications for the early detection of heart disease, and magnetic resonance imaging (MRI) scanners and associated measurement applications that assist with the treatment of neurodegenerative disease through the differential diagnosis of early-stage brain disease. For treatment, examples include Hitachi’s long-time involvement in the research and development of cancer therapy equipment that uses particle beams and automated cell culture equipment for regenerative medicine.

Hitachi Business Infrastructure R&D

Hitachi has embarked on the group-wide Hitachi Smart Transformation Project aimed at transforming the infrastructure of its business to make it optimally suited to the global operations of its Social Innovation Business. Along with their own internal reforms, the R&D divisions are also working on developing technologies that can bring benefits to operations throughout Hitachi.

To reduce direct material costs, for example, which account for the bulk of product costs, Hitachi is working on developing alternative materials that can eliminate the need for rare metals. This work has already produced high-performance electric motors that can achieve equivalent performance despite not using rare metals. These feature a new electromagnet and mechanical design comprising an amorphous[c] stator and permanent magnet rotor, and a technique for speed control without using an angle sensor. Hitachi has also developed new materials for joints in electrical and electronic circuits, including low-melting Vanadate glasses that have a similar soldering temperature to gold-tin solders, but at only one-fifth the cost.

Production accounts for the next largest proportion of product costs. To improve production costs, Hitachi is undertaking R&D on the optimization of global supply chains, for example. This involves working on R&D that considers a variety of factors, ranging from the characteristics of production line design to the tariffs imposed by nations along the chain in particular, and that seeks to optimize everything from suppliers to transportation routes and methods, as well as the location of overseas warehouses and other sites. Hitachi is also developing advanced computer simulation techniques to reduce the number of product prototypes significantly. Simulations that take advantage of the latest information processing have already achieved notable results in reducing the production costs of fluid machinery in particular, including double-suction centrifugal pumps or scroll compressors and fans for air conditioning.

(c) Amorphous
A non-crystalline material with a structure that, like a liquid, is not periodic. An amorphous metal is a solid formed by the rapid cooling of certain alloys from the molten state such that, like a liquid, it does not adopt a crystalline structure. As amorphous metals have lower energy losses than the electrical steel sheet used in motors in the past, their use in motor cores can significantly improve efficiency.

Open Innovation

Hitachi's R&D strategy involves strengthening links with external customers, technology partners, and society through open innovation.

As noted at the beginning of this article, interaction with customers is the basis of the Social Innovation Business. The European Rail Research Centre located in Hitachi's European R&D facilities, for example, has incorporated knowledge of the issues faced by European customers, which are different to those in Japan, into technology development from an early stage. Hitachi has also undertaken a joint experiment with King Abdulaziz University in the Kingdom of Saudi Arabia on water quality monitoring in that nation. It is also researching advanced information and communication technology (ICT) integration platforms for electric vehicles together with 13 partners, including European automobile manufacturers.

To respond to the diverse challenges faced by customers, it is important that Hitachi works with technology partners as well as on its own in-house technology development. For example, the European R&D facility is collaborating with the Cavendish Laboratory at the University of Cambridge in the UK to strengthen basic research. Hitachi is also working with Hokkaido University on particle beam cancer therapy systems and with the Institute of Physical and Chemical Research (RIKEN) on holographic electron microscopes[d] with atomic resolution.

In addition to these specific collaborations, Hitachi has also been working to bring about major innovations in society in cooperation with government innovation policies, including through the activities of the Council for Science, Technology and Innovation of the Cabinet Office.

Hitachi established a research section in 1918, the first such independent research organization, eight years after the company was founded. This was accompanied by the first publication of *Hitachi Hyoron*. The first edition stated the founding principle of the publication to be achieving innovation through the open publication of information in order to "reach a genuine consensus between producers and

(d) Holographic electron microscopes
Also called an electron interference microscope. A microscope that uses electron beam interference to measure phase changes in a material. It can measure not only the three-dimensional topography of a material surface but also atomic-scale electric and magnetic fields by using an image sensor or similar to record the pattern formed by interference between electrons that have passed through the material and the incident beam from the electron source, and then subjecting this to image processing.

consumers.” Now, 96 years later, this remains the core principle of *Hitachi Hyoron*. Beyond this, it has also been adopted as an important business principle underlying Hitachi’s latest mid-term plan. As the most upstream part of a “producer” organization, measures aimed at achieving a “genuine consensus” with “consumers” are at the heart of Hitachi’s strategy for R&D.

KEY R&D POLICIES FOR FY2014

To achieve this mid-term plan, Hitachi has identified the following four key strategies for FY2014.

Shift to a Customer-driven Research Approach

Hitachi is placing greater emphasis on three approaches in particular to make its R&D divisions more customer-driven, this being the basis of its Social Innovation Business (see Fig. 3).

The first is ethnographic[e] research. This is a technique whereby researchers observe the workplace to identify customers’ latent needs and underlying challenges. It has already been used to identify workplace efficiency measures for rolling stock maintenance in the UK. Approaches based on this technique have already been tried in such workplaces as data centers and a factory that produces particle beam therapy systems in North America; construction machinery maintenance in Australia and the Republic of South Africa; and a software development center in China.

The second is the experience-oriented approach[f]. This is used in the planning stages of system development to ensure system requirements development is undertaken in the best way possible by having the people involved learn and share information about the problems faced by an activity or service, and their solutions. Having already utilized it in several dozen projects involving customer activities such as sales, sales agencies, reception desks, call centers, and maintenance and operation, Hitachi intends to further extend this technique.

The third approach is “vision design.” This technique is used to identify future challenges for society and then to paint a detailed picture, from a consumer’s perspective, of what society would be like after overcoming these challenges. Called the “Kizashi Project,” it has already been deployed in Japan and the Republic of Indonesia, with plans in the near future for its use in the prediction of future trends in Brazil in collaboration with the University of Campinas, as noted earlier.

(e) Ethnography
Originally used in fields such as anthropology and sociology, ethnography is a methodology for conducting field work to survey and record the behavior patterns of a society or other group. The term is also used for survey documentation. It has been increasingly used by corporations in recent years to study consumers. Unlike statistical or quantitative analyses such as questionnaires, it is characterized by qualitative analysis using techniques such as interviews or observation.

(f) Experience-oriented approach
The experience-oriented approach is a new system development technique proprietary to Hitachi for working together with the customers who use IT to generate “experiences” (human experience values such as delight, impressions, or intellectual gratification) and share “impressions” during the progress of a project.

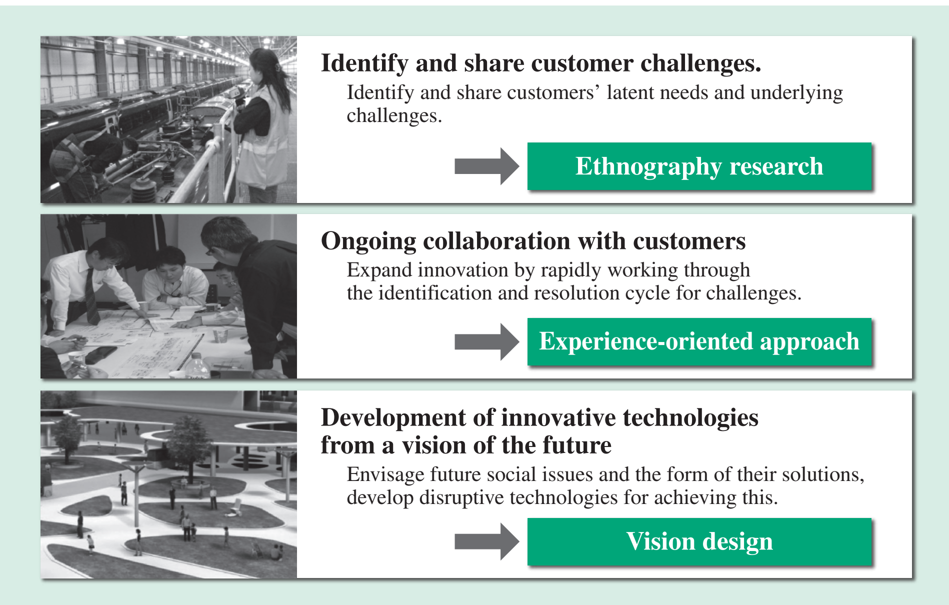


Fig. 3—Customer-driven Approach to Research.
Because a policy of working with customers to identify challenges is important to the Social Innovation Business, Hitachi is placing greater emphasis on its three “research approaches” of ethnographic research, the experience-oriented approach, and vision design.

Expansion of Service Businesses

Hitachi is seeking to expand its service businesses to bring about early-stage innovation with reference to the challenges and other needs identified by adopting a customer-driven approach. To lead this process, R&D at Hitachi is expediting the development of service platforms that utilize such technologies as the cloud or big data, and work aimed at supporting the specific services described below that operate on these platforms.

In the healthcare business, Hitachi is leading the health management service business for health insurers by using big data from the 110,000 people enrolled in Hitachi's health insurance program to study the progression of lifestyle-related and other diseases. Hitachi is also strengthening R&D that provides direction for construction machinery operation and maintenance services used by mining companies, and cybersecurity and physical security services for information and telecommunication businesses.

Strengthening of "Number One Product" Businesses

For product businesses that act as proprietary solution platforms, Hitachi is strengthening, in particular, further technical innovation in "number one products" and the creation of new "number one products" in the following fields.

For the healthcare business, Hitachi is strengthening development of superconducting MRI scanners with strong magnetic fields and particle beam cancer therapy systems. In the case of particle beam cancer therapy systems, Hitachi is engaging in joint development with the Graduate School of Medicine at Hokkaido University and other work under the Funding Program for World-Leading Innovative R&D on Science and Technology (FIRST) operated by the Cabinet Office's Council for Science and Technology Policy (as it was known in 2009), having already developed tumor-tracking[(g)] and spot scanning[(h)] precision treatment techniques, and with further technology enhancements in progress. Elsewhere, Hitachi is strengthening such technologies as the "remove technology of radioactive nuclide" and large offshore wind power generation for the power systems business; railway signal technology for Europe and a wind tunnel with the highest speed in Japan for the infrastructure systems business; flash modules and high-speed data access platforms for the information and telecommunication systems business; hybrid shovels for the construction machinery business; magnets that do not contain dysprosium for the high functional materials business; and automatic driving technologies for the automotive systems business.

(g) Tumor-tracking
A cyclical radiotherapy technique whereby a gold marker is implanted near a tumor and two X-ray fluoroscopes are used to detect its location and calculate it in three dimensions so that a particle beam can be applied at those instants when the marker is within a few millimeters of the intended location.

(h) Spot scanning
A technique for pinpoint irradiation in which the particle beam is scanned over the target area and applied one spot at a time. This allows the particle beam to be targeted with high accuracy to match the complex shape of the tumor.

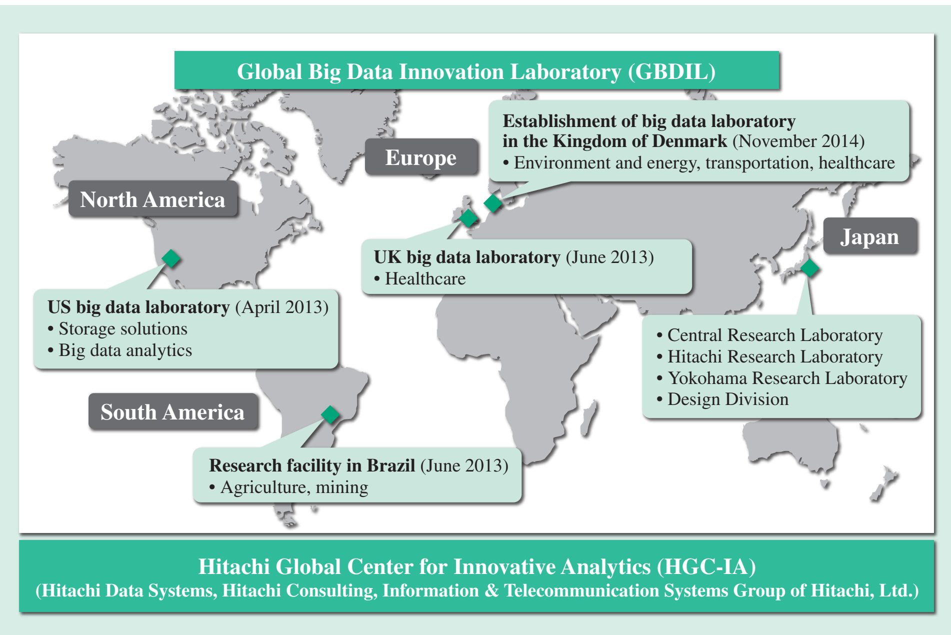


Fig. 4—Overseas Facilities for Big Data Research.
With the research and development associated with big data expected to expand in the future, Hitachi is establishing an organizational structure under which different facilities can work together around its core laboratory in the USA.

Contributing to Expansion of Overseas Business

The three main R&D policies for expanding Hitachi's overseas businesses are as follows.

The first is to build a global research network. In the case of big data in particular, Hitachi has established a structure whereby research facilities in Japan, Europe, Asia, India, Brazil, and elsewhere can work together based around its big data laboratory in the USA (see Fig. 4). In the case of automotive systems, research facilities in the USA, Japan, Europe, China, and elsewhere also work together on engine and chassis development, undertaking R&D that takes account of the different standards that apply in different countries.

The second policy is to build local value chains. In Europe, for example, Hitachi is seeking to establish an organizational structure that spans the entire local value chain, having set up facilities that include the European Rail Research Centre, the European Nuclear Research Centre, and a big data laboratory at the University of Manchester Innovation Centre.

The third policy is the global standardization of operations. For design work, Hitachi has utilized cloud computing to configure an environment under which facilities around the world can access a supercomputer in Japan. For materials procurement, R&D is working on things like materials analysis and production technology to increase the proportion of materials procured locally.

EXAMPLES OF INNOVATIVE R&D

The subject of this issue of *Hitachi Review* is innovative R&D. The seven articles described below provide examples. These articles correspond to the key FY2014 policies for R&D described above.

The first three articles deal with the shift to a customer-driven approach to research. The article entitled "Design Approach based on Social Science for Social Innovation Business" provides a detailed explanation of the ethnographic research, the experience-oriented approach, and vision design referred to above as key policies for customer-driven research. The article, "Concept of Energy Efficient Datacenter in ASEAN Region" has as its starting point customers who, unlike those in Japan, are based in a subtropical climate, describing technology for maximizing the efficiency of data center energy use in such a climate. "Combustion Analysis Techniques for Development of Next-generation Engine Systems" describes technology for designing components and control techniques that are optimal for customers, involving the detailed analysis of the physical phenomena that occur inside an engine.

The next two articles deal with the expansion of service businesses. "Privacy-preserving Analysis Technique for Secure, Cloud-based Big Data Analytics" describes a technology for analyzing customer data in encrypted form. This makes it possible to outsource certain statistical processing to a big data analytics service without divulging the content of the data being processed. "High-definition 3D Image Processing Technology for Ultrasound Diagnostic Scanners—Realistic 3D Fetal Imaging—" describes technology for the ultrasound diagnostic equipment used in obstetrics that provides the basis for a service that provides pregnant women and their families with three-dimensional (3D) fetal images.

The final two articles deal with the strengthening of "number one" product businesses. "First-principles Materials-simulation Technology" describes technology that guides and assists the development of functional materials through the precise analysis of the electronic states of materials. This work is contributing to the development of new materials such as light sources for use in devices that combine photonics and electronics, and magnets that are able to operate at high temperatures. "Light Water Reactor System Designed to Minimize Environmental Burden of Radioactive Waste" describes a nuclear reactor that can burn up the long-lived radioactive waste produced by nuclear power generation as fuel. This dramatically reduces the quantity of long-lived radioactive waste.

All of the technologies described in these articles directly or indirectly contribute to the expansion of Hitachi's overseas business.

POSITIONING FOR THE FUTURE

This article has focused on describing the R&D that is leading Hitachi's 2015 Mid-term Management Plan, with the primary mission of R&D being to lead the future growth of Hitachi over the longer term. In terms of basic research aimed at the further growth of Hitachi that will trigger a paradigm shift, Hitachi is primarily working on human-centered science, life science, information science, and extreme physics. Human-centered science is being approached both from the direction of analyzing such things as brain activity and human behavior, and from the direction of real-world actions performed by artificial intelligence, robots, or other machines[1]. In life science, Hitachi continues to work in such fields as regenerative medicine and single-cell genome analysis. In information science, Hitachi is working on leading-edge research into building silicon devices that can implement qubits (quantum bits), the core of a quantum computer, and also into information storage and telecommunications. Work in extreme physics includes an electron microscope with atomic resolution, advanced techniques for simulating physical phenomena, and the development of associated theories.

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Featured Articles

Design Approach based on Social Science for Social Innovation Business

Kaori Kashimura
Yujin Tsukada
Takafumi Kawasaki
Hiroki Kitagawa
Yukinobu Maruyama

OVERVIEW: As for contributing to the further development of Hitachi's Social Innovation Business, the Design Division of Hitachi, Ltd. has been developing and utilizing a human-centered design approach based on social science. This approach offers three mechanisms: "ethnographic research" for clarifying the fundamental and hidden needs on-site, an experience-oriented approach for revealing issues with customers and co-creating the ideal image by visualizing experience value, and "vision design" for capturing trends in social issues and people's values with an illustration of the ideal image of the future. In this article, the method of applying these mechanisms and their impacts will be explained in detail using case studies.

INTRODUCTION

Hitachi is committed to a Social Innovation Business in which all of its employees currently engage in related activities enthusiastically. Hitachi's Social Innovation Business "integrates cutting-edge information technology (IT) and infrastructure technologies that have been developed over many years (at Hitachi) to improve safety and security throughout society[1]."

The following three considerations are essential for research and development in Hitachi's Social Innovation Business[2]. The first is that providing equipment and systems by the traditional method is not adequate for solving social issues. Every problem of energy, traffic congestion, water treatment, and healthcare involves a variety of stakeholders that naturally complicate its trend of subjects and values. Engagement should not be limited to resolving local issues, but should be able to optimize the entire condition. The second consideration is that accurately identifying the real circumstances from an intense examination of the issues is crucial for solving complicated problems. The reason is that clients themselves actually have a hard time recognizing existing problems due to the complexity of issues. The last essential consideration is that exploring the solution of issues collaboratively with clients who are in charge of the infrastructure business is expected. To be able to research and agree on an effective solution collaboratively requires an active involvement in conventional business objectives such as enhancing the efficiency of indirect operations and shortening the lead time, and a careful analysis of how, when, and why the problems occurred in people's everyday lives and daily business operations. The results of these two tasks must be fully transparent to clients and business partners.

From such a background, the Design Division at Hitachi, Ltd. has developed and utilized a human-centered research design approach based on social science.

DESIGN APPROACHES BASED ON SOCIAL SCIENCE

Typically, most of Hitachi's local business activities are to provide technologies that fulfill the customer's specifications. In Hitachi's Social Innovation Business, it is required to capture the demands of the end users and employees that are to collaborate with customers in the upstream phase of development and to propose specifications that satisfy customers' needs instead of waiting for specifications from customers. And there are many cases when customers ask for a proposed vision of what society should be prior to technological considerations.

Ethnographic Research

Ethnographic research is an approach to social science that performs detailed observation of people's actual behavior with a product or service, which is then analyzed qualitatively[3]. This method is capable of capturing the relationship between people and the environment or man-made objects, and of clarifying an overall image of people's behavior, their underlying values, and their unfulfilled needs and desires. Oftentimes, what users desire is different from how users behave. Actually, there are many users who merely accept a product or a service and are not able to express their disappointment in a survey that asks about any unsatisfactory performance in systems. Ethnographic research is an effective research method for acquiring clues to a solution from clarified hidden needs and fundamental problems that are difficult to obtain in a questionnaire or group interview.

Experience-oriented Approach

The experience-oriented approach is a super-upstream process in system development, which was systematized by Hitachi in 2009[4], [5], [6]. The unique feature of the experience-oriented approach is that in addition to designers, both system engineers and business consultants can engage the discussion in the super-upstream process. By utilizing the experience design technologies that have been cultivated from Hitachi's original design projects over the years, it is possible to visualize the fundamental issues and the hidden needs in a new system image, and to co-create the ideal image while discovering objectives with customers in a collaborative way.

Vision Design

In Social Innovation Business, it is very common that developed products and services will not be implemented five or ten years later. In this case, the ideal image (future vision) of how prosperous life would be and how happiness would be shared in the future needs to be illustrated by capturing the trends in people's values and social issues. Hitachi defines this as vision design[7], [8]. In a society that can achieve the future vision, a highly profitable service can be developed by anticipating how service value would be evaluated and how people would assess the issues.

ETHNOGRAPHIC RESEARCH OF THE PIPE MANUFACTURING MANAGEMENT SYSTEM FOR A POWER PLANT

In this section, the features and effects of ethnographic research will be explained through a case study that was conducted of a pipe manufacturing management system for a power plant.

Purpose

The construction of a power plant is a large-scale project covering 150 km of pipes, 6,000 valves, and 2,100 km of cable. In order to execute the construction without any delays, it is necessary to deliver components such as pipes to the construction site according to a schedule. The situation in this case was that the delivery of 150 km of pipes had been regularly delayed, and it was affecting the progress of construction. This research was conducted for the purpose of extracting the fundamental causes for the occurrence of late deliveries.

Research Subjects

In the pipe manufacturing factory, there are eight processes for different unit workers (see Fig. 1). This research investigated all eight of these processes.

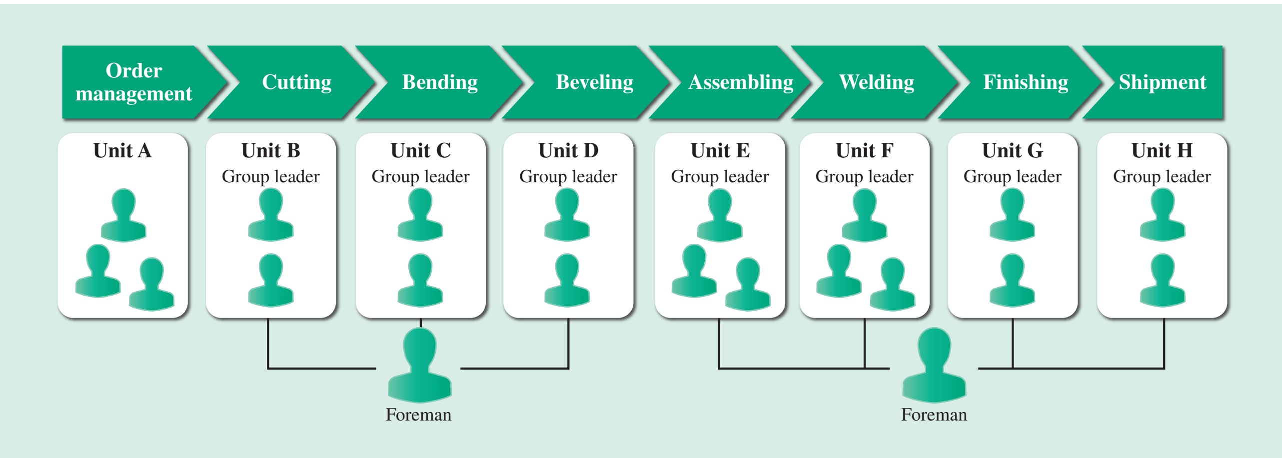


Fig. 1—Overall Image and System of Pipe Manufacturing Processes.
Each unit consists of one unit leader and several unit staff members for different processes.

Fig. 2—On-site Observation.
Capturing the actual operation in detail by working with the on-site worker side-by-side (the ethnographers are on the left and the right).

Research and Analysis Methods

Three company ethnographers visited the factory and conducted 2-3 hours of observation for each unit and 90 minutes of interviews for four days in order to obtain the data. During observation, the ethnographers dressed and equipped themselves the same as the on-site workers. The purpose of this was to differentiate ethnographers from regular visitors and governmental inspectors and to effectively build trust with the participants (see Fig. 2).

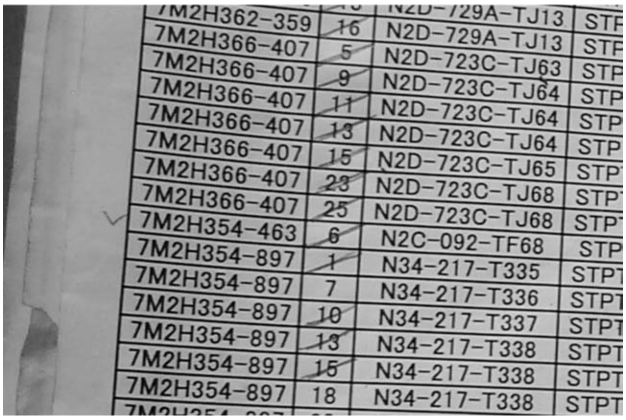
Conducting observations while building trust with the participants allows ethnographers to obtain deeper insights into how workers arrange and perceive their daily tasks. By not focusing on one worker, the information is acquired through observing overall task handling including other workers and engagements with other units. This enabled the ethnographer to identify the hidden needs of workers and the fundamental issues in the organization.

Summary of Research Results

Through this research, the conditions of various handling methods used independently on the workers' own discretion and the reality of unavoidable on-site circumstances were identified. In this section, two of the research results will be explained.

Each Unit Manages its Own Project Schedule

It was discovered that each unit generates its own project schedule for each process as a means of avoiding delays. The schedule for handling each pipe is calculated according to the delivery schedule of pipes (see Fig. 3). This was considered to help smooth collaboration among units because the content was used for making adjustments with other units.



7M2H362-359	16	N2D-729A-TJ13	STF
7M2H366-407	5	N2D-723C-TJ63	STP
7M2H366-407	9	N2D-723C-TJ64	STP
7M2H366-407	11	N2D-723C-TJ64	STP
7M2H366-407	13	N2D-723C-TJ64	STP
7M2H366-407	15	N2D-723C-TJ65	STP
7M2H366-407	23	N2D-723C-TJ68	STP
7M2H366-407	25	N2D-723C-TJ68	STP
7M2H354-463	6	N2C-092-TF68	STP
7M2H354-897	1	N34-217-T335	STPT
7M2H354-897	7	N34-217-T336	STPT
7M2H354-897	10	N34-217-T337	STPT
7M2H354-897	13	N34-217-T338	STPT
7M2H354-897	15	N34-217-T338	STPT
7M2H354-897	18	N34-217-T338	STPT

Fig. 3—Self-generated Work Flow in Each Group.
Marking with red pen and highlighters on the work flow that was generated on personal computer (PC); the work flow was printed from and updated on PC once every two weeks.

This schedule was generated by the unit leader on a personal computer (PC) and was printed out for the daily on-site tasks, but was only updated once every two weeks instead of daily. It did not reflect the situations of the other units in real time.

Units Carry Out Schedule Differently and Change Processes

The schedule was prepared with a series of process steps; however, there were many cases where the tasks were not performed as planned.

For example, unit B, which handles cutting in Fig.1, determines which pipes to work with for that day from the schedule. Their tasks begin after confirming the daily work schedule; however, finding the pipes to be processed in storage occasionally takes more than one hour. Frequently, the drawings also were not prepared sufficiently due to printing delays. From these reasons, the problem of not being able to carry out the task on the original pipes planned for that day occurred.

Each time the pipes were not found or the drawings were not ready, the schedule was changed in order to work on a different task that could be executed immediately because the workers did not wait.

Specify the Mechanism Causing Delays through Analysis

In each observation, it seems like the immediate change was preventing the delivery delay; however, one change of a unit definitely affects the tasks of other units in a collaborative labor of eight units.

When unit B, which was in charge of cutting, worked on other pipes as described above, pipes of a different diameter would be delivered to the next unit, C, unpredictably. During the bending process, it is more efficient to carry out one task on the same diameter of pipe at once due to the time-consuming process of adjusting the diameter of the machine. If different diameter pipes were delivered from unit B, then unit C would not be able to carry out one task for the same diameter pipes and spent an enormous amount of time on adjusting the diameter of the machine.

Why would unit B change the schedule and deliver different pipes the next time? And why did not unit C stop the task for the moment? It was determined that the workers felt strong pressure from a lack of tolerance for any delays due to chronic delivery delays that were happening all over the pipe manufacturing factory.

With a schedule that is only updated once every two weeks, it is difficult to grasp the status of other units and to arrange procedures with a long-term perspective. As a result, the workers could only focus on the tasks of their own unit.

Thus, a situation in which it was easy to make short-sighted decisions from the schedule without an overall view of it, and the strong pressure of "preventing delivery delays" that caused each unit to make decisions that were best for its part of the process, instead of what was best for the whole process.

Improvement Proposal

A specific IT system that is capable of capturing the status of work flow in real time was implemented to solve the difficulty of inspecting every detail at the work site. The situation where workers were spontaneously changing the process flow in order to optimize their work actually intensified the delays. This key finding was explained fully to the on-site workers. Through these two improvement features, the on-site workers changed their attitudes towards daily tasks and were able to engage in the improvement plan independently so as not to repeat the same mistakes with the newly installed IT system.

As a result, the delay rate was successfully reduced from 17% to 1% in the piping manufacturing process.

Impact of Ethnographic Research

As described above, ethnographic research is a method that is capable of obtaining data that is difficult to reveal through other research methods. That data can consist of the background and the mechanisim of problems occurring on-site. An enormous impact can be achieved by resolving the fundamental problems.

Furthermore, ethnographic research is not only capable of transforming workers' attitudes towards their own daily work routines and of smoothing the implementation of new systems by sharing the research results, but is also capable of leading to the improvement of operation processes.

Hitachi will utilize ethnographic research in various industrial fields starting with its Social Innovation Business as one of the methods for capturing fundamental objectives on-site.

APPLICATION OF EXPERIENCE-ORIENTED APPROACH TO RESEARCH OF ACTUAL CONDITIONS IN EVACUATION CENTERS OF SENDAI CITY AND TO DEVELOPMENT OF A DISASTER MANGEMENT PLAN

After the Great East Japan Earthquake, the City of Sendai and Hitachi, Ltd. initiated a disaster management solution, known as the "Sendai Model," for the purpose of sharing experience that has been learned worldwide. They cooperated in conducting research at the evacuation centers, which was the main concern for citizens, and in developing an effective solution model.

In this activity, the evacuation center's actual conditions, which were relatively unknown, were carefully examined with a consideration of the various stakeholders' perspectives. In addition, solutions that were required by the evacuation center were structured with the perspective of optimizing operations, facilities, systems, and so on.

Investigation/Research Methods

The following four challenges were encountered while conducting the research.

(1) All evacuation centers in Sendai City were closed at the beginning of this research.

(2) Problems of the evacuation centers were different in different disaster-stricken areas.

(3) Management officials at each evacuation center have different views due to their positions.

(4) Five months had passed since the earthquake, so the memories of the local officials and the community directors were fading.

With these challenges in mind, the experience-oriented approach was applied as the investigation approach for conducting research and developing a solution. The experience-oriented approach is

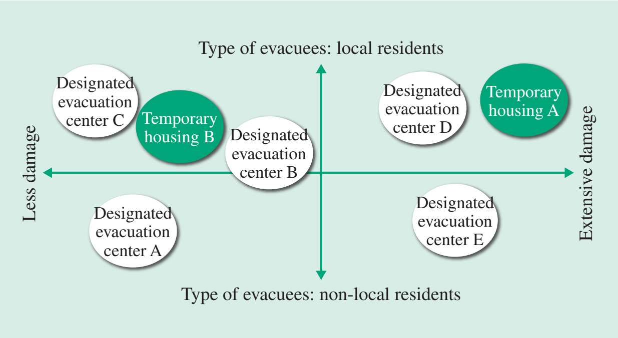


Fig. 4—Characteristics of Researched Evacuation Centers.
Seven evacuation centers are selected that are basically different from the perspectives of the size of disaster and the composition of evacuees (ratio of local residents and non-local residents).

Hitachi's own original method for developing opitimized requirements while emphasizing "user experience (the value of experience)."

Research Subjects

Seven locations were chosen for this research. These locations included the coastal region where the damage was severe and the inland region where the problem was residents who were unable to return home (see Fig. 4).

Interview Subjects and Methods

The evacuation center directors, the community directors, and the local officials were the interview subjects for a total of 17 rounds of interviews (27 people in total). The interview method used was an in-depth interview that was designed and conducted by the researchers of Design Division, Hitachi, Ltd. Taking the possibly ambiguous memories of the stakeholders into consideration, a "time series chart" was constructed for each evacuation center. From this chart, the actual conditions on-site were extracted from the experiences that were recovered by the interviewees.

This time series chart is a table that allows all the events that occurred from the opening of an evacuation center to its closing to be plotted. The main content included the number of evacuees that were accommodated, the status of lifeline infrastructure such as electricity, water, gas, and public transportation in the area, the activities of the facility directors who operate the evacuation centers, the community directors, the evacuees, and the local government officials, and the daily reports that were provided by Sendai City (see Fig. 5 and Fig. 6).

After each interview was conducted, the new findings would be added to the chart. If the original content was different from the findings, the chart would be revised carefully. With the support of the Sendai City officials, the findings were reconstructed and the actual conditions of the evacuation centers were shared utilizing these time series charts.

Actual Conditions and Issues in the Evacuation Centers

Due to the fact that the degress of damage was different in each of these seven evacuation centers, the period of operation from opening to closing and the problems that occurred were unquestionably different. This research was able to extract the fundamental issues at each evacuation center by examining three phrases: coming to the evacuation center (Coming), living in the evacuation center (Living), and leaving the evacuation center (Leaving) (see Fig. 7).

In terms of the policy for responding to these issues, it was possible to identify two essential areas in which disaster relief resourses should be concentrated.

Date	3/10	3/11	3/12	3/13	3/14	3/15	3/16
Number of evacuees	XXX	300	2,300	1,200	XXX	XXX	XXX
Infrastructure conditions			Electricity	Water	Gas		
Designated evacuation center facility director	XXXXX	XXXX	XXXX	XXXX	XXXX	XXXXX	XXXX
Community directors	XXXX	XXX	XXX				XX
Evacuees	XXX	XX	XXX				XX
District office	XXXX	XXXX	XXX				XX
Other	XXX	XXXX	XXX	XXXX	XXX	XXXX	XXX

Events recorded in the daily reports were plotted on the time series chart.

Fig. 5—Image of Time Series Chart.
The stakeholders of the evacuation centers are listed vertically, the time frame is listed horizontally, and then the information from the daily reports of the evacuation centers are plotted accordingly.

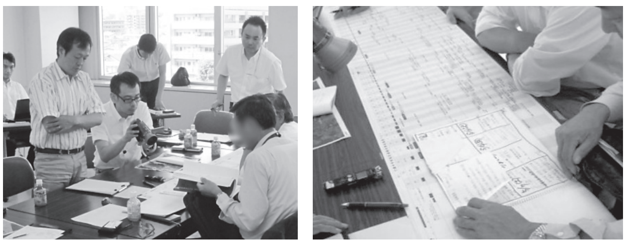


Fig. 6—Interview Research Using Time Series Chart.
The actual conditions that are not described in the daily reports of the evacuation centers are obtained in interviews by asking the stakeholders to recall the event from the disaster training prior the Great East Japan Earthquake to opening/closing the evacuation centers after the disaster.

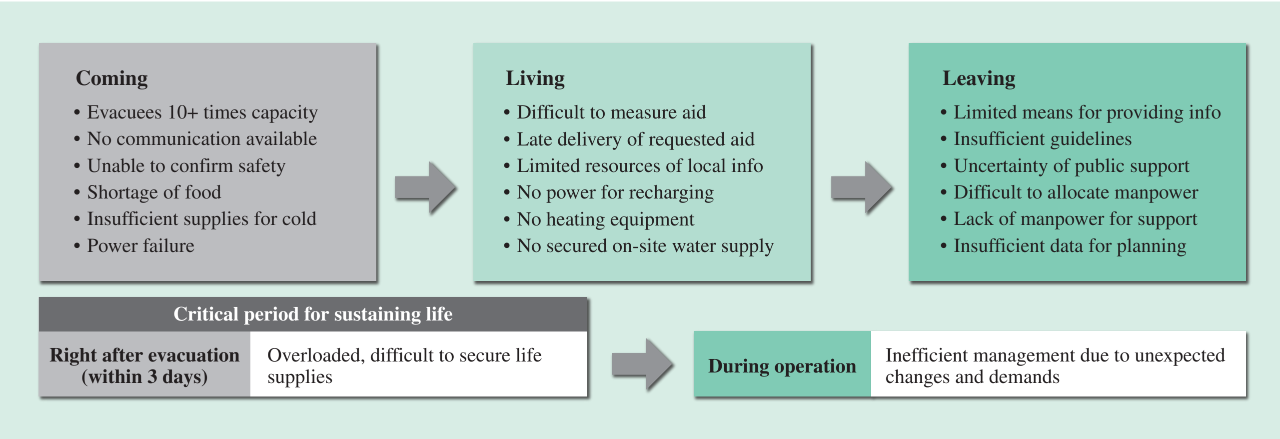


Fig. 7—Changes in Issues from Opening to Closing the Evacuation Centers Obtained from the Research Results.
The three phases of an evacuation center, with its distinctive conditions and concerns, are identified for further analysis. Responding to evacuees' changing needs during the several months of evacuation life is required for operation.

One is in maintaining the lives of the numerous evacuees who were evacuated temporarily due to not being able to return home in the first three days right after the disaster. The other is in operating evacuation centers safely and efficiently while responding to the evacuees' needs, which vary as time passes in the middle period of an evacuation.

Re-examining Disaster Management Plans

The findings listed above were analyzed, disaster management plans were developed, and the following recommendations were concluded.

Considering the Grouping of Evacuation Centers

In Sendai City, there was a "centralized" management system for evacuation centers. The city office managed each district office, which handled the evacuation centers within the district. In addition, the "lateral connections" between the district offices and between the evacuation centers were weak.

Capturing the reality of the disaster status was difficult because the coordination with the disaster management officials did not proceed smoothly because the local government was also damaged by the disaster. One method of solving this issue of "centralization" is to develop a management/coordination system that is a "self-governed spreading" style.

The "self-governed spreading" system will allow the nearby evacuation centers to create an "evacuation-center group" that is centered around a disaster management base. This group will allow the evacuation centers to support each other during a disaster. If the local government is damaged by a disaster like this time, the evacuation centers can help each other within the group before public aid can be put into place. After public aid is functioning, the representative of the evacuation-centers group can report and request the local government to provide support and make adjustments accordingly (see Fig. 8).

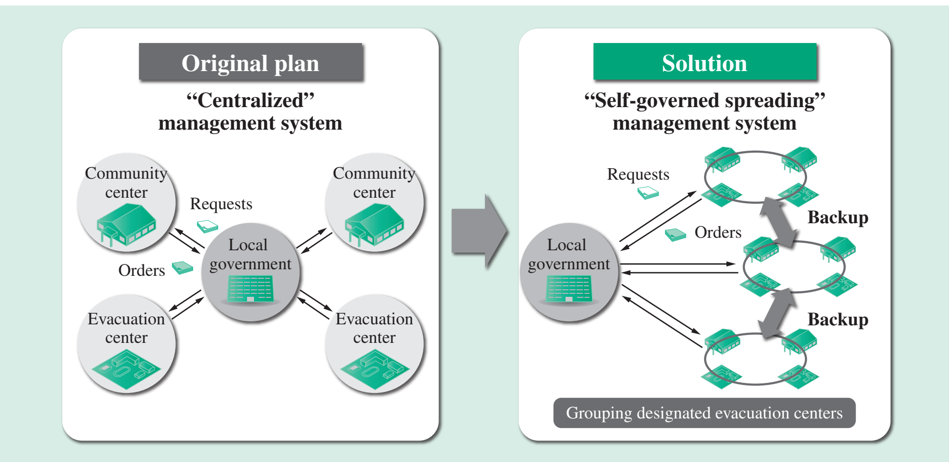


Fig. 8—Concept of "Evacuation-center Group" by Using "Self-governed Spreading" System.
A grouping system that allows nearby evacuation centers to support each other in case local government is unable to function after disaster.

The conclusion was that it is possible to efficiently manage and coordinate evacuations by balancing the "utilization and control of self-governance" where local government is in control of multiple "evacuation-center groups" while each "evacuation-center group" is proficient at operating its own disaster relief activities. Like the Great East Japan Earthquake, it is possible that an entire "evacuation-center group" could be damaged totally based on the scale of the disaster. To prepare for this kind of catastrophic case, a mutual support framework (a "sister evacuation centers" concept) of the coordinated "evacuation-center groups" that connects evacuation centers with different geographical features (e.g., coastal or mountainous regions) would be effective.

Classification of Management Plans for Evacuation Centers

Evacuation center planning was established uniformly for all the local governments regardless of their geographical differences. However, in reality, the types of regions of evacuation centers can be largely defined as "urban" and "suburban." The type of disaster victims who were in each evacuation center can vary depending on the factors of the surrounding environment (whether it is in a business district or near a major station) and the population during the day or night (e.g., having fewer people but mainly elderly during the daytime).

It would be ideal to conduct a test for the features and the needs of the disaster victims in each evacuation center. However, in reality such testing is impractical. Therefore, the evacuation centers' operations were classified into four types depending on their regional characteristics. It was proposed that evacuation center management should be planned and prepared for according to each regional type (see Fig. 9).

For example, the "urban" type requires communication methods and creation of strategies for evacuees who come in other than local residents, such as the effective utilization of office buildings or commercial facilities and the investigation of information transmission methods for massive numbers of evacuees.

On the other hand, the "suburban" type of evacuation center requires the support of self-governed evacuation and recovery activities of the local community, such as allocation of user-friendly equipment for women and children with the assumption of managing the evacuation during the day time and acquiring telecomunication methods to avoid creating any isolated areas.

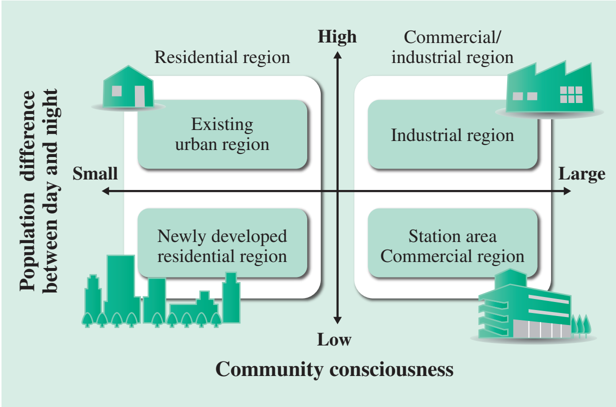


Fig. 9—Categorization of Evacuation Operations for Responding to Regional Features.
The regional types are categorized from the perspective of local community awareness and population gap between day and night.

Solution Development

A conceptual image of installing the IT systems, the electricity sources, and the sanitation equipment for a typical designated evacuation center that is in a commercial area near a station is shown in Fig. 10. This is based on the result of categorizing evacuation management depending on regional characteristics, as described above.

This type of evacuation center is established for evacuees who are unable to return home in excess of the number in the conventional estimate based on the results of this research. The evacuation center will have access control from the beginning and be equipped with a system for managing and utilizing evacuee information for distributing relief to support the needs of evacuees such as stockpiling food, water, and electricity to last the first three days after a disaster.

Currently, several systems have been developed from the proposed solution that was clarified by this research. The aim is to provide a comprehensive and effective disaster management proposal not only for Sendai City but also for any other local government.

APPLYING VISION DESIGN FOR THE HEALTHCARE SERVICES OF A UK NATIONAL HEALTHCARE SERVICE PROVIDER

Vision design is a research methodology developed by the Design Division since 2010 as a technology for thoroughly sharing the purposes and strategies of business development among the stakeholders in the Social Innovation Business. This methodology

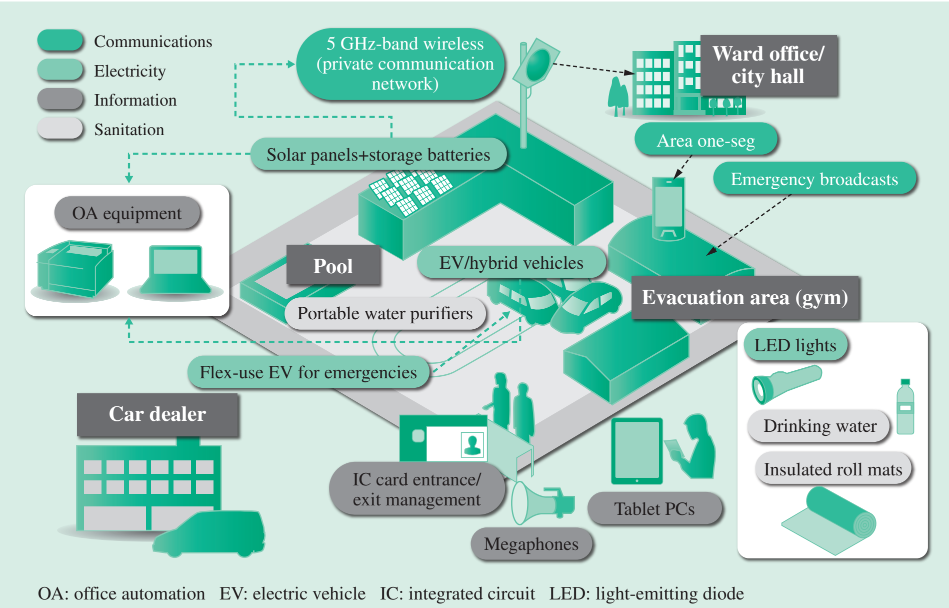


Fig. 10—Solution for Evacuation in Commercial Area near Station.
Due to estimated large numbers of evacuees who are unable to return home after a disaster, the evacuation center should have an IT system for providing access control, and for managing/utilizing evacuees' data efficiently.

is capable of illustrating a future vision of society in which the captured social issues are solved, while grasping the future trends through analyzing the environmental variants from a citizens' perspective (see Fig. 11). The following will describe a case study of an application of vision design to issues for which the burden of social responsibility over healthcare has grown significantly due to an increased number of lifestyle-related diseases from an aging society.

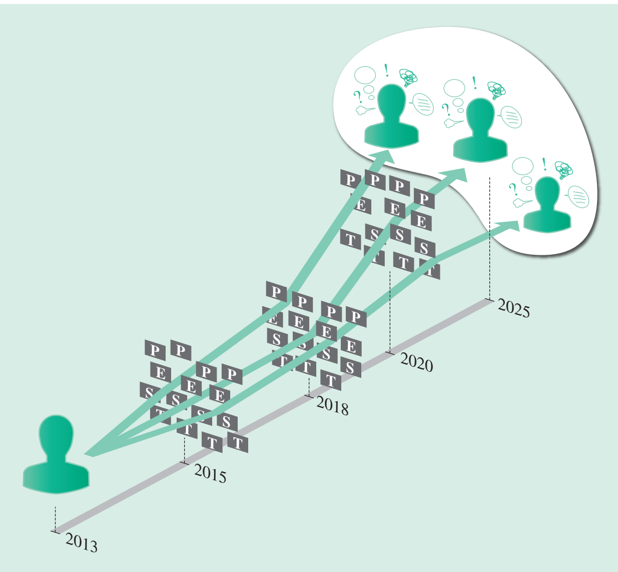


Fig. 11—Concept of Vision Design.
The methodolgy is for sharing development goals and strategies among stakeholders based on an illustrated vision of future society where the captured social issues have been solved, while grasping future trends.

Background of Research

Hitachi considers healthcare to be one of the essential infrastructures for supporting a 21st-century society and would like to contribute to realizing a society where everyone can live safer and more healthy lives by developing various innovative technologies, and the related systems, solutions, and services while utilizing Hitachi's total technology. This project was chosen as a research case in 2012 to accelerate healthcare-related business developments. In 2013, a vision video from one of the deliverables was employed and presented as part of a proposal for implementing a digital medical IT platform in the UK in collaboration with a business entity. This was evaluated by the National Health Service (NHS) England (Greater Manchester) ("NHS GM") and led to the execution of a validation project aimed at improving healthcare through the use of informatics.

Research Challenges

For developing a vision design of healthcare, the year 2025 has been determined as the target for realizing all of the hypothesized innovations. The following three challenges were encountered while conducting the research.

(1) Investigating the challenges of a super-aging society

(2) Comparing and contrasting healthcare systems worldwide

(3) Proposing a service solution that is capable of providing affordable healthcare that covers the entire society

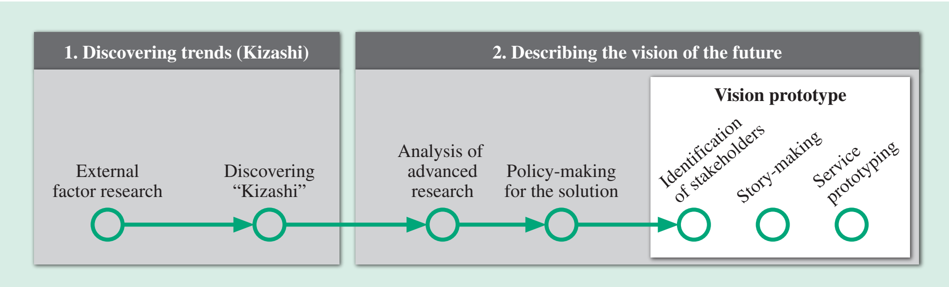


Fig. 12—Process of Vision Design Methodology.
Vision design methodology consists of a Kizashi approach that identifies the changing values in lifestyle and social trends, and a prototype approach that offers a simulated images of the future society.

Research Methods

Vision design methodology consists of a "Kizashi" approach that identifies the changing values in lifestyle and social trends, and a prototype approach that offers a visual simulation of future society (see Fig. 12).

The Kizashi approach is not a future prediction approach that makes predictions based on an evaluation of the continuously shifting past, present, and future, but extracts multiple values from the perspectives of people, and discovers the possible changes from the multi-dimensionally and intuitively analyzed variants. In this case, (1) the challenges of a super-aging society have been investigated through "generating Kizashi," which analyzes the changing values of people in the future who will face the problems. Next, overseas innovation projects have been researched and analyzed as precedents of the healthcare field. (2) The solution strategy has been structured based on a comparison of healthcare systems globally. Finally, (3) an "extraction of a future vision" was executed as a total service solution for realizing efficient healthcare that covers the entire society. Furthermore, the ideal specifications for users such as attractive usability, functionality, and control methods were clarified in the generated "vision prototype" of the healthcare field. In terms of the technology, a specification of proposal was developed with the research laboratories. Any technology that exceeds the current level of technology will be registered as Hitachi's intellectual property. Interviews were conducted with the stakeholders of business entities, public administrations, and medical organizations to verify the validity of solutions to challenges including system, regulation, and business challenges. Feedback was obtained from researchers of aging society and external experts with regard to the acceptibility of the solutions.

Results

Observation of Challenges in a Super-aging Society

(1) Increasing numbers of elderly people receiving care

In a super-aging society, it is important to understand the difficulties and the means of coping of elderly people who are taking care of their own health based on a limited income. Home visit research was conducted of the single-occupant households of elderly people living in cities and underpopulated areas where there is increasing concerns about the future. One of the Kizashis, called "singleship (single person safety net)," was identified as an essential feature. Through this "singleship" kizashi it was understood that policy making needs to respect the independence and the problem-solving capabilities of elderly people, and to build a society that is capable of protecting the single lifestyle with safety, security, and wellbeing.

(2) Problems of comprehensive medical service due to distributed health records

Currently, health records in Japan are managed separately at each hospital. This is considered to be the cause that is preventing proper diagnosis and early treatment for elderly people whose illnesses are easily triggered from the complex factors of everyday life. Thus, the participatory research was conducted in the form of a home visit from a doctor. While elderly people were being examined by the doctor, the nurses from the medical team were able to identify unsanitary household tools and the lack of sanitation associated with a poor health condition. This has helped in terms of treatment. A Kizashi, called "borderless medical (eliminating barriers to medical services)," was identified as an essential feature. Through this "borderless medical" kizashi it was understood that a multifaceted understanding is not only needed for diagnosing illnesses but also for daily care.

(3) Lack of community support education for responding to the shortage of care workers

Most likely, it will be difficult to rely only on a human resources collaboration of care workers from foreign countries in the midst of a shortage of care workers due to a decreasing labor force, so interviews and research were conducted on the organizations promoting community care support and supporting pediatric patients. A kizashi called "community education (promoting education to improve regional power)" was identified as an essential feature. Through this "community education" kizashi it was understood that it is necessary to promote mutual cooperation and understanding of the elderly within the local community by encouraging volunteers, and so on.

Comprehending Merits/demerits of Health Systems through Global Comparisons

(1) Europe

One-stop examinations, including family members, by a general practitioner (GP) are attractive, but there is a long wait time to see a professional doctor.

(2) USA

A variety of new healthcare services provided by private organizations emerge dynamically; however, the options are limited depending on individual income. Recently, it is moving toward being corrected.

(3) Japan

The health system allows all citizens to enroll in any sort of medical insurance. Patients are able to access any hospital freely; however, medical records are managed separately at each hospital, which prevents patients from receiving comprehensive healthcare service.

Proposing a Service Solution that is Capable of Providing Affordable Healthcare Covering the Entire Society

The hard-working employees who support economic growth are also the core that support healthcare costs and knowledge for parents, children, and spouses in a super-aging society. In the current social system, this concentrated burden urgently requires improvement, which is not very different globally. Therefore, a service scheme was proposed that can achieve the three pillars of "life," "policy," and "finance" based on supporting each other by sharing medical records focusing on the three stakeholders, including insurance companies, hospitals, and patients. This will achieve an "environment that does not sacrifice health" with reduced personal effort and burden, and an "environment with no lack of healthcare functions in nearby towns" with minimal social burden. To realize broad services that cover everything from prevention and treatment to care with cooperation of the whole society, a future vision was illustrated of "realizing a society that supports patients and their families reasonably" and promoting redistribution of the roles of the public, industries, and individuals utilizing IT.

Effects

The following effects were obtained from the results of this research.

The activity of Hitachi's proposal to NHS GM based on "healthcare vision" was validated, its Proof of Concept (POC) projects were initiated for using informatics to improve healthcare services. The reason that NHS GM agreed with this activity was because Hitachi presented a vision that was capable of comprehending the conditions of NHS. NHS explained that they confidently believe that "only Hitachi is capable of recognizing our problems." In these POC projects, IT utilization was determined for constructing an integrated platform for secure healthcare and a lifestyle improvement program for realizing a model that provides broad services from prevention and treatment to care. The people and systems in the proposal have been illustrated in detail in a vision video that was effective for sharing the development goals and strategies with stakeholders (see Fig. 13).

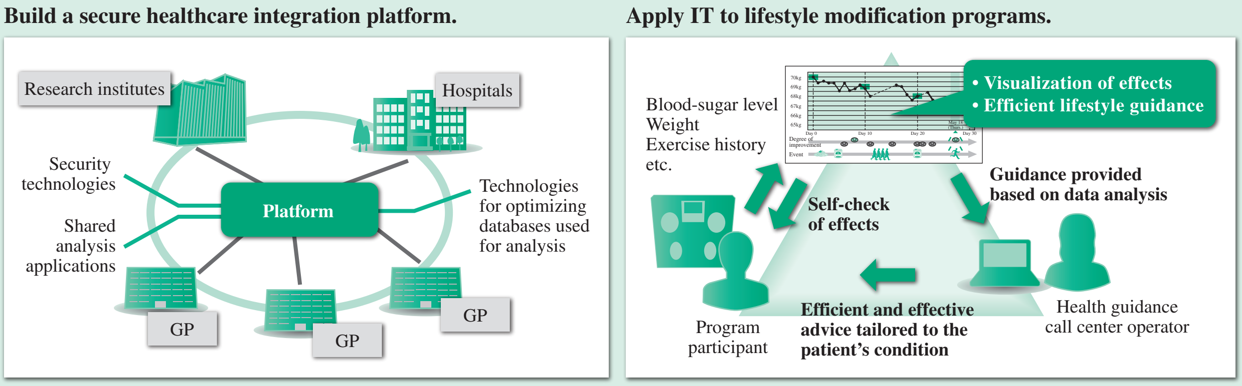
Future Steps

Expanding Application Range

Through vision design, the POC projects led to successful results through conducting the proposal activities collaboratively by sharing the long-term goals and strategies of development with the stakeholders in the informatics field; mainly from the healthcare business. From here on, the aim is to further promote the sharing and exchanging of information with both internal and external stakeholders involved in the internal medical equipment business, smart cities, and local authorities regarding the "healthcare vision." At the same time, another aim is to contribute to social business development and a wide range of healthcare products based on a service cycle linked to illness prevention, care, and welfare, as well as conventional diagnosis and treatment. The application of social innovation businesses such as mobility and energy will continue to be investigated while collaborating with research and development and business entities.

Challenges for Global Expansion

In the beginning, this research was launched as a methodology development based on case studies of Social Innovation Business for developed economies in which a super-aging society is developing dynamically. Following Hitachi's corporate strategy in recent years, it has been necessary to contribute to supporting infrastructure development in emerging markets.



NHS GM: National Health Service Greater Manchester, an organization representing 10 medical commissions in the Manchester region
GP: General Practitioner (equivalent to a clinic in Japan)

Fig. 13—POC project with NHS GM.
Case study of a POC project performed with NHS GM providing services from prevention to treatment linked by region.

However, these emerging markets are different from developed economies where information for conducting business planning is easy to access. Eliminating preconceptions, understanding local values and lifestyles, including the religious and historical background, and tackling public information in the local language are so essential that collaborating with local outstanding partners is eventually the key to creating opportunities in operating infrastructure developments. As part of this activity, the "Brazil Kizashi project" has been conducted with the University of Campinas since February, 2013. This project is a collaborative research project between an academic research team led by a social science professor at the university and Hitachi. As a partner who is going to co-develop Brazilian society, the vision design will be utilized to distinguish and analyze the needs of future social trends in Brazil.

CONCLUSIONS

In this article, we have introduced three social science design approaches for the Social Innovation Business.

These approaches can not only be applied independently, but they can also be linked collaboratively with each other in accomplishing a goal. For example, the experience-oriented approach is used for ethnographic research in order to understand customer issues in the early phase. Vision design is used for anticipating and investigating the values of future users while creating ideal images of business operation and uncovering current issues through ethnographic research. Depending on the case, higher effects can be received by combining these approaches.

Currently, the need for these approaches in Social Innovation Business are increasing and the capability of responding to this is an urgent matter. Also, effective methods of utilizing these approaches to create high-value services when developing a new service business will be in great demand in the future.

ACKNOWLEDGMENTS

The authors would like to take this opportunity to express their gratitude for the considerable effort and cooperation received from Sendai City Office, each ward office, community directors, etc. in the investigation and conducting of interviews at evacuation centers during the development of the "Sendai Model" disaster management solution. And in the application of vision design to the healthcare field, for which the authors received great assistance from everyone involved, beginning with Dr. Mike Burrows (Director of NHS GM).

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Featured Articles

Concept of Energy Efficient Datacenter in ASEAN Region

Ken Naono, Dr. Eng.
Jun Okitsu
Nordin Zakaria, Dr. Eng.
Low Tang Jung, Dr. Eng.
Shaharin Anwar Sulaiman, Dr. Eng.
Mohd Fatimie Irzaq Khamis
Tatsuo Fujii

OVERVIEW: Datacenters are a fundamental part of the social infrastructure in today's world. While outdoor free air is used to cool datacenter computers, the technique is difficult to apply in hot countries. This article outlines the concept behind an energy-efficient datacenter called the GDC-DC that is the product of joint research by Hitachi and Universiti Teknologi PETRONAS. To achieve energy efficiency in the ASEAN region, optimization is extended beyond datacenter energy demand to include the energy supplied by GDC. GDC uses SACs because of their superior energy efficiency compared to ECs. Operational data from the GDC plant at Universiti Teknologi PETRONAS was used to estimate the PUE using Hitachi's SAC at 1.21 (1.0 is energy use for computer execution and 0.21 is for computer cooling). This compares to typical PUE values in Malaysia of 1.6, with world-leading datacenters achieving about 1.1. The research found that use of SAC played a key role in achieving lower PUEs, even in hot areas where free cool air cannot be used.

INTRODUCTION

DATACENTERS are a fundamental part of the social infrastructure in today's world. However, the cooling required to remove heat from computer hardware means their energy consumption is growing rapidly. Even the state-of-the-art datacenters are using free cooling, which means that datacenters tend to be located in cool region where they can make use of the free cool air outside. The best achieve power usage effectiveness (PUE) values as low as 1.1 or 1.07 (the closer the PUE is to 1.0 the better).

However, it is difficult to make use of free cool air in hot countries such as Malaysia. One Malaysian datacenter, for example, has only been able to achieve a PUE of about 1.6 despite considerable efforts to optimize the cooling facilities.

To overcome this problem, joint research by Hitachi and Universiti Teknologi PETRONAS (UTP) has devised a concept called "Gas District Cooling based Datacenter" (GDC-DC). The concept extends energy optimization beyond datacenter energy demand to include the energy supplied by GDC. GDC uses steam absorption chillers (SACs), which are more energy-efficient than electric chillers (ECs). Malaysia has already been using GDC with SACs for more than 10 years. Another feature of the Association of Southeast Asian Nations (ASEAN) area is the availability of natural gas resources and pipelines.

Research into the concept has focused on four areas: GDC-DC energy gap modeling, GDC-DC campus grid job scheduling, the GDC-DC energy sensing system, and GDC plant maintenance efficiency. This article describes the concept behind GDC-DC and reviews the main research work undertaken for proof-of-concept.

BASIC CONCEPT OF GDC-DC

The GDC plant supplies the UTP campus with electricity and chilled water produced using natural gas. Since 2003, the plant has been supplying electricity and chilled water to campus buildings that house the "Campus Grid," a network of thousands of personal computers (PCs). The UTP GDC plant is fitted with SACs (which Hitachi has introduced in 2013) that efficiently produce chilled water from the waste heat of a gas turbine (see Fig. 1).

Research at UTP has focused on four areas: GDC-DC energy gap modeling, GDC-DC campus grid job scheduling, the GDC-DC energy sensing system, and GDC plant maintenance efficiency.

The research into GDC-DC energy gap modeling involved determining the gap between demand for chilled water and the supply of energy, and then conducting optimization modeling in the form of

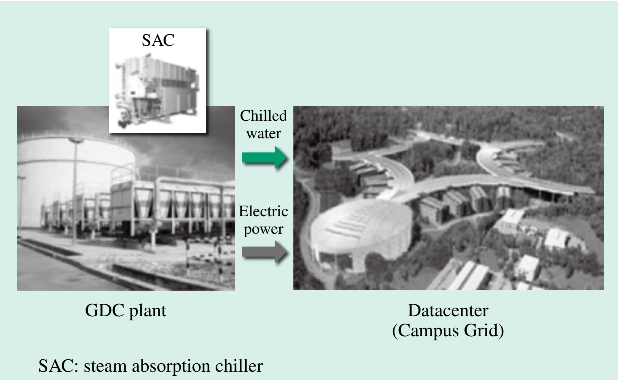


Fig. 1—Gas District Cooling based Datacenter (GDC-DC).
The concept behind datacenter energy management at the Universiti Teknologi PETRONAS (UTP) campus involves using SACs for their higher efficiency. It also features a GDC plant that supplies both chilled water and electric power to the campus, which includes a datacenter.

a minimization problem (minimizing this supply-demand gap)(1). The GDC plant is controlled to ensure that the electricity supply matches demand, with the supply of chilled water being proportional to the amount of electricity supplied. In other words, the supply of chilled water is determined not by demand for chilled water but by demand for electricity, resulting in a supply-demand mismatch.

Research into GDC-DC campus grid job scheduling, meanwhile, involved designing new job scheduling algorithms to minimize this energy gap(2), (3). When there is an excess supply of chilled water, such as at night, the job scheduling algorithm changes the execution timing of some batch jobs to shift the data center's demand for chilled water from day to night. Because the data center workload includes batch jobs with one- or two-day completion requirements, it has the flexibility to make these schedule changes.

Research into the GDC-DC energy sensing system looked at the system design of data aggregation from the GDC plant as well as from the datacenter into an energy management computer. The energy gap calculation uses GDC plant operational data (such as chilled water flow rate and temperature) to estimate energy supply, and uses datacenter energy consumption and environmental data (such as electricity consumption and temperatures inside and outside the datacenter) to estimate energy demand. Data from the GDC plant and datacenter are gathered from supervisory control and data acquisition (SCADA) systems, and also from wireless sensors. The diversity of communication protocols used in

TABLE 1. COP Comparison of SAC and EC.
Note that the supply of chilled water is presented in units of MWh rather than tons.

Performance indicator	SAC	EC
Power consumption (MWh)	6.2	11.4
Chilled water supply (MWh)	79.0	61.7
Chilled water per unit of electric power (COP)	12.7	5.4

EC: electric chiller COP: coefficient of performance

the SCADA systems makes data connectivity an important issue. The Plant Information (PI) System* developed and supplied by OSIsoft, LCC(4) is used for this purpose.

GDC plant maintenance research used root cause analysis (RCA) correlation calculations to determine which system components adversely affect GDC performance(5), (6). Good maintenance of the GDC plant is important because the operational efficiency of this plant has a major impact on GDC-DC. The reason ECs are used instead of SACS, despite the superior energy efficiency of the latter, is because ECs are easier to maintain. For example, measured by the standard coefficient of performance (COP) the energy efficiency metric, the SACs at UTP are twice as effective as the ECs (see Table 1).

ENERGY GAP MODELING AND ENERGY SENSING SYSTEM FOR GDC-DC

The architecture for GDC-DC includes the GDC plant, UTP campus, and an integrated control system (see Fig. 2).

The GDC plant includes a gas turbine generator (GTG), heat recovery steam generator (HRSG), SAC, EC, and thermal energy storage (TES), with electricity sensors and temperature sensors. The GTG simultaneously generates electricity and waste heat from natural gas. The electricity is supplied to the UTP campus. The HRSG generates steam from the waste heat, and the SAC generates chilled water from the steam. This chilled water is also supplied to the UTP campus. The EC, meanwhile, generates chilled water from electricity. Chilled water from the EC is stored in the TES during the night and supplied to the UTP campus during the day. When the electric power generated by the GTG is insufficient, supplemental power is provided to the GDC plant from Tenaga Nasional Berhad (TNB), the Malaysian national electricity supply company. In addition to its labs,

* PI System is a trademark of OSIsoft, LLC.

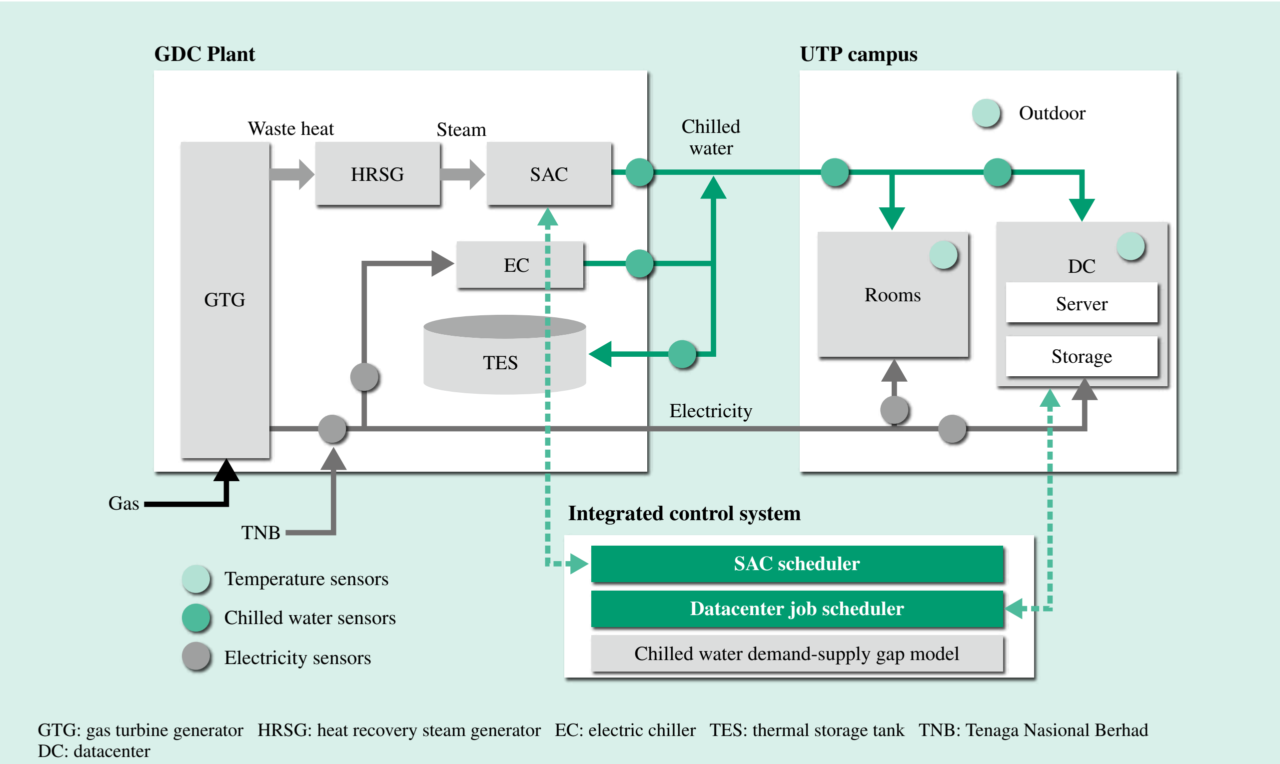


Fig. 2—GDC-DC Architecture (Sensing System and Energy Control).
The SAC scheduler and datacenter job scheduler control the SACs and datacenter jobs, respectively, using sensor data and based on the gap between supply and demand for chilled water.

classrooms, and other teaching facilities, the UTP campus also has a datacenter that houses servers and storage. Chilled water is the primary means of cooling the datacenter and teaching facilities, and it is supplemented with electric air conditioning.

Under the GDC-DC concept, the integrated control system calculates the gap between supply and demand for chilled water based on sensing data from electricity sensors, temperature sensors, and chilled water sensors (flow rate, pressure, and temperature) in the GDC plant and UTP campus. The integrated control system controls SAC scheduling and datacenter job scheduling to minimize the supply-demand gap and improve the datacenter energy efficiency.

The derivation of the chilled water demand-supply energy gap model is described in detail elsewhere[1]. The core of the model is as follows.

$$H\_GAP(t) = | H\_SAC(t) - H\_demand(t) |$$

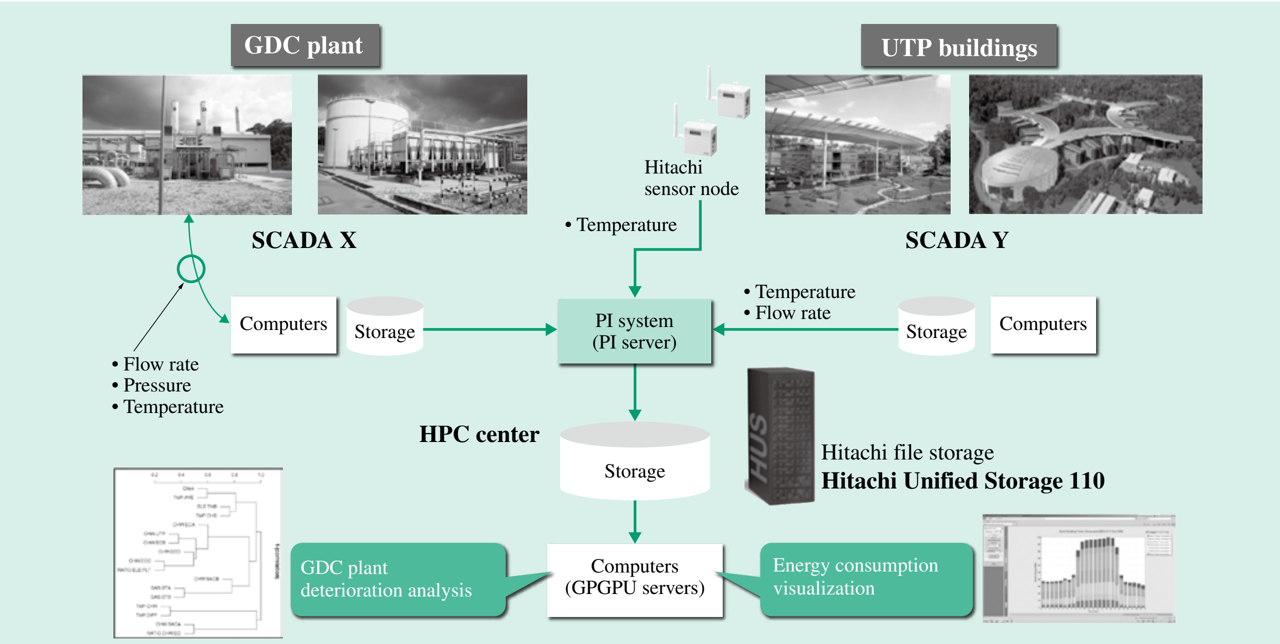
where:
H_GAP(t): Energy gap at time t
H_SAC(t): Chilled water energy from SAC at time t
H_demand(t): Energy demand at time t

The model is based on the assumptions that, (1) Chilled water is mainly supplied from the SAC, with supplementary supply from the EC, and (2) Supply and demand of electric power must be kept in balance.

H_demand(t) is calculated from the heat generated in the campus buildings (teaching facilities and datacenter), and the heat entering from outside the buildings. These are calculated using the sensors depicted in Fig. 2.

There are two ways to minimize the energy gap *H_GAP(t)*. One is to control supply when *H_SAC(t)* > *H_demand(t)*. The other is to control demand when *H_SAC(t)* < *H_demand(t)*. Supply-side control includes SAC scheduling and use of the TES[5]. Demand-side control includes datacenter job scheduling[2], [3].

Connectivity between the two SCADA systems is an important element of the data processing system architecture (see Fig. 3). These are the SCADA system for the GDC plant and the SCADA system for the UTP buildings. Because they use different data formats, the PI System, an interconnectivity system developed and supplied by OSIsoft[4], plays the critical role. The PI System supports interconnectivity between more than 400 different SCADA and distributed control systems (DCSs).



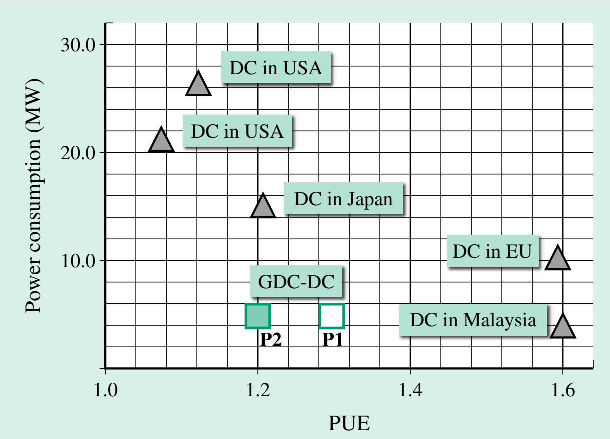
SCADA: supervisory control and data acquisition PI: Plant Information HPC: high performance computing
GPGPU: general-purpose computing on graphics processing units

Fig. 3—Energy Monitoring Network at UTP GDC-DC.
The PI System is used for interconnectivity between the two SCADA systems, which use different data formats. Data is stored in the HPC center, and can be viewed or analyzed by applications such as GDC plant deterioration analysis and energy consumption visualization.

PUE ESTIMATES FOR GDC-DC

Although GDC-DC has not yet completed overall system development, the estimated energy efficiency can be calculated from GDC plant operation data and from the temperatures inside and outside the campus buildings. As UTP has installed additional SACs between 2012 to 2014 to cope with campus expansion, estimates are calculated for three different SAC operation patterns (see Table 2).

The estimates show that GDC-DC performs competitively even in comparison with the world's best data centers in cool climates (see Fig. 4). Changing from ECs to SACs played a major role in this improvement, primarily as a result of the better COP of SACs, as shown in Table 1.



PUE: power usage effectiveness P1, P2: See Table 2

Fig. 4—Comparison of Estimated PUE of GDC-DC (Two Operation Patterns) with other Datacenters.
Despite being situated in a hot climate, the estimated PUEs for GDC-DC are better (lower) than those of other Malaysian data centers, and are competitive with those in Japan.

Table 2. Chiller Operation Patterns.
Day is from 7 am to 7 pm, and night is from 7 pm to 7 am.

Pattern (Year)	Day	Night
P1 (2013)	SACs from other suppliers and EC	EC
P2 (2014)	SACs supplied by Hitachi	EC
P3 (2015 planned)	SACs supplied by Hitachi	SACs supplied by Hitachi

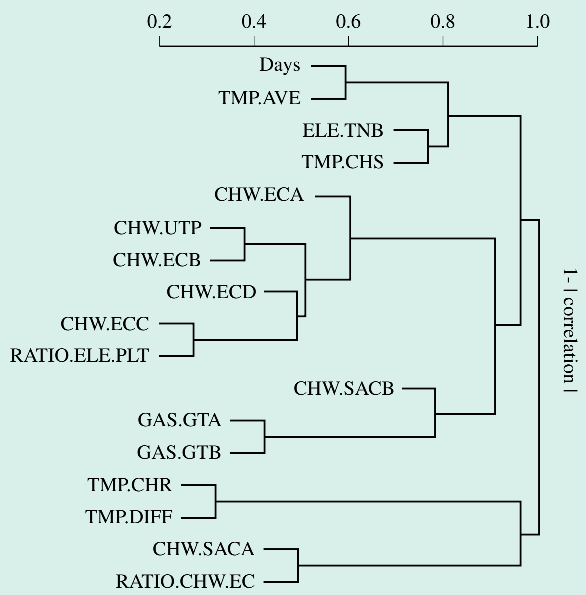
DETECTING CAUSES OF GDC PLANT PERFORMANCE DETERIORATION

Despite their energy efficiency benefits, use of SACs in GDC plants is not currently widespread in Malaysia due to their more difficult operation and maintenance (O&M). Accordingly, to achieve the energy efficiency benefits of GDC-DC in practice, it is crucial to consider O&M and to tackle the factors that cause performance deterioration in GDC plants.

Energy consumption has been rising at the UTP GDC plant over the last two years. However, the reasons for this had remained unclear despite the plant having invested in the maintenance and cleaning. In response, the authors undertook an RCA(6) by calculating correlations between historical data stored in the GDC plant SCADA system (See Fig. 5).

Before performing the analysis, it was expected that RATIO.ELE.PLT would be tightly correlated with RATIO.CHW.EC because all the four ECs at the UTP GDC plant were of the same age and had the same specifications. In fact, the analysis revealed that RATIO.ELE.PLT is more tightly correlated with CHW.ECC than with the other ECs. This suggested that EC-C required additional maintenance. The plant manager also reported that the pumps used with EC-C had suffered from problems in the past. This indicated that maintenance of EC-C and its pumps had been insufficient, and that maintenance of the other chillers has been appropriate.

The results of this analysis also indicate that the ongoing collection and analysis of data from the SCADA and sensing systems are very important for maintaining the energy efficiency of GDC-DC.



Days: elapsed days from 2010 April 4
TMP.AVE: temperature of outdoor average within one day
ELE.TNB: electricity from Tenaga Nasional Berhad (external supply)
TMP.CHS: temperature of supplied chilled water to campus buildings
CHW.ECA: chilled water supply from EC-A
CHW.UTP: chilled water demand from entire UTP
CHW.ECB: chilled water supply from EC-B
CHW.ECD: chilled water supply from EC-D
CHW.ECC: chilled water supply from EC-C
RATIO.ELE.PLT: ratio of electricity consumption of GDC plant to that of entire UTP
CHW.SACB: chilled water supply from SAC-B
GAS.GTA: gas consumption in gas turbine A
GAS.GTB: gas consumption in gas turbine B
TMP.CHR: temperature of returned chilled water from campus buildings
TMP.DIFF: temperature of chilled water difference between supplied to and returned from campus buildings
CHW.SACA: chilled water supply from SAC-A
RATIO.CHW.EC: ratio of chilled water energy of EC to that of whole plant chillers

Fig. 5—Root Cause Analysis Based on Correlations between Daily GDC Plant Data at UTP from 2010 to 2012.
The left-to-right position of the variable pairs represents their degree of correlation (where left means more tightly correlated). For example, RATIO.ELE.PLT is tightly correlated with CHW.ECC.

RELATED WORK

Research into chilled water demand has included extensive study of optimization methods for reducing demand. These include relaxing the temperature requirements for datacenter servers that have a high guaranteed operating temperature(7), and the use of datacenter job scheduling to minimize thermal variance(8), (9). Research into chilled water supply has also studied optimization methods for increasing supply, including SAC optimization(10) and TES optimization(11). In the case of GDC, however, it is necessary to consider both supply and demand, with operational efficiency being highly dependent on the gap between supply and demand for chilled water. When supply exceeds demand, for example, decreasing demand is not an efficient way to reduce CO_2 emissions. Similarly, when demand exceeds supply, increasing supply is also inefficient. Therefore, the gap model selects the best form of optimization for GDC efficiency based on actual conditions.

The research into supply and demand for chilled water also included study of optimization methods. These included thermal storage tank optimization based on chilled water demand prediction(12), chilled water distribution network optimization based on building cooling load patterns(13), and electricity demand forecasting for GDC optimization(14). However, because these methods are intended for supply optimization based on demand information, their efficiency is lower than optimizations that consider both supply and demand. This is because optimizing supply but not demand requires a larger margin to deal with unexpected increases in demand. When demand optimization is also performed, these unexpected increases can be mitigated. In other words, efficiency can be improved by taking account of the supply situation when optimizing demand.

CONCLUSIONS

This article has described collaborative research between Hitachi and UTP for energy efficient datacenters in order to contribute to the development of Malaysia. The authors have created the GDC-DC concept for realizing energy efficient data centers in the ASEAN region, where free cool air is not available. The research found that using SACs in the GDC plant is key to achieving lower PUE. The research also clarified the importance of the sensor data collection network, including the SCADA and wireless sensors, to system design for maintenance of the GDC plant.

Future work will include a detailed study of GDC-DC grid job scheduling, and the implementation and evaluation of an energy sensing system that will incorporate the PI System. By combining job scheduling and energy sensing systems with GDC-DC energy modeling and more efficient practices for GDC plant maintenance, GDC-DC can provide data centers with world-class energy efficiency, not only on campus but also in other university-related industrial uses.

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Featured Articles

Combustion Analysis Techniques for Development of Next-generation Engine Systems

Yoshihiro Sukegawa
Kazuhiro Oryoji
Eiji Ishii, Dr. Eng.

OVERVIEW: Improving the fuel economy and emissions of vehicle engines requires a detailed understanding of the various physical processes taking place inside the engine so as to identify optimal combustion control techniques and engine component designs. Based on numerical techniques established by its power plant business for the analysis of two-phase flow, combustion, and other phenomena, Hitachi has developed techniques for using simulations to estimate flow, mixture formation, and combustion in engine cylinders. Hitachi has also combined these estimation techniques with a concentration physical simulation model for PM such as soot, an area in which there has been strong demand for emission reductions in recent years. This model calculates the process of PM formation based on detailed chemical reaction mechanisms. Hitachi has gone on to use this new combustion simulation technique to propose a combustion control concept that reduces emissions at cold engine start-up.

INTRODUCTION

PROVIDING vehicle engines with cleaner exhaust gas and better fuel economy is important for making effective use of energy resources and protecting the environment. The development of engine control techniques and components capable of efficient combustion are essential to overcoming these challenges.

For example, the fuel economy and emissions of direct injection gasoline engines (a type of fuel-efficient engine that is becoming increasingly common) are improved through the precise control of fuel spray, air flow, and other processes inside the cylinder to achieve a suitable mixture for combustion. This involves optimizing a wide variety of parameters, including the fuel spray and gas flow, injection, ignition, and valve timing. Using computer simulations to analyze the behavior of the fuel, air, and combustion gas in detail is an effective technique for efficiently identifying the optimal combination of these parameters.

Engines are characterized by the presence of complex dynamic phenomena such as those associated with the mutual interaction of gases and liquids, chemical reactions, turbulent flow, and moving boundaries. To deal with these accurately, Hitachi uses engine analysis techniques that were developed by making enhancements to numerical analysis techniques established by Hitachi's power plant business for two-phase flow, combustion, and other phenomena.

This article describes the computational methods used in simulation techniques for estimating engine flow, combustion, and exhaust, and presents examples of their use for engine analysis.

USE OF COMPUTER SIMULATIONS FOR COMBUSTION ANALYSIS

In the case of a direct injection gasoline engine, the following phenomena occur within each engine stroke.

(1) The down-stroke of the piston draws in air (gas flow).

(2) Fuel is injected into the air inside the cylinder.

(3) A fuel-air mixture is formed by fuel vaporization from the injected fuel droplets and air.

(4) Ignition causes flame propagation in the mixture, resulting in a rise in the temperature and pressure inside the cylinder.

(5) The nitrogen oxides (NO_x), particulate matter (PM), and other compounds formed during combustion become the emissions.

Accordingly, a combustion simulation needs to model the gas flow, fuel spray behavior, droplet vaporization, mixing of air and fuel, flame propagation, formation of emissions, and other phenomena, and to obtain these numerically. The following sections describe the mathematical models used for the main phenomena, as well as the computational methods used.

Gas Flow and Fuel Spray Model

The flow and mixing of gas is obtained by solving the equations for the conservation of mass, momentum, and energy in the mixture, and for the conservation of mass of the fuel components and combustion gas. These conservation equations are represented by the following partial differential equation (equation 1).

$$\frac{\partial F}{\partial t}+\frac{\partial V_iF}{\partial x_i}+\frac{\partial q_i}{\partial x_i}+S=0 \qquad (1)$$

Where, t represents time, x_i represents the coordinates, and V_i represents the gas velocity (i=1, 2, 3). The first term on the left represents the variation with time, the second term represents the convection, the third term represents diffusion due to molecular motion and turbulent flow, and the fourth term represents the creation or elimination of physical quantity ("source term"). F is a vector comprising the physical values to be solved for, which include the mixture density, momentum, internal energy, fuel component density, and combustion gas density. The q_i term represents phenomena that come about due to the spatial gradient of physical quantities, such as the stress due to viscosity and the flux due to conduction and diffusion. For example, equation (2) is a conservation of momentum equation that represents the stress resulting from molecular viscosity and eddy viscosity.

$$q_i=(\mu_m+\mu_t)\frac{\partial V_i}{\partial x_i} \qquad (2)$$

Where, μ_m is the coefficient of molecular viscosity and μ_t is the coefficient of eddy viscosity. The coefficient of eddy viscosity is obtained using turbulence models. Turbulence models can be broadly divided into Reynolds-averaged Navier-Stokes simulation (RANS) time-averaged turbulence models and large eddy simulation (LES) space-averaged turbulence models. Since LES can perform more detailed analyses than RANS, being able to deal directly with transient turbulent flow behavior, the method described here uses LES.

The conservation equations are coupled with the gas state equation to obtain the gas pressure and temperature.

$$P=\rho T\Sigma Y_jR_j \qquad (3)$$

Where, Y_j is the mass fraction of component j and R_j is the gas constant for component j. The finite volume method[1] is used for the spatial discretization of equation (1). The finite volume method splits the flow field into computational cells consisting of small polygons (see Fig. 1) and formulates the balance of flux across the cell boundaries and the quantities created or eliminated within the cell as shown in equation (4).

$$\frac{d}{dt}(\Delta V_k \cdot F_k)=-\sum_i V_{Ci}F_i\cdot\Delta S_i-\sum_i q_i\cdot\Delta S_i+\Delta V_k\cdot S_k \qquad (4)$$

Since equation (4) is an ordinary differential equation with respect to time, numerical integration methods such as the Euler or Runge-Kutta methods can be used to solve it for each time step.

The fuel spray behavior is obtained using a discrete droplet model (DDM)[2] which introduces particles representing droplets into the gas flow field and tracks their movements. Because the actual number of droplets in the engine is very large, modeling them all in a computer is impractical. Instead, the method tracks the behavior of a group of particles, called a "parcel," that comprises a number of droplets with the same initial conditions (size, velocity, temperature, and coordinates) (see Fig. 2). Equation (5) is the equation for the motion of a parcel.

$$\frac{dV_d}{dt}=\frac{3\rho}{4\rho_d d}C_D|V-V_d|(V-V_d) \qquad (5)$$

Where, V_d is the parcel velocity, V is the gas velocity, C_D is the drag coefficient, ρ_d is the droplet density, and d is the droplet diameter. The instantaneous velocity of a parcel can be obtained from equation (5), and the

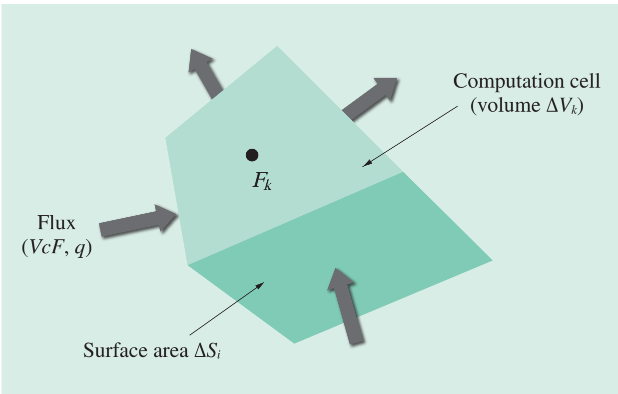


Fig. 1—Computation Cell for Finite Volume Method.
The figure shows the computation cell for the finite volume method and the model diagram of the flux across the cell surface.

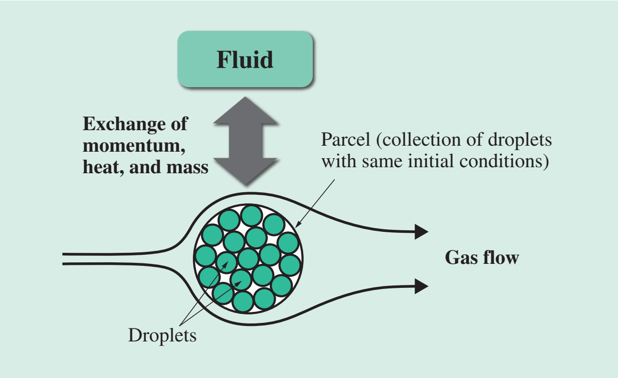


Fig. 2—Use of Parcels to Model Droplets.
The diagram shows the concept behind using parcels to model droplets. The droplets are modeled as parcels, each of which is made up of a number of droplets treated as having the same initial conditions.

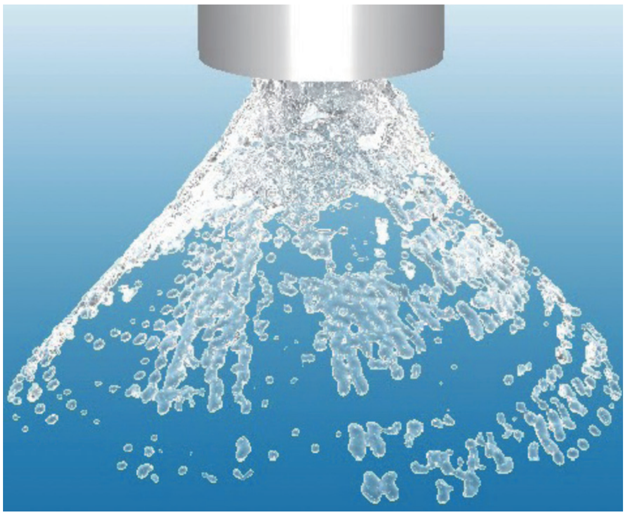


Fig. 3—Simulation of Spray Formation by Injector.
This shows an example of using the particle method to simulate the behavior of fuel sprayed from the nozzle of a swirl-type fuel injector. The simulation involves an integrated analysis that considers the formation of a liquid film in the nozzle and the formation of droplets by the breakup of the film.

trajectory of the parcel at any point can be determined by integrating this velocity over time.

An exchange of momentum occurs between droplet and gas via friction, an exchange of heat via heat transfer, and an exchange of mass via evaporation. These processes are represented on the gas side by the source term in equation (1).

When a DDM is used for the analysis of engine combustion, a number of sub-models are adopted in addition to the parcel's conservation of energy equation to consider factors such as evaporation, breakup, drag, collisions with walls, and turbulence.

To take account of the injection of fuel into the engine, the DDM requires that the physical quantities (coordinates, velocity, diameter) of a parcel at a fuel injector be provided as boundary conditions. These are obtained by a spray formation simulation(3) that performs an integrated analysis of the liquid flow, liquid film formation, and process by which the film breaks up into droplets in the fuel injector nozzle (see Fig. 3). This simulation uses the particle method (a mesh-free method for the micro-level tracking of the gas-liquid interface), which can model atomization from the injectors with comparatively low computational requirements.

Combustion Model

Combustion is a chemical reaction between fuel and oxidizer. The temperature, pressure, and other changes that result from combustion are calculated as the consequence of changes in the gas composition resulting from the reaction.

The combustion of gasoline can be approximated by the overall reaction shown in equation (6).

$$C_8H_{18} + 12.5O_2 \rightarrow 8CO_2 + 9H_2O \tag{6}$$

By introducing the progress variable C (= 0–1), which represents the progress of the reaction from the left side of the equation to the right, the gas composition can be obtained using this progress variable and the fraction of the fuel component f. For example, the mass fractions of the fuel (C_8H_{18}) and oxygen (O_2) are given by equation (7) in the case when fuel and air combust in accordance with the stoichiometric mixture ratio.

$$\left.\begin{array}{l} Y_{C8H18} = f\,(1-C) \\ Y_{O2} = 0.233\,(1-f)\,(1-C) \end{array}\right\} \tag{7}$$

Since multiplying the progress variable C by the mixture density ρ gives the burned gas density, the progress variable can be obtained by solving the conservation of mass equation for the burned gas in the form of equation (1).

The rate at which combustion progresses is determined by the source term in the conservation of mass equation for the burned gas, and how to express this source term is the key to combustion modeling. Under the conditions in an engine cylinder, the strength of the flow varies widely depending on driving conditions and spatial position. Accordingly, what is needed is a combustion model with a wide scope of application regardless of the flow conditions. A hyperbolic tangent approximation (HTA) combustion model(4) was selected to satisfy this criterion. While the progress variable C progresses from 0 to 1 in the flame zone, there is likely to be a degree of consistency in the shape of the C distribution. Accordingly, the HTA model uses equation (8) to represent this distribution.

$$C = \frac{1}{2}\left[1 + tanh\left[\frac{2x}{\delta}\right]\right] \quad (8)$$

Where, δ is the flame thickness and x is the distance in the thickness direction. Considering the one-dimensional conservation of mass equation for the burned gas and assuming the C distribution is approximated by equation (8), equation (9) is obtained by solving for the rate of creation of burned gas ω.

$$\omega = \frac{8\rho_u S_L C^2 (1-C)}{\delta} \quad (9)$$

This model can be used for both laminar and turbulent flow cases. Furthermore, because it is independent of the turbulent flow model, the model has a wide range of applications including use with RANS or LES.

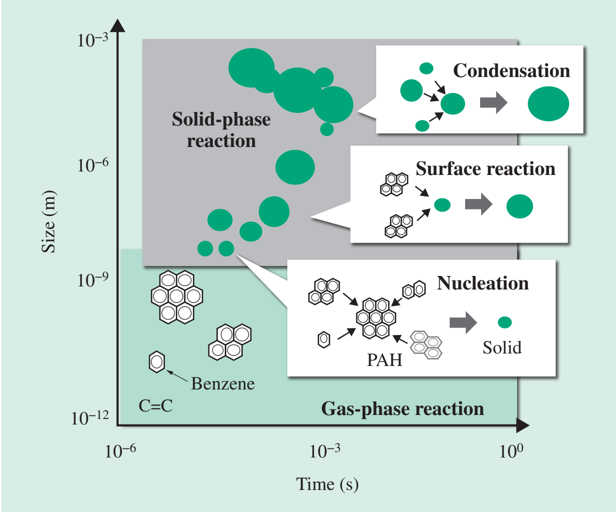


Fig. 4—PM Formation and Growth Process.
The graph shows the formation and growth of PM, with the horizontal axis representing the elapsed time and the vertical axis representing the particle size.

Emission Model

The emissions resulting from engine combustion, which need to be estimated, consist primarily of NOx, unburned hydrocarbons (HC), carbon monoxide (CO), and PM. The following section describes the model used to calculate PM emissions.

PM is the result of particles formed by processes such as volatile fuel components condensing or reacting chemically. Regulations on PM are becoming stricter throughout the world, with strong demand for vehicle engines to achieve combustion with low PM emissions.

Fig. 4 shows the process of PM formation and growth. Formation and growth can be broadly divided into two stages. First, a gas-phase reaction forms PM precursors. This is then followed by a solid-phase reaction causing the PM formed by the collision of precursors to grow in size. Starting from the acetylene formed by the thermal decomposition of hydrocarbon fuel, the gas-phase reaction forms benzene and also polycyclic aromatic hydrocarbons (PAHs) made up of multiple benzene rings linked together. These PAHs are the precursors of PM. The formation and growth of PM take place in the solid-phase reaction, which consists of the formation of PM through collisions between PAHs (nucleation), collisions between PM and PAHs or acetylene (surface reactions), and collisions between PM (condensation).

A two-equation model is used for the solid-phase reaction[(5)]. This model estimates the PM number density and mass by solving for their variation over time. It is assumed that the variation over time in the number density depends on nucleation and condensation, and that the variation over time in the mass depends on nucleation and surface reactions. For example, equation (10) represents the rate of formation of PM particles in terms of their number density [the particulate number (PN)].

$$\frac{d\,(\mathrm{PN})}{dt} = R + W - G \quad (10)$$

Where, R is the nucleation rate, W is the surface reaction rate, and G is the condensation rate, each of which needs to be modeled. For example, the model represented by equation (11), which assumes acetylene as the PM precursor, is proposed for the nucleation rate[(6)].

$$R = c_1 N_A \left[\frac{\rho Y_{C2H2}}{M_{C2H2}}\right] exp\left[-\frac{21100}{T}\right] \quad (11)$$

Where, N_A is Avogadro's number, Y_{C2H2} is the acetylene concentration, M_{C2H2} is the molecular weight of acetylene, T is the temperature, and c_1 is a model constant. Since the acetylene and other components present in trace quantities are not considered in the overall equation [equation (6)], solving the PM model equation requires the use of elemental reaction equations (chemical reaction formulae for smallest units) to calculate the chemical reactions in detail. In this study, the components present in trace quantities are obtained by solving the elemental reaction equations for 781 chemical species and 2,247 reaction

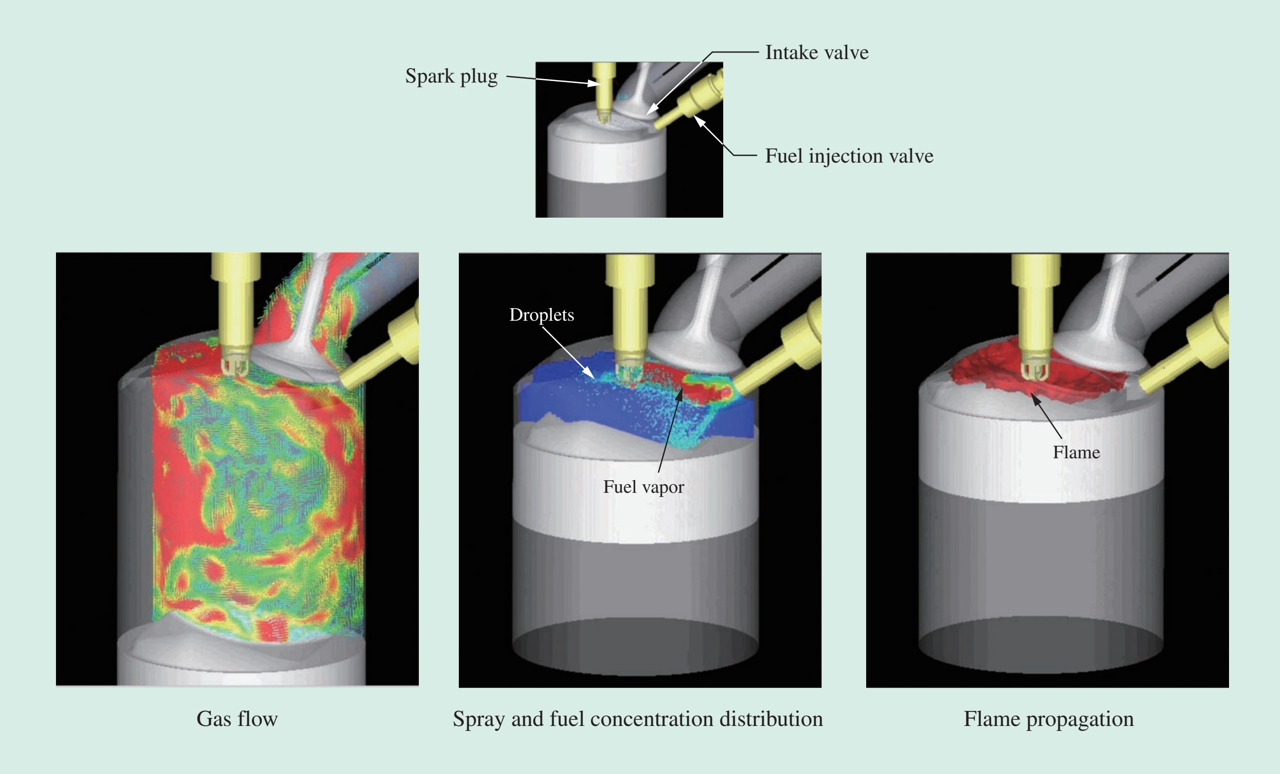


Fig. 5—Example Application of Combustion Simulations to Direct Injection Gasoline Engine.
The figures show a simulation of a direct injection gasoline engine. On the left is a vector diagram of air velocity for a vertical cross-section through the center of the intake valve. The vector color represents the magnitude of the velocity, with red being fastest. The center figure shows the spray droplet distribution and fuel concentration distribution for a vertical cross-section through the center of the cylinder. The color represents the fuel concentration, with red being highest. The right-hand figure shows a three-dimensional representation of the flame surface shape.

formulae for gasoline combustion, based on isooctane and normal heptane being the main fuel components.

By utilizing the computational methods described above, it is possible to perform a coupled simulation that extends from the engine intake stroke to the exhaust stroke and encompasses gas flow, fuel-air mixture formation, flame propagation, and emissions formation. Fig. 5 shows the use of the method to simulate a direct injection gasoline engine.

EXPERIMENTAL VERIFICATION OF SIMULATIONS

Verification of Gas Flow and Spray Simulations

Fig. 6 shows a comparison of experimental measurements and simulation results(7) for the flow in an engine cylinder. The results indicate that the simulation can reproduce the flow with good accuracy, including good agreement for the pattern and velocity of the circulating flow that occurs at the bottom of the intake valve.

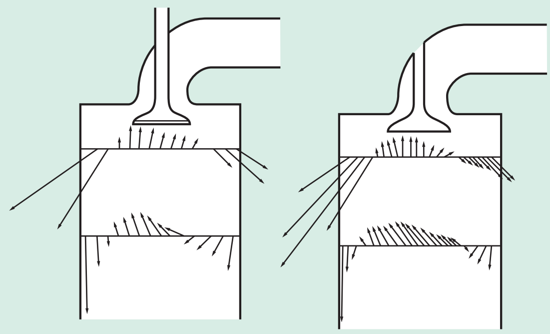


Fig. 6—Comparison of Simulation Results and Experimental Measurements for Flow in Engine Cylinder.
The diagrams show the air velocity vector in an engine cylinder. The vector length represents the magnitude of the velocity. The diagram on the left shows the measurement results from a laser Doppler flowmeter, and the diagram on the right shows the simulation results. A circulating flow occurs under the intake valve. The simulation results are in close agreement with the measurements for both the velocity direction and magnitude.

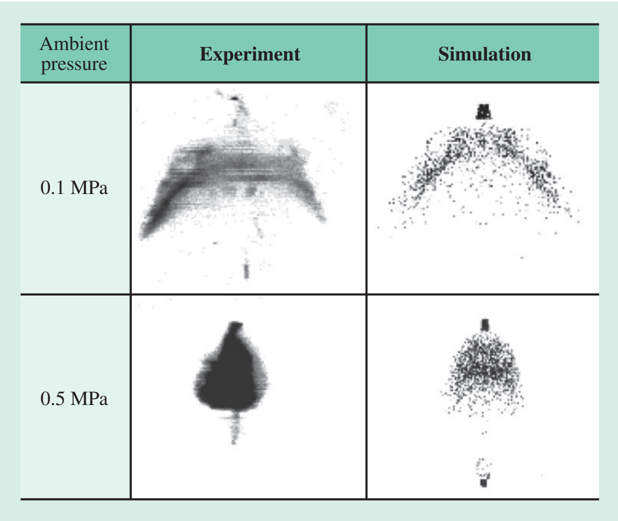
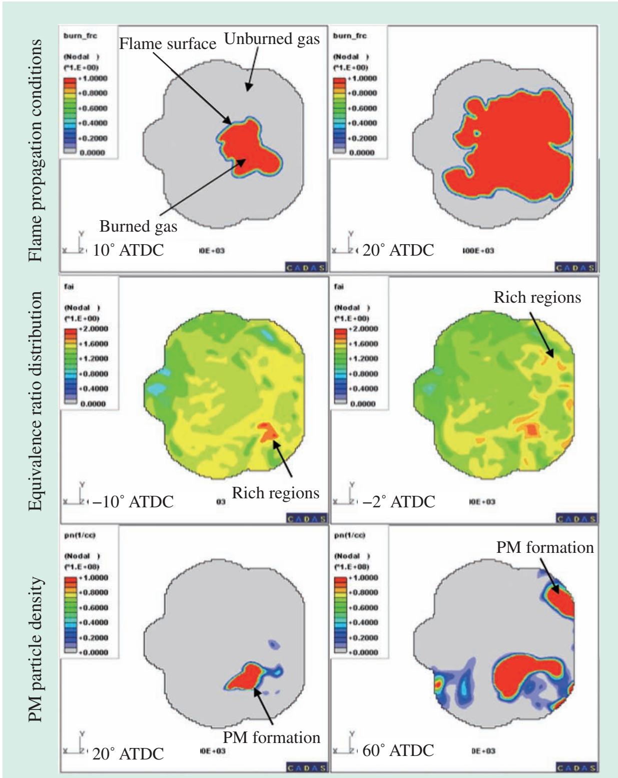


Fig. 7—Comparison of Experimental Measurements and Simulation Results for Fuel Spray.
The figures show a central cross-section of the spray injected into still air using swirl-type injectors. The spray is injected from top of the figure toward the bottom. The figures on the left show a photograph of the actual spray captured using slit light, and those on the right show the simulation results. The results are shown for the cases when the air pressure is 0.1 MPa (atmospheric pressure) and 0.5 MPa (pressurized). Whereas the spray disperses outward at atmospheric pressure, the increased air resistance in the pressurized case makes the spray more consolidated. These changes in spray behavior at different pressures are reproduced by the simulation.



ATDC: after top dead center

Fig. 8—Example Simulation of Combustion and PM Formation.
These contour graphs represent a horizontal cross-section across the engine cylinder and show the results of simulating combustion and PM formation in a direct injection gasoline engine. The top graphs show the distribution of combustion gas, with the red regions representing burned gas and the grey regions representing unburned gas. The boundary between the two is the flame surface. The graphs in the middle show the distribution of the equivalence ratio (fuel concentration), with red representing fuel-rich regions. The bottom graphs show the density of PM particles, with red representing regions of high PM concentration. The graphs show how high concentrations of PM are formed in the fuel-rich regions in the cylinder.

Fig. 7 shows a comparison of experimental measurements and simulation results for the fuel spray. The fuel injection valves used in the analysis are swirl-type fuel injectors that atomize the fuel by imparting a swirling motion to it, and which produce a hollow cone-shaped spray when the ambient pressure is 0.1 MPa. With an ambient pressure of 0.5 MPa, the spray becomes more consolidated due to a flow from the surroundings being drawn into the center of the swirling spray. These differences in spray shape associated with differences in ambient pressure were accurately reproduced by the simulation.

Verification of Combustion Simulations

Fig. 8 shows an example simulation of combustion and PM formation. It uses a contour diagram to show the simulation results over a horizontal cross-section of a direct injection gasoline engine cylinder. From the top, the diagrams show the flame propagation (burnup fraction distribution), equivalence ratio distribution, and PM particle density distribution respectively. The simulation models the ignition of the flame by the spark plug at the center of the cylinder and its propagation out to the cylinder walls. From the equivalence ratio distribution and PM particle density distribution, it can be seen that PM formation starts primarily from a fuel-rich area that forms at the exhaust side of the cylinder (right).

Fig. 9 shows a comparison of experimental measurements and simulation results for the time-evolution of pressure inside an engine cylinder. Fig. 10 shows a comparison of experimental measurements and simulation results for the number of PM particles emitted by the engine. These show good agreement between the experimental and simulation results for how the equivalence ratio changes the behavior of combustion pressure and the quantity of PM emissions.

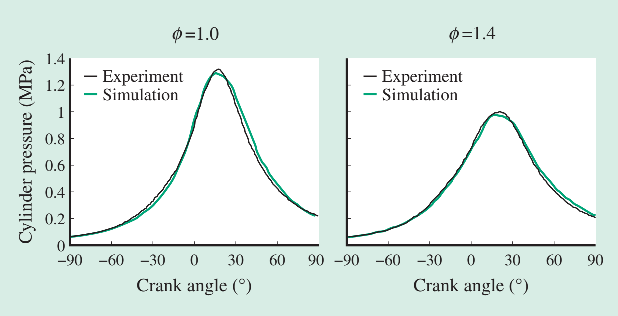


Fig. 9—Comparison of Time-evolution of Pressure Inside Engine Cylinder.
The graphs show a comparison of experimental measurements and simulation results for the time-evolution of pressure inside an engine cylinder. The horizontal axis represents the engine crank angle, with 0° representing the uppermost point of the piston's stroke (top dead center). The black lines are the experimental measurements and the green lines are the simulation results. The graphs on the left show the case when the mean equivalence ratio is 1 (stoichiometric mixture ratio) and those on the right show the case when the mean equivalence ratio is 1.4 (fuel-rich mixture). The combustion rate and cylinder pressure vary depending on the equivalence ratio. This variation is reproduced by the simulation.

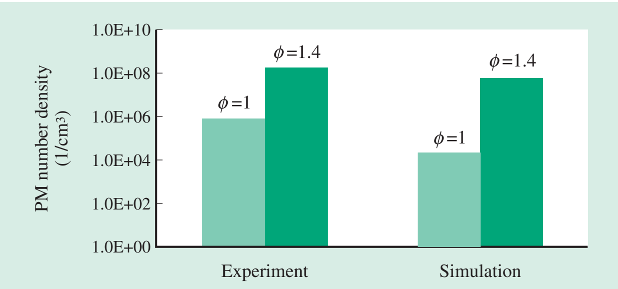


Fig. 10—Comparison of PM Number Density.
The graphs show experimental measurements and simulation results for the number density of PM emitted by the engine. The graph on the left shows the measurements and the graph on the right shows simulation results. ϕ is the mean equivalence ratio. The higher the mean equivalence ratio (the richer the mixture) is, the more PM concentration increases. This effect is reproduced by the simulation.

APPLICATION TO SPARK IGNITION ENGINES

Use for Reducing Unburned HCs

The use of exhaust heating to achieve early activation of the catalyst and promote the oxidation of unburned HCs are effective techniques for reducing emissions after a cold start-up. A good way to achieve exhaust heating is to delay combustion by making the spark timing later than normal. However, while the exhaust temperature is increased by a later spark timing, it has the unfortunate side effect of increasing cyclic torque variation. To prevent this, it is necessary to improve the ignitability of the mixture to stabilize combustion, particularly at the early stage when the engine is most prone to cyclic variation. Accordingly, Hitachi has used a computer simulation to develop a combustion concept that reduces unburned HCs after a cold start-up. The following section describes an example[8].

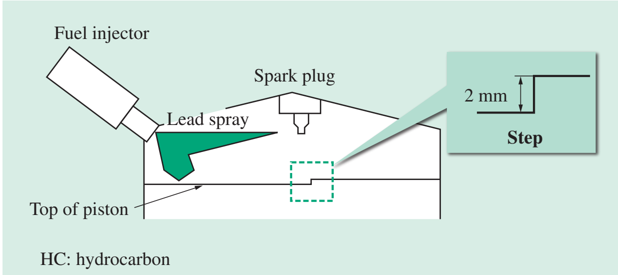


Fig. 11—Piston Shape and Spray Direction.
The diagrams show the engine piston shape and spray shape used by a combustion concept for reducing unburned HC. The concept involves locating a small step in the center of the piston's top surface (stepped crown) and using injectors that produce an asymmetrical spray.

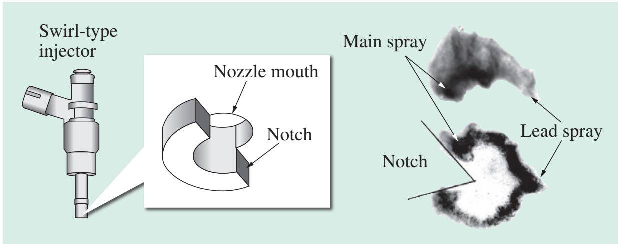


Fig. 12—Nozzle Shape and Spray Pattern.
The diagrams show the nozzle shape for producing an asymmetrical spray and the resulting spray pattern (obtained by observation). A notch in the tip of the nozzle of the swirl-type injector produces both a lead spray with high penetration force and a main spray with superior atomization.

The combustion concept is based on using a piston with a stepped crown (see Fig. 11). This involves having a small step in the central part of the top surface (crown) of the piston. It also uses swirl-type fuel injectors that can produce an asymmetrical spray with respect to the spark plug and piston axes[9] (see Fig. 12). These injectors have a step-shaped notch in their nozzles to generate an asymmetrical spray. Consisting of both a lead spray with high penetration force and a main spray with superior atomization, a feature of the spray is that the injection direction of the lead spray remains unchanged at high ambient pressures. The injectors are located so as to aim this directed lead spray at the area under the spark plug electrodes.

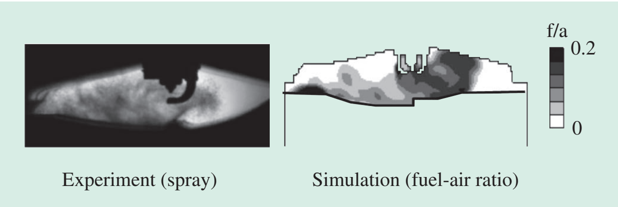


Fig. 13—Fuel Behavior in Engine Cylinder.
The figures show the behavior of fuel in the engine cylinder around the time of ignition when using the combustion concept for reducing unburned HC. The figure on the left shows the fuel spray distribution observed in a transparent engine and the figure on the right shows the fuel concentration (fuel-air ratio) distribution obtained by simulation. A flow from the center of the piston toward the spark plug concentrates the fuel around the spark plug.

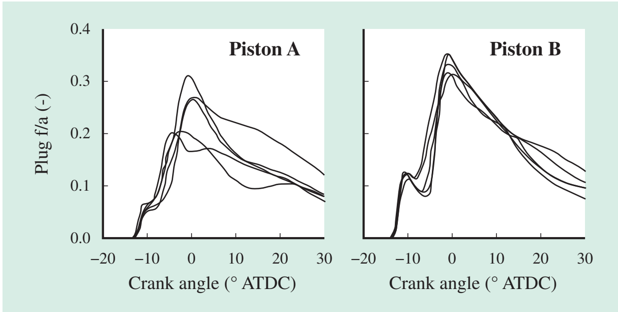


Fig. 14—Variation in Mixture Concentration around Spark Plug for Different Spray Shapes (Simulation Results).
The graphs show the results of simulating how small changes in the fuel spray shape affect the fuel concentration (fuel-air ratio) in the vicinity of the spark plug. Reducing variability helps achieve stable combustion. Simulations were used to design the optimal piston shape for producing a robust mixture.

When this piston-shaped spray is used to inject fuel during the latter part of the compression stroke, the rapid gas flow produced by the lead spray causes the pressure around the spark plug to drop. The flow resulting from the main spray, meanwhile, decelerates at the stepped crown of the piston and causes an increase in pressure. This pressure difference causes an upward flow from the stepped crown toward the spark plug, resulting in the fuel around the top of the piston being concentrated around the spark plug (see Fig. 13).

For most hydrocarbon fuels such as gasoline, flame propagation is improved by using a mixture that is slightly richer than the stoichiometric mixture ratio. Accordingly, the initial combustion can be stabilized by concentrating the fuel around the spark plug in this way, allowing a longer delay in ignition timing after a cold start-up. The benefits of simulation include, for example, its use to determine the optimal piston shape quickly.

Fig. 14 shows the results of a simulation of different piston shapes conducted to determine how the mixture concentration in the vicinity of the spark plug is influenced by small changes in the spray shape. The results show that piston B has a more robust mixture formation with less variability in mixture concentration.

Fig. 15 shows measurements of exhaust temperature and cumulative unburned HC emissions after a cold start-up. The exhaust temperature was measured at the part of the manifold where the exhaust pipes from each cylinder merge and the HC was measured at the tail pipe (after passing through the three-way catalyst). The measurements were conducted for pistons with and without a stepped crown. Because the more stable combustion for the pistons with a stepped crown allows the ignition timing to be delayed, the exhaust temperature is 120°C higher than for the other piston and the cumulative unburned HC emissions are 33% lower. It is believed that this reduction in unburned HCs is a result both to the greater oxidization of unburned HCs in the exhaust pipe due to the higher exhaust temperature and the earlier activation of the three-way catalyst. These verification results demonstrate that this combustion concept is an effective way of reducing unburned HCs after a cold start-up.

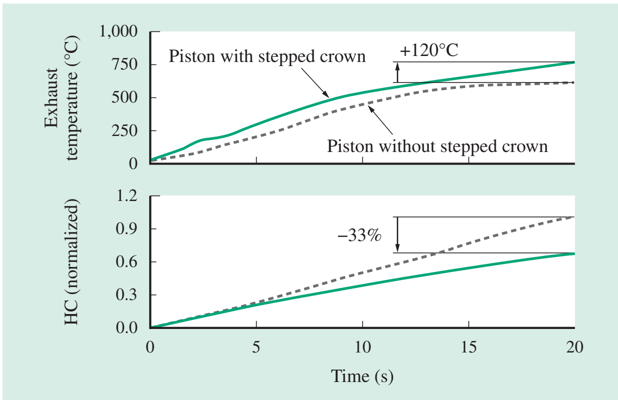


Fig. 15—Exhaust Temperature and Cumulative Unburned HC Emissions after a Cold Start-up (Measurements).
The graphs show measurements for the exhaust temperature and cumulative unburned HC emissions after a cold start-up. This demonstrates how the concept increases exhaust temperature and reduces unburned HCs.

Use for Reducing PM

Fuel droplets that have adhered to the piston surface and cylinder walls are the main cause of PM in cold gasoline engines. Because fuel that has adhered to a surface is impeded from mixing with the air, the

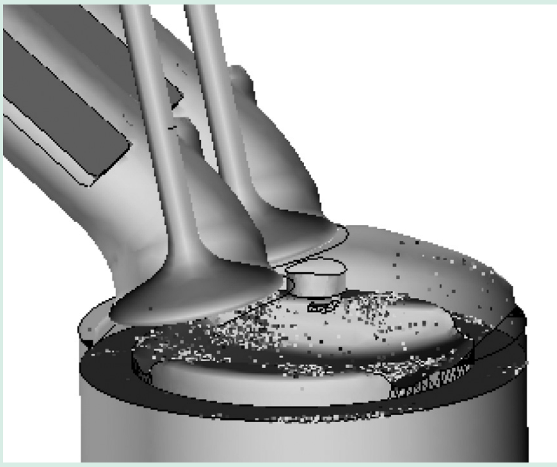


Fig. 16—Results of Simulating Adhesion of Droplets to Surfaces (without Split Injection).
The figure shows the results of simulating the adhesion of fuel droplets to surfaces in a direct injection gasoline engine. This adhesion is a cause of PM formation in cold engines.

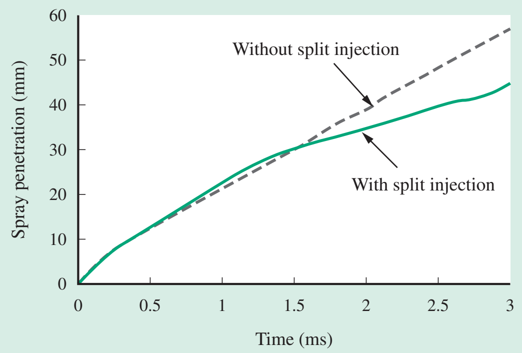


Fig. 17—Results of Simulating Spray Penetration.
The graphs show the results of simulating the spray penetration (distance reached by leading edge of spray). Split injection reduces penetration because it increases the interference between spray and air.

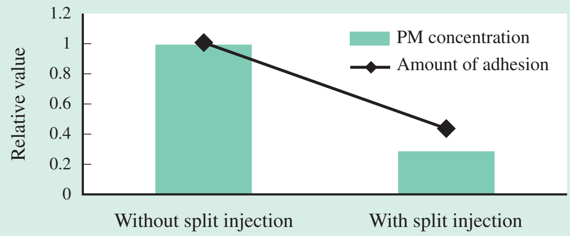


Fig. 18—Adhesion and PM Reduction Benefits of Split Injection (Simulation Results).
The graph shows the results of simulating the reduction in fuel adhesion and PM resulting from use of split injection. The shorter penetration when using split injection reduces PM by reducing the adhesion of fuel to surfaces.

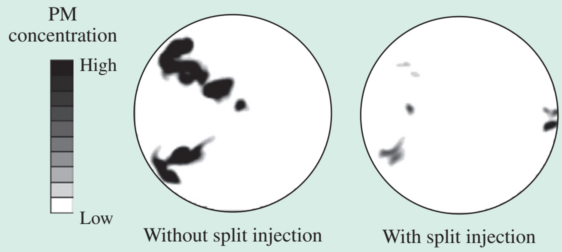


Fig. 19—Results of Simulating PM Concentration Distribution.
The figures show the results of simulating the distribution of the PM concentration across a cross-section of an engine cylinder. Black represents high PM concentration. The results show that use of split injection shrinks the region of high PM concentration.

phenomenon results in the formation of a localized region of fuel-rich mixture that is the source of PM. Fig. 16 shows the results of a simulation of fuel droplets adhering to surfaces in a direct injection gasoline engine.

Because a direct injection gasoline engine involves the injection at high speed of fuel droplets into the confined space inside the cylinder, the penetration force of the spray itself tends to cause droplets to adhere to surfaces. An effective way to reduce the penetration force of the spray is to repeat injection a number of times. Fig. 17 shows the results of a simulation demonstrating how use of this split injection technique reduces the depth of spray penetration. Performing injection intermittently increases the interference between spray and air and increases the deceleration of droplets due to air resistance. By reducing the adhesion of fuel to cylinder walls, split injection significantly reduces the quantity of PM formed (see Fig. 18 and Fig. 19).

CONCLUSIONS

This article has described combustion simulation techniques used to aid engine system development.

The new techniques use simulations to estimate a series of physical phenomena that occur inside a cylinder as part of the engine cycle, including flow, fuel spray, mixture formation, and combustion. They also use detailed chemical reaction mechanisms as a basis for estimating the PM and other emissions that are formed during combustion.

These simulation techniques can be used for the efficient development of engine systems, which contain a large number of control parameters. The use of simulations to view what is happening inside the cylinder is also likely to suggest ideas for innovative approaches to combustion control.

The complexity of what happens inside an engine means that numerous challenges remain in the field of simulations. Examples include combustion problems such as knocking or preignition, detailed ignition phenomena, flame quenching and heat transfer in the vicinity of surfaces, and cyclic variation. The more closely engine combustion is studied, the greater the demands that are likely to be placed on simulations. Hitachi intends to continue enhancing its simulation techniques to contribute to future engine system development.

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Featured Articles

Privacy-preserving Analysis Technique for Secure, Cloud-based Big Data Analytics

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Yoshinori Sato

OVERVIEW: Big data analytics, the process of collecting and analyzing large amounts of data to obtain new knowledge, is being applied in a wide range of fields, including the analysis of purchase histories, medical data, and sensor data. While this has been accompanied by a growth in services that offer to perform these analyses in the cloud, it has also been recognized that analyzing data on a third-party cloud server runs the risk of information leaks due to unauthorized access or criminal activity within the service provider. To overcome this problem, Hitachi has proposed a privacy-preserving analysis technique that uses searchable encryption, which can perform text matching of encrypted text, to perform tasks such as statistical analysis and analysis of correlation rules without decrypting the data. This technique reduces the risk of information leaks because it allows data analysis to be outsourced without divulging the content of the data to the service provider conducting the analysis.

INTRODUCTION

BIG data analytics, the process of collecting and analyzing large amounts of data to obtain new knowledge, is being used to analyze data such as purchase histories, medical data, and sensor data. One common technique for analyzing purchase histories is the analysis of correlation rules (also known as association rule learning). This involves identifying correlations between a particular product and other products that can be utilized in marketing, such as noting that customers who purchase diapers also often purchase beer. Big data analytics identifies knowledge like this that is hidden in large quantities of data. As a current trend in information technology (IT), it is being used in market analysis and a wide variety of other fields.

Complementing this, it is anticipated that software-as-a-service (SaaS) services that analyze customers' data on cloud servers will become widely used. A recognized problem when having analysis performed on a third-party cloud server, however, is the risk of information leaks due to unauthorized data access or criminal activity within the service provider, and therefore the challenge is to develop secure ways of performing this data analysis. Accordingly, Hitachi is working on the research and development of a privacy-preserving analysis technique that can analyze encrypted data without having to decrypt it.

This article describes a technique that can perform two of the most basic forms of analysis, namely statistical analysis and the analysis of correlation rules, without decrypting the data being analyzed. The technique reduces the risk of information leaks by allowing cloud users to outsource analyses such as these by supplying the third-party cloud service provider with data in encrypted form to avoid divulging its content. Along with ensuring the security of the encrypted data, Hitachi also focused on processing efficiency when developing this technique to ensure that it would be capable of analyzing large quantities of data. Experimental testing confirmed that the privacy-preserving analysis technique is practical for use on medium-sized quantities of data, with correlation rule analysis of 100,000 records of encrypted data completing in approximately 600 seconds (10 minutes).

PRIVACY-PRESERVING ANALYSIS TECHNIQUE

Fig. 1 shows the system configuration for privacy-preserving analysis provided by a third-party cloud service. The privacy-preserving analysis system

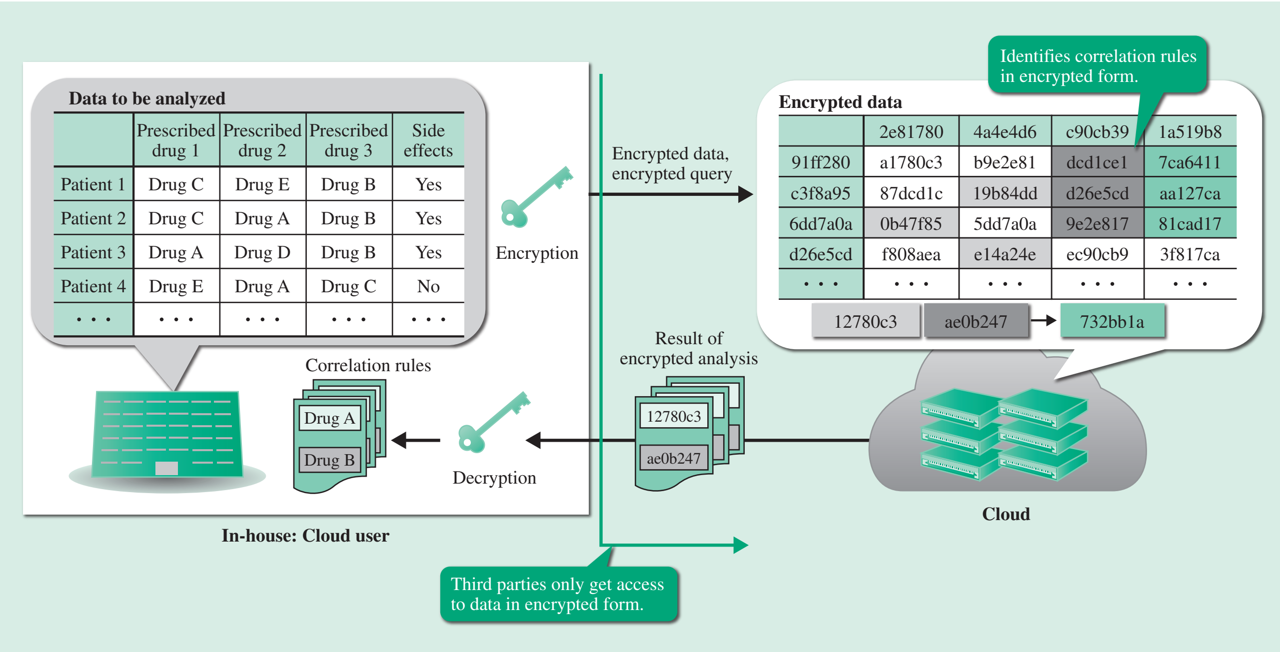

Fig. 1—System Configuration for Privacy-preserving Analysis.
Data is stored in the cloud in encrypted form. To perform an analysis, an encrypted analysis query is passed to the cloud. Storing the cloud data in encrypted form reduces the risk in the event of an information leak.

works by the cloud user with the data to be analyzed (indicated by "in-house" in the figure) encrypting the data using their own key and then supplying it to the third-party cloud service. The user then issues an encrypted analysis query (instruction) to the cloud service. The service uses the encrypted query to perform an analysis on the encrypted data, obtaining a result, also in encrypted form, that is returned to the user. The entire analysis is conducted in encrypted form, with neither the data nor the query being decrypted by the cloud service at any point. Finally, the cloud user decrypts the result to obtain the desired information.

The requirement in the past for data to be decrypted for processing when performing an analysis raised the risk of information leaks. With the privacy-preserving analysis technique, on the other hand, because the data in the cloud remains encrypted, the risk when an information leak occurs is reduced.

The following sections describe techniques for performing statistical analysis and correlation rule analysis of encrypted data using searchable encryption, which is able to perform text matching on encrypted text (testing for an exact match between the plain text versions of the original text and query text). Statistical analysis and correlation rule analysis have been chosen as example analysis applications because they are the most basic forms of data mining.

Searchable Encryption

"Searchable encryption" is a generic term for encryption techniques that allow not only conventional encryption and decryption, but that can also perform text matching using an encrypted query on encrypted text. While encryption and decryption keys respectively are required for encryption and decryption, text matching does not require any special information and therefore can be performed by a cloud service that does not have the keys. However, some techniques also have a separate private key for text matching so that it can only be performed by authorized users.

A number of searchable encryption techniques exist[(1), (2), (3), (4), (5)], and can broadly be divided into those that use a common key system and those that use a public key system. Common key systems use the same key for both encryption and decryption. They are best suited to large quantities of data because they tend to execute more efficiently than public key systems. While public key systems have separate encryption and decryption keys, meaning the encryption key can be made publically available without compromising security, they require greater computing resources for encryption and decryption because they tend to require more complex processing than common key systems.

For reasons of efficiency, Hitachi chose to develop the privacy-preserving analysis technique based on its common-key searchable encryption technique[(5)] so

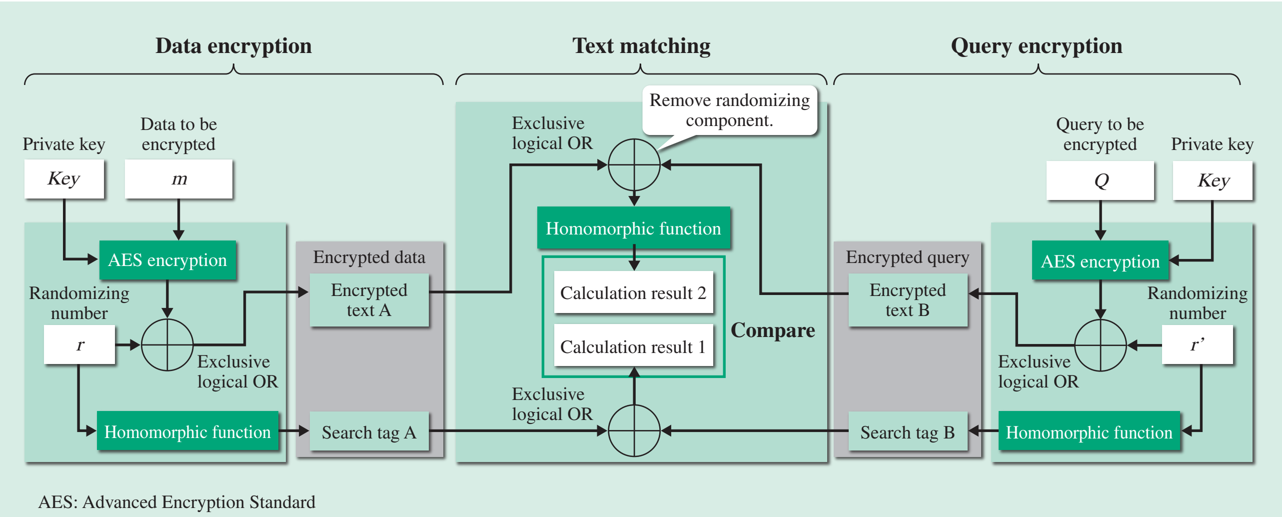

Fig. 2—Overview of Data Encryption, Query Encryption, and Text Matching Using Hitachi's Proposed Searchable Encryption Technique.
The security of the encryption algorithm is enhanced by using random numbers to randomize both data and query encryption. Also, with each step being designed using high-speed encryption primitives, the algorithm can execute searches about 1,000 times faster than searchable encryption algorithms based on public key encryption.

that it would be capable of analyzing large quantities of data. The searchable encryption algorithm has a high level of security, using random numbers to randomize both data and query encryption to encrypt the same plain text (or plain text query) differently each time (see Fig. 2). Since each step of the algorithm is designed using high-speed encryption primitives, such as Advanced Encryption Standard (AES), the most standardized form of common key encryption, it can execute searches about 1,000 times faster than searchable encryption algorithms based on public key encryption[5].

Privacy-preserving Analysis Using Searchable Encryption

By using the above text matching function for searchable encryption, a cloud service can determine the frequency of occurrence of an encrypted query in a database without decrypting the encrypted data. By submitting the appropriate encrypted query to the cloud service, the user can run data mining algorithms on encrypted text that are able to work using only the frequency of occurrence of items. Examples of such data mining algorithms include simple statistical analysis and correlation rule analysis (described below). In terms of the assumptions underlying the use of these searchable encryption techniques, it is important to note that, although the plain text is not divulged to the cloud service, it is possible to obtain frequency of occurrence information from the encrypted data. On the other hand, both the plain text and frequency of occurrence information for the encrypted data are kept confidential from third parties who do not have the encrypted query.

Correlation Rule Analysis

Correlation rule analysis is a data analysis technique for identifying relationships between phenomena from tabular transaction data such as purchase histories[6]. That is, it identifies cases in which if one particular phenomenon occurs (the antecedent), another particular phenomenon has a high probability of occurring also (the consequent). The following describes how correlation rule analysis is performed for a table of transaction data listing the drugs prescribed to a number of patients (see Table 1).

TABLE 1. Transaction Data
Each line indicates the drugs prescribed to a patient and whether or not they suffered side effects.

	Prescribed drug 1	Prescribed drug 2	Prescribed drug 3	Side effects?
Patient 1	Drug A	Drug B	Drug C	Yes
Patient 2	Drug B	Drug A	Drug F	Yes
Patient 3	Drug B	Drug D	Drug E	No
Patient 4	Drug C	Drug E	Drug F	No
Patient 5	Drug E	Drug A	Drug B	Yes
Patient 6	Drug A	Drug D	Drug E	No
Patient 7	Drug C	Drug B	Drug A	Yes
Patient 8	Drug C	Drug E	Drug F	Yes

Each line (transaction) in the table lists the drugs prescribed to a particular patient. For example, patient 1 was prescribed drugs A, B, and C. In this case, the aim is to look for a rule that states that, if a patient is prescribed drug A (the antecedent), then they are likely also to be prescribed drug B (the consequent). This is represented below by the notation, "correlation rule A ⇒ B." Each correlation rule is evaluated in terms of three indicators: the "support," "confidence," and "lift." These are defined as follows.

The support for correlation rule A ⇒ B is:

$$\text{Supp}(A \Rightarrow B) = \frac{\text{Total number of transactions containing A and B}}{\text{Total number of transactions}}$$

The confidence for correlation rule A ⇒ B is:

$$\text{Conf}(A \Rightarrow B) = \frac{\text{Total number of transactions containing A and B}}{\text{Total number of transactions containing A}}$$

The lift for correlation rule A ⇒ B is:

$$\text{Lift}(A \Rightarrow B) = \frac{\text{conf}(A \Rightarrow B)}{\text{supp}(B)}$$

For example, the support, confidence, and lift for the correlation rule "Drug A ⇒ Has side effects" in Table 1 are:

$\text{Supp (Drug A} \Rightarrow \text{Has side effects)} = \frac{4}{8} = 0.5$

$\text{Conf (Drug A} \Rightarrow \text{Has side effects)} = \frac{4}{5} = 0.8$

$\text{Lift (Drug A} \Rightarrow \text{Has side effects)} = \frac{0.8}{0.625} = 1.28$

The following section describes the meaning of these indicators.

The aim of correlation rule analysis is to identify the relationships between phenomena that occur frequently in a transaction table, and the support indicates the probability of occurrence in the table. Typically an analysis will focus on those phenomena with high support values. Confidence indicates the probability that the consequent will occur given that the antecedent has occurred. That is, it can be interpreted as the conditional probability. The lift is this conditional probability divided by the probability of occurrence of the consequent. If the lift is significantly greater than one, it indicates a strong correlation between the antecedent and consequent. In the above example, the lift for "Drug A ⇒ Has side effects" is 1.28. This means that a patient who has been prescribed drug A is 1.28 times more likely to have side effects than a patient selected at random. Actual analysis involves identifying correlation rules with high values for support, confidence, and lift, so that further analysis can be performed to determine why there should be a correlation between these phenomena, and the information is provided as feedback for marketing or other activities.

An important point to note with correlation rule analysis is that the definitions of support, confidence, and lift mean that the analysis can be performed using frequency of occurrence information (number of transactions that contain a specific item). It is this fact that makes it possible to use searchable encryption to perform correlation rule analysis on encrypted data.

Privacy-preserving Statistical Analysis and Correlation Rule Analysis

This section describes how searchable encryption is used to perform statistical analysis and correlation rule analysis on encrypted data.

The table at the top of Fig. 3 lists transaction data from Table 1 that has been encrypted using Hitachi's proposed searchable encryption technique. For example, "drug A," the prescribed drug 1 for patient 1

	Prescribed drug 1	Prescribed drug 2	Prescribed drug 3	Side effects?
Patient 1	91ff280	a1780c3	b9e2e81	dcd1ce1
Patient 2	c3f8a95	87dcd1c	19b84dd	d26e5cd
Patient 3	d26e5cd	f808aea	e14a24e	ec90cb9
Patient 4	2e81780	4a4e4d6	c90cb39	8a212a2
Patient 5	1a519b8	2e81780	3116aea	a96abe3
Patient 6	7a0a43a	dd20a06	278fe21	24ae1e1
Patient 7	e0b47f8	1fff808	a19b84d	16ebc4a
Patient 8	06dd7a0	ae0b47f	a4e4d6e	ab3fc32

Calc. support, confidence and lift for correlation rule 12780c3 → ae0b247

No. of transactions containing 12780c3 = 5

No. of transactions containing ae0b247 = 5

No. of transactions containing 12780c3 and ae0b247 = 4

Supp 12780c3 → ae0b247 = 0.5

Conf 12780c3 → ae0b247 = 0.8

Lift 12780c3 → ae0b247 = 1.28

Fig. 3—Correlation Rule Analysis of Encrypted Transaction Data.

The diagram shows how the support, confidence and lift are calculated for the encrypted queries (12780c3 and ae0b247).

in Table 1, is encrypted as "91ff280." Note also that the prescribed drug 2 for patient 2, also "drug A," is encrypted differently, as "87dcd1c." That is, Hitachi's proposed searchable encryption technique encrypts different instances of the same plain text differently, making the encrypted text on its own difficult to distinguish from a random string. Accordingly, even if the encrypted transaction data were leaked to a third party, they would not be able to use it to reconstruct the plain text version.

Now, consider the case of a cloud user who wants to use the cloud to execute the calculations needed to determine the support, confidence, and lift values for the correlation rule A ⇒ B for phenomena A and B. As explained above, the point to note about this calculation is that it only requires four values from the table: the "number of transactions containing A," "number of transactions containing B," "number of transactions containing both A and B," and "total number of transactions." The total number of transactions is known from the table size.

The cloud user first uses searchable encryption to encrypt A and B and generate the encrypted queries, Query (A) and Query (B). Next, these encrypted queries are submitted to the cloud service where the searchable encryption text matching function is used on the encrypted transaction data and queries to calculate the number of transactions containing A, containing B, containing both A and B, and the total number of transactions. These are then used to obtain the support, confidence, and lift values. That is, the support, confidence, and lift values for the encrypted correlation rule Query (A) ⇒ Query (B) are obtained by using searchable encryption text matching in place of conventional text matching. Statistical analysis can be performed using this text matching function in the same way.

Fig. 3 shows how searchable encryption text matching is used to determine the number of transactions that contain the respective encrypted queries, Query (drug A) (12780c3) and Query (has side effects) (ae0b247), and to calculate the support, confidence, and lift values for the correlation rule Query (drug A) ⇒ Query (has side effects). The point to note is that this process uses only encrypted data, with no need to pass plain text information to the cloud. Furthermore, rather than calculating the support, confidence, and lift values for a specific correlation rule A ⇒ B, conventional correlation rule analysis identifies all correlation rules for which the support, confidence, and lift are above specified thresholds. To achieve this, the cloud user needs to create encrypted queries for all phenomena [Query (A), Query (B), and Query (C), for phenomena A, B, and C, and so on] and request the cloud service to perform all the associated analyses.

Sequence of Steps for Privacy-preserving Analysis

Fig. 4 shows a flow chart for the privacy-preserving correlation rule analysis described above when it is used by a cloud user and cloud service. The point to note is that only encrypted data is provided to the cloud.

(1) The cloud user uses common key searchable encryption to encrypt the transaction data (T) and submits the resulting encrypted transaction data [E(T)] to the cloud database.

(2) The cloud user uses searchable encryption to generate encrypted queries {Q(A), Q(B), Q(C), …} for the set of items {A, B, C, …} for which to conduct the correlation rule analysis (or statistical analysis) of the transaction data, and then forwards these to the cloud service in the form of an analysis request. The

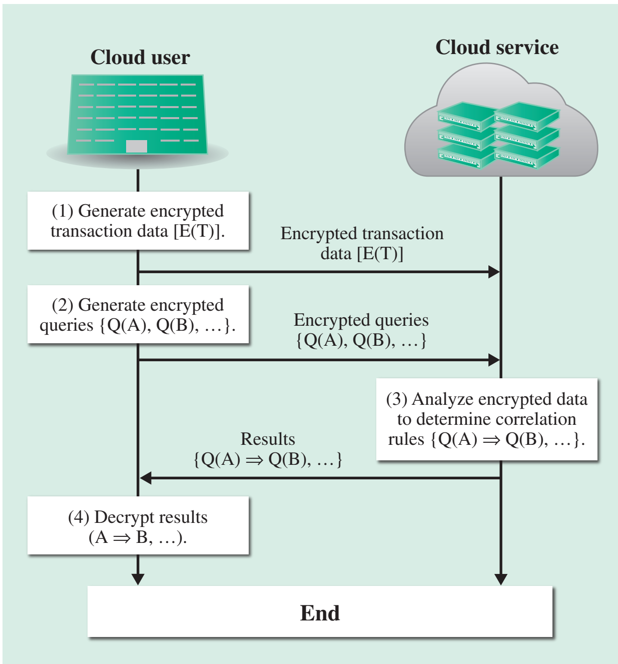

Fig. 4—Flowchart for Correlation Rule Analysis of Encrypted Transaction Data.

(1) Cloud user encrypts transaction data and stores in cloud. (2) Cloud user encrypts queries, which represent the set of items for which to perform correlation rule analysis, and submits these to the cloud. (3) Cloud service determines correlation rules without decrypting and returns the results to the cloud user. (4) Cloud user decrypts the results to obtain the correlation rules.

cloud user also specifies a set of thresholds for the support, confidence, and lift (a, b, c).

(3) The cloud service applies the correlation rule analysis technique for encrypted text (which uses searchable encryption text matching) to determine which of the correlation rules represented by the received queries {Q(A), Q(B), Q(C), …} have support, confidence, and lift greater than or equal to the respective thresholds (a, b, c). The set of those rules that satisfy this criterion {Q(*) ⇒ Q(*), …} is then returned to the cloud user. Statistical analysis works in the same way.

(4) Because the cloud user already knows the correspondence between the set of items {A, B, C, …} and set of associated queries {Q(A), Q(B), Q(C), …}, they can decode the received set of rules {Q(*) ⇒ Q(*), …} and obtain the desired analysis result. That is, the correlation rules for which the support, confidence, and lift exceed the specified thresholds (a, b, c).

Through this procedure, the cloud user can perform a correlation rule or statistical analysis on the cloud without divulging plain text data.

Prototype Performance Evaluation Trial

A trial analysis for determining correlation rules from encrypted test data was conducted using the procedure described above. As in the reference quoted below[6], the trial used 100,000 transactions of test data, each containing ten items of data on average, and with a total of 1,000 different item values.

Hitachi's proposed technique was used for searchable encryption. This searchable encryption technique can perform text matching about 1,000 times faster than searchable encryption based on public key systems. Since determining the total number of transactions containing each item takes up the majority of the execution time during correlation rule analysis, the analysis execution time is approximately one-thousandth of that when public key searchable encryption is used. In a trial run on a conventional personal computer (PC), determining the correlation rules in 100,000 encrypted transactions completed in approximately 600 seconds (10 minutes).

This result demonstrates that the privacy-preserving analysis technique is practical for use on medium-sized quantities of data containing several tens of thousands of records. Meanwhile, although not part of the trials reported here, because the execution time can be expected to scale with the quantity of data, further enhancements such as speed improvement or parallelization will be needed if analyses are to be performed on large data sets containing between several million and several hundred million records. Hitachi hopes to make dealing with large quantities of data the subject of future research.

CONCLUSIONS

This article has described a privacy-preserving analysis technique that can be used to analyze data in encrypted form to provide data security when performing big data analysis on third-party cloud servers.

The core of the proposed method is a searchable encryption technique that permits searching of data in encrypted form and can be used for statistical or correlation rule analysis of encrypted data. Because this privacy-preserving analysis technique only requires encrypted data and encrypted queries, it reduces the risk in the event of unauthorized access or a data leak.

In the future, Hitachi intends to continue with the research and development of advanced security techniques that support both the robust protection and utilization of big data, and to supply highly secure solutions.

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Featured Articles

High-definition 3D Image Processing Technology for Ultrasound Diagnostic Scanners

—Realistic 3D Fetal Imaging—

Masahiro Ogino
Takuma Shibahara, Ph.D.
Yoshimi Noguchi
Takehiro Tsujita
Masaru Murashita
Tsuyoshi Mitake

*OVERVIEW: Hitachi has developed ultrasound diagnostic scanners for use in obstetrics that can provide realistic 3D fetal images by using high-quality rendering techniques capable of representing the scattering and shading of light, and skin color correction techniques that can represent "preferred colors." Realtime operation has also been achieved through the use of parallelization to perform shading plane calculations on multiple processor cores. These technologies were first introduced on three models of cart type ultrasound diagnostic scanners and the Noblus*1 digital ultrasound diagnostic scanner, which went on sale in April 2013. The high image quality of these scanners and the display of high-quality 3D images on portable devices help deliver new added value to clinicians who operate this equipment and to pregnant women and their families who are the ultimate beneficiaries of the technology, and enhance the product brand image of Hitachi Aloka Medical, Ltd.*

INTRODUCTION

COMPARED to other diagnostic equipment such as magnetic resonance imaging (MRI), computed tomography (CT), and X-ray machines, the particular advantages of ultrasound diagnostic scanners include that they are minimally invasive, provide realtime performance, and are able to perform scans at the bedside. These features have made them essential diagnostic tools in modern medical practice. The global market for ultrasound diagnostic scanners is approximately 580 billion yen, and is growing at an annual rate of 5.1%. Hitachi Aloka Medical, Ltd. has the leading share of the Japanese market and is working to improve its products to reach the top of the global market.

In modern medical practice, three-dimensional (3D) ultrasound imaging is used not only by clinicians to perform diagnosis, but also for other purposes such as presenting clear explanations to patients or clinicians from other specialties.

This article describes the development of high-quality rendering and skin color correction techniques for the ultrasound diagnostic scanners used in obstetrics. These image processing techniques are intended to present realistic and appealing 3D fetal images to ensure ease-of-diagnosis while also providing pregnant women and their families with reassurance and an emotional connection.

3D IMAGE PROCESSING FOR FETAL ULTRASOUND

The fact that the diagnostic work of clinicians is made easier by the ability of 3D fetal imaging to present morphological information that is difficult to identify from two-dimensional (2D) images is well known(1).

At the same time, pregnant women and their families like to see realistic and appealing 3D fetal images, as has been widely reported in magazines for pregnant women(2). Clinicians also appreciate the benefits they provide for managing the feelings experienced by the mother, and there have been initiatives aimed at using the emotional lift that parents gain from viewing these images to also provide medical benefits(3).

This has created a need for the ultrasound diagnostic scanners used in obstetrics to display 3D images that have value to both clinicians and pregnant women.

*1 Noblus is a trademark of Hitachi Aloka Medical, Ltd.

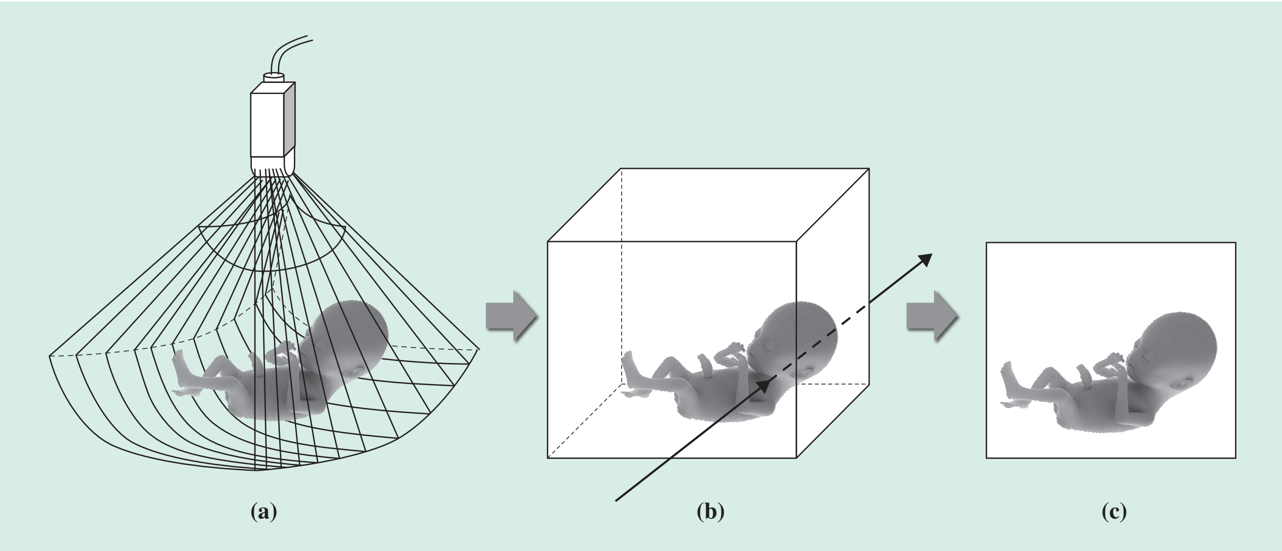

Fig. 1—Procedure for Acquiring 3D Fetal Ultrasound Images.
The probe collects 3D spatial data (a), voxelization is then performed on the collected volume data (b), and then rendering generates the two-dimensional image (c).

Fig. 1 shows the procedure for acquiring 3D fetal ultrasound images. The probe (freehand scanning or mechanically swept probe) transmits ultrasonic waves into the 3D space containing the fetus and receives the echoes to acquire ultrasonic volume data [(a) in Fig. 1]. After the voxelization of this volume data [(b) in Fig. 1], rendering is performed to generate the 3D fetal image projected onto a 2D plane [(c) in Fig. 1].

The following section describes the rendering process.

Volume Rendering

Volume rendering is a method for projecting the internal structure of a 3D object (volume data) onto a 2D surface. This explanation refers to the commonly used ray casting technique(4) (see Fig. 2). To generate a display image, ray casting identifies the volume data (voxel values) that lie on the line (ray) from the viewpoint to each projection point on the projection surface, and then calculates the pixel values for the projection points from the sum of these voxel values. Fig. 3 shows an example 3D fetal image generated using this method.

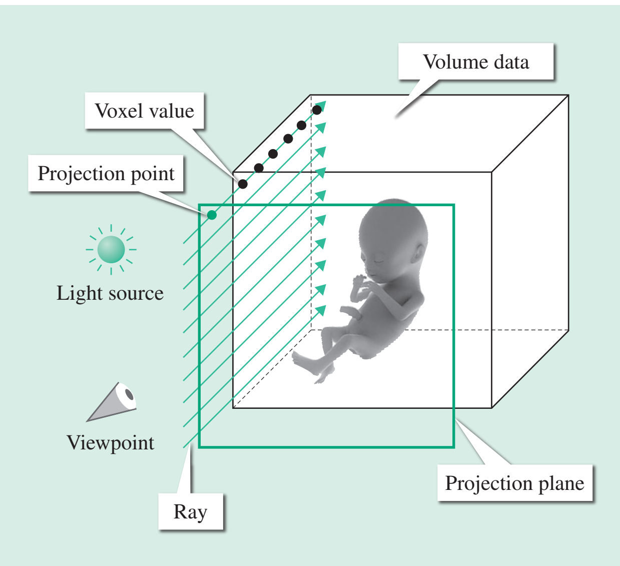

Fig. 2—Ray Casting.
Ray casting is a conventional volume rendering technique.

Fig. 3—Example of 3D Fetal Imaging Using Conventional Ray Casting Technique.
The ability to achieve a 3D effect and replicate skin coloring and texture is limited.

Although Fig. 3 shows the limited ability to create a 3D effect and express skin color and texture, these can be improved along with more accurate imaging of morphological information by faithfully recreating the behavior of natural light. As a result, this method has the potential to provide clinicians with images that facilitate diagnosis while also presenting pregnant women and their families with a favorable impression. Hitachi has now developed the realistic 3D imaging algorithm, which consists of a new rendering technique that can represent light scattering and absorption, and a correction technique that achieves appealing skin color using a method for quantifying subjective responses based on machine learning. Along with showing the fetus more realistically, these techniques produce appealing display colors.

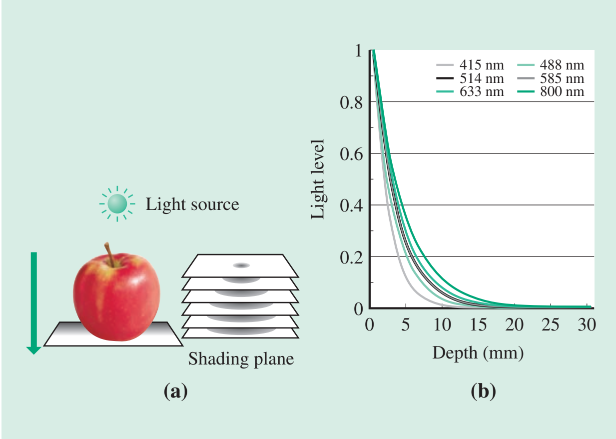

Fig. 4—Shading Plane Generation.
Figure (a) shows how the shading plane is generated and (b) shows examples of the attenuation characteristics of biological tissue at different wavelengths[6].

Realtime Processing

Since the realtime updating of volume data (3 to 4 volumes per second) is essential for displaying 3D fetal ultrasound images, rendering must be capable of processing images even faster (realtime rendering). Since rendering typically has a high computational cost, and because resources are limited on the image processing engines used in ultrasound diagnostic scanners, implementing rendering in a commercial scanner requires improvements to the algorithm through the use of techniques such as optimization and parallelization that take account of the hardware configuration. The system described here uses proprietary optimization techniques to achieve realtime rendering and display without the need for hardware modifications.

The following sections describe the principles behind the new realistic 3D imaging algorithm and techniques for improving its speed so that it can be incorporated into commercial scanners.

ALGORITHM

Replicating the color of a medium such as human skin that undergoes internal scattering generally requires the use of an extremely complex calculation called subsurface scattering[5]. If this subsurface scattering can be replicated, it can provide a realistic representation of skin.

High-quality Rendering Techniques

To represent shading when rendering is performed using the ray casting technique described above, the shading is created from the angle formed by a vector perpendicular to the light source (normal vector). When using the normal vector to create shading, however, it is difficult to replicate the shading due to indirect or transmitted light and therefore difficult to form a highly realistic 3D image. Furthermore, because the gradient calculations used to obtain the normal vector involve differentiation, this method can make images harder to read when used on noisy ultrasound images because it tends to emphasize the noise.

The proposed method uses a shading plane that takes account of the scattering and absorption of

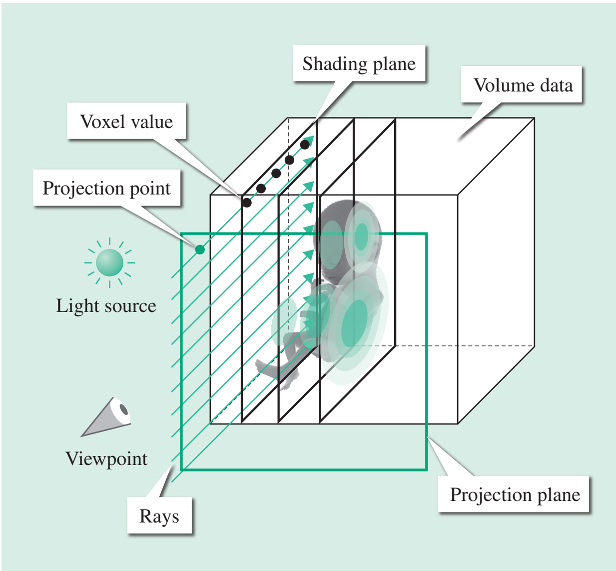

Fig. 5—Overview of New Rendering Method.
Rendering is performed by generating shading planes that replicate the scattering and absorption of light, and summing the product of this and the voxel values.

Fetus phantom supplied by Computerized Imaging Reference Systems, Inc.

Fig. 6—High-quality Rendering Technique.
The images were rendered using the previous technique (left) and proposed technique (right).

light to achieve natural shading [see Fig. 4 (a)]. The shading plane is generated by sequentially calculating the degree of attenuation with each unit length, the incident light from the surroundings, and the light emitted into the surroundings, with ray casting being performed by sequentially updating the shading plane from the light source direction (see Fig. 5). The shading plane is also generated for each wavelength emitted by the light source. This results in a different degree of attenuation in the light from the tissue surface for each wavelength[6] [see Fig. 4 (b)]. This technique is able to represent the deep reds (non-neutral colors) in shaded regions (dark regions) that are characteristic of the subsurface scattering of skin. Fig. 6 shows an example of rendering using this technique. As can be seen, this achieves better shading expression and more realistic display of 3D fetal images than the previous method.

Skin Color Correction

The color of skin is said to be something that people hold in their memory, and extensive research has been conducted into appealing skin color[7]. Having studied the relationship between how skin color is represented and the impression created by the fetus, Hitachi has developed a method based on machine learning that provides a technique for quantifying its subjective appeal.

The proposed method uses ranking learning based on deep learning[8] to assess the appeal of the fetus (see Fig. 7). Also, the subjective assessment and ranking of appeal is used to provide teaching data for learning. The proposed method consists of two steps. The first step is the automatic generation of characteristic quantities. This involves extracting several million small patch images at random from the collection of photographs of babies used as learning data, forming

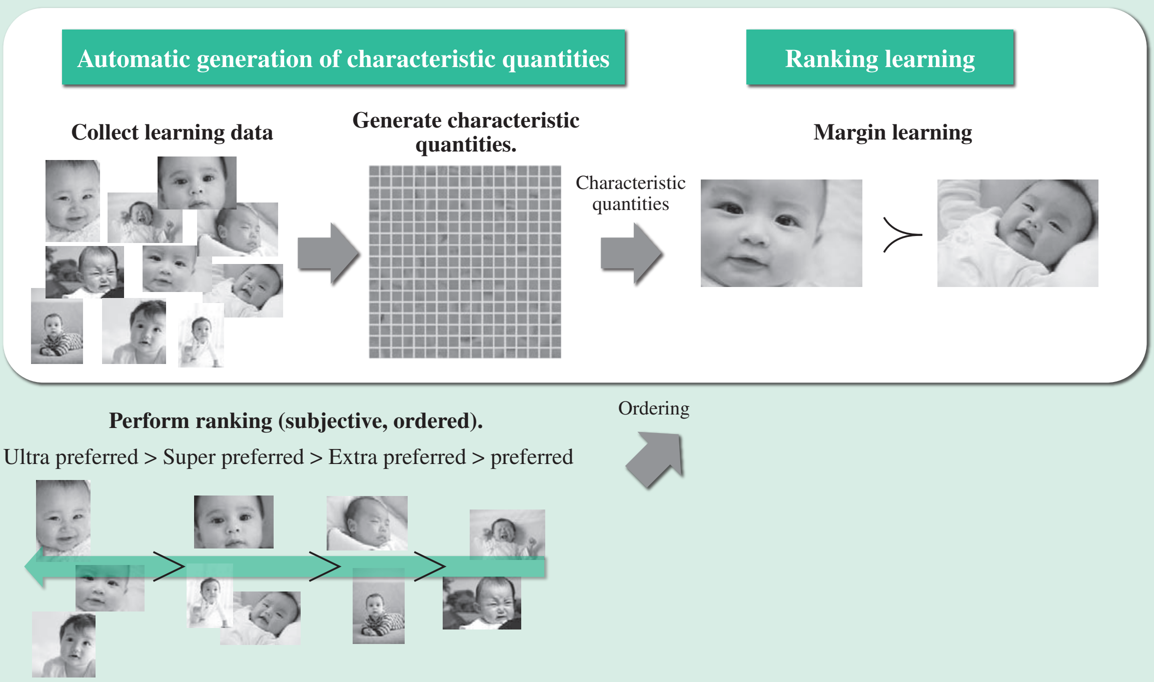

Fig. 7—Configuration of Subjective Analysis System Based on Deep Learning.
The analysis is performed in two steps: automatic generation of characteristic quantities and ranking learning.

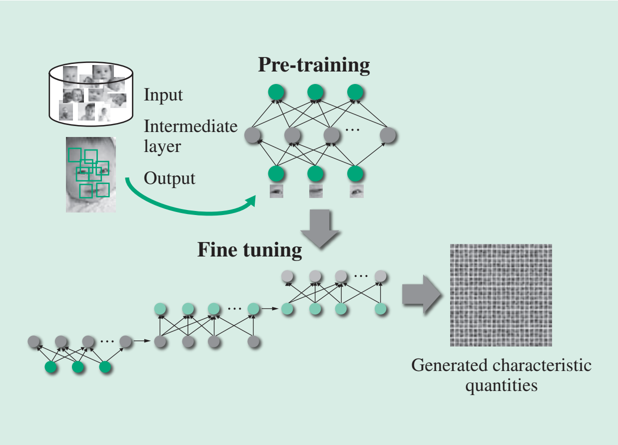

Fig. 8—Automatic Generation of Characteristic Quantities.
Learning is performed using multiple neural net layers to automatically generate highly abstracted characteristic quantities.

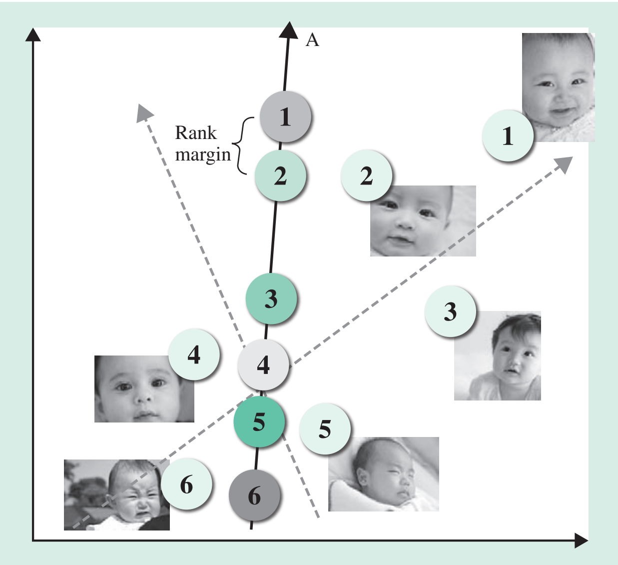

Fig. 9—Ranking Learning.
The A axis in the characteristic quantity space is set so as to match the rankings of the subjective results.

a neural net (NN) with a single intermediate layer, and conducting pre-training until the error between input and output is eliminated. Next, fine-tuning is performed using a number of stages of the above NNs to generate a vector of characteristic quantities with a high degree of abstraction (see Fig. 8). The second learning step consists of optimizing the ranking learning parameters so that the characteristic quantity vectors obtained for each image match the subjective assessment rankings. High accuracy is achieved through optimization involving margin maximization (separation) when ratings are higher or lower, and also margin minimization (joining) when the ratings are

TABLE 1. Learning Conditions for Automatic Generation of Characteristic Quantities
The table lists the learning conditions and parameters used in ranking learning based on deep learning.

Parameter	Value	Remarks
No. of images	400	Acquired from Google* Images*
No. of patches	9,000,000	Size: 6 × 6 pixels
Characteristic quantity	1,936 dimensions	
Total number of neural nets	5 layers	

* Google and Google Images are registered trademarks of Google Inc.

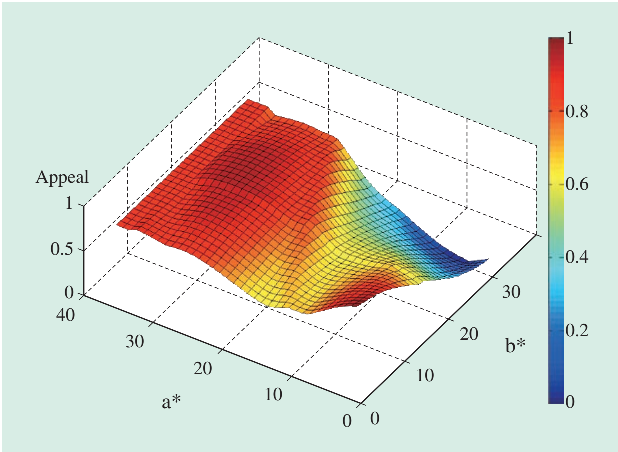

Fig. 10—Appeal Color Map.
The map indicates that red regions tend to have stronger appeal.

equal (see Fig. 9). For example, if photographs 1 and 2 in Fig. 9 are ranked as having the same degree of appeal and photograph 3 is ranked as having a lower appeal, the A axis in the characteristic quantity space is set such that photographs 1 and 2 are placed closer together and photograph 3 is farther away.

Table 1 lists the learning conditions.

When the performance of the subjective analysis system produced by this learning was assessed using 10-fold cross validation, it achieved an accuracy of 94% in identifying rankings up to the top 10.

Fig. 10 shows the appeal rankings produced when approximately 1,000 3D color fetal images produced by the high-quality rendering technique described earlier were input into the subjective analysis system with different values for the a* and b* parameters in the L*a*b* color space. These results show a tendency for redder skin colors to be more appealing. Drawing on these results, the attenuations needed to obtain appropriate a* and b* parameters for the display colors used in 3D images were calculated for each wavelength to produce four different skin color rendering patterns (see Fig. 11).

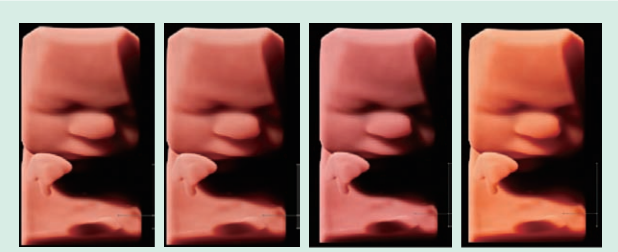

Fig. 11—Skin Color Rendering Patterns.
The patterns were generated based on the appeal color map.

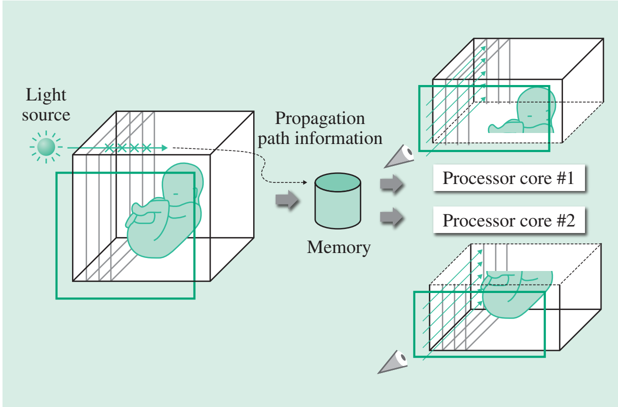

Fig. 12—Speed Increase through Pre-calculation of Path Information and Parallelization.
The calculation time was reduced by storing memory access information and by executing calculations concurrently.

Processing Speed Improvement

Hitachi Aloka ultrasound diagnostic scanners are fitted with high-speed, multi-core processors(9) to provide realtime rendering and display of 3D ultrasound images without the use of custom hardware.

However, the high-quality rendering calculation requires more than 10 times the processing time of the previous method. Accordingly, to achieve realtime rendering and display, the path information of light propagation is pre-calculated and the shading plane calculation is executed concurrently on multiple processor cores (see Fig. 12). The sequential calculation of the shading plane involves random memory access, which degrades the computational efficiency of the processor. To counteract this, the system achieves high-speed data access by storing path information in a way that enables efficient memory access, minimizing the memory access overhead by using this information in the shading plane calculation. Parallelization is also used to execute the shading plane calculation concurrently on multiple processor cores.

These measures have reduced the time required for the shading plane calculation to one-sixth its previous level, making it possible to perform realtime rendering and display.

EVALUATION AND RESULTS

This technology has been incorporated into cart type of ultrasound diagnostic scanners and the Noblus digital ultrasound diagnostic scanner*2, which went on sale in April 2013. These scanners feature a frame rate that is six times faster than the previous models, together with realtime rendering and display. They also allow the user to select from the four different ways of representing skin color described above.

The scanners have undergone clinical evaluation in actual medical practice, where they were favorably received by both clinicians and pregnant women.

The technology is used in all of Hitachi's ultrasound diagnostic scanners, from the top-end models to mass-market models. Its inclusion in the Noblus (see Fig. 13) in particular means that realistic 3D fetal imaging is now available in a portable ultrasound diagnostic scanner. Fig. 14 shows an example image produced using high-quality rendering techniques.

Fig. 13—Noblus Digital Ultrasound Diagnostic Scanner.
The Noblus provides realistic 3D fetal imaging in a portable scanner.

*2 Marketed as the Noblus advanced versatile ultrasound scanner. Medical equipment certification number: 224ABBZX00092000

Fig. 14—Example of Realistic 3D Fetal Image.
High-quality rendering techniques help achieve a 3D effect and more accurately expresses skin color and texture.

CONCLUSIONS

This article has described a highly realistic volume rendering technique and a skin color correction technique that produces appealing colors, techniques that deliver new value to clinicians who operate the ultrasound diagnostic scanners used in obstetrics and to pregnant women and their families who are the ultimate beneficiaries. This technology, which has been incorporated into three models of cart type ultrasound diagnostic scanners and the portable Noblus digital ultrasound diagnostic scanner, has earned a good reputation in medical practice.

The next step is the application of this technology to diagnosis. 3D imaging has already entered widespread use in obstetrics, and its uses are expected to expand further with the addition of new clinical possibilities. To provide the quality of images that clinicians require for diagnosis, it is important to provide the clinical benefits of displaying these images in three dimensions. With regard to image quality, improvements are being made to core image processing techniques such as higher resolution and noise suppression. Hitachi intends to further develop the shading expression technique described in this article to achieve more complex representation of light scattering and absorption, and to determine what these mean in clinical terms. Hitachi also believes that the subjective quantification technique described here for evaluating the appeal of images has the potential to quantify what good image quality means to clinicians.

Hitachi intends to continue using dialogue with the people who work in the medical field as the basis for supplying valuable solutions.

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Featured Articles

First-principles Materials-simulation Technology

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Tomoyuki Hamada, Dr. Eng.

OVERVIEW: First-principles materials-simulation technology guides and assists the development of functional materials by high-precision calculations of electronic states. The accurate determination of electronic states is an important basis for understanding the mechanisms by which material functions come about so that their performance can be improved. It also enables theory-based materials design by predicting the functions of unknown materials. This article describes three current areas of work that use this technology, namely predicting the efficiency of germanium light sources for "photonics-electronics convergence systems," the development of techniques for predicting the Curie temperature in the design of magnetic materials able to function at high temperature, and the development of highly efficient analysis techniques for strongly correlated materials that are difficult to analyze using standard methods.

INTRODUCTION

MATERIALS technology is an important field of technology that underpins innovation at Hitachi. While developing new materials is not easy, improving the performance of these materials or providing them with new functions can make a major impact, because they form a core part of numerous products and services.

In research aimed at enhancing the functions of materials, it is important to proceed on a basis of understanding the basic mechanisms by which those functions (physical properties) come about. At the cutting edge of development, it is not uncommon for the newness of materials to render existing knowledge irrelevant, and yet it is this that offers the key to higher performance.

To understand new materials, it is important first to determine their electronic states. Most material properties are a consequence of the behavior of electrons. This applies not only to electrical properties, such as whether the material is a metal, a semiconductor, or an insulator, but also such characteristics as melting point, boiling point, modulus of elasticity, and chemical reactivity. Optical and magnetic functions can also be explained in terms of electronic states.

First-principles calculation (simulation) is an essential tool for determining these electronic states. This method uses quantum mechanics (first principles) as the sole basis to calculate electronic states, without resorting to empirical parameters determined by experiment. Electronic states are calculated entirely from the atomic species and their positions. If necessary, the positions of atoms can be determined by searching for minimum-energy configurations. Because no empirical parameters are necessary to obtain results in agreement with experiments, even unknown materials that do not yet exist can be calculated with confidence. That is, first-principles calculation can be used not only to understand existing materials, but also as a valuable tool for theoretical materials design tasks, such as predicting the physical properties of unknown materials in advance of experiment, narrowing down promising candidate materials, and predicting optimal composition.

While a wide range of calculation methods fall under the term "first-principles calculation," density functional theory (DFT), which is based on the calculation of electron density distributions, is widely used because of its speed and accuracy. In fact, the term "first-principles calculation" is often synonymous with DFT. This section describes research that is based on DFT.

Although first-principles calculation technology is known to be useful, there is still a problem that even DFT, one of the fastest methods in first-principles calculations, imposes high computational costs, making it difficult to apply to computational models that simulate a large number of atoms. This has led to problems such as an inability to calculate systems that require a large model or a loss of accuracy due to use of an oversimplified model. However, with computing hardware continuing to improve in speed by a factor of around 1,000 every decade[(1)], calculations are now much faster than they were 10 or 20 years ago. Together with advances in computational algorithms designed to take advantage of computer architectures with higher degrees of parallelism, this means that it is now possible to use much larger models. This has considerably expanded the range of phenomena that can be simulated, with the result that first-principles simulation is playing an increasingly important role in materials research.

At the Advanced Research Department, Central Research Laboratory, Hitachi, Ltd., first-principles simulation is used for research into a wide range of materials, including magnetic materials, lithium battery materials, light-emitting materials, thermoelectric materials, catalysts, and polymers. Because it is the novelty of a computational model or calculation method that provides new knowledge, research into these materials at Hitachi includes continually working to improve and extend simulation techniques to expand the range of phenomena that can be simulated and to improve accuracy.

This article describes such research into light-emitting materials, magnetic materials, and strongly correlated materials

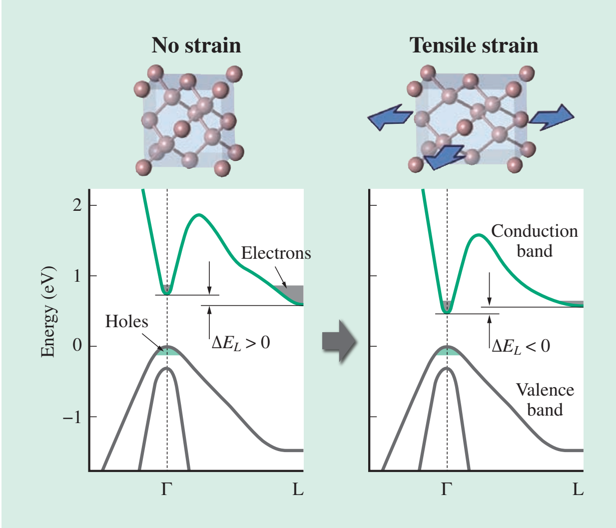

Fig. 1—Effect of Strain on Band Structure of Germanium.
When strain is not present, germanium is an indirect-gap semiconductor with the L point as the lowest point of the conduction band. When a large strain is present, germanium becomes a direct-gap semiconductor with the Γ point becoming the lowest point.

EFFICIENCY PREDICTION FOR GERMANIUM LIGHT SOURCES

Use of optical wiring is one way to improve the performance and power consumption of silicon devices. The best way to achieve this at low cost is to develop a "photonics-electronics convergence system" (system that combines both photonics and electronics) in which light sources are fabricated on a silicon substrate using monolithic integration. Unfortunately, it is difficult to fabricate group III-V compound semiconductors, a well-known light source material, using the processes used in silicon chip manufacturing. Although the group IV element germanium has a good affinity with silicon processes, it suffers from a low light emission efficiency. This section describes the prediction of germanium light emission efficiency, which is part of the effort being made to overcome this difficulty so that germanium can be turned into a practical new light source material.

Germanium is an indirect-gap semiconductor (see Fig. 1). The injection of current causes an accumulation of electrons at the bottom of the conduction band and holes at the top of the valence band. When there is an unoccupied state (a hole exists) in the valence band immediately below the conduction band electron, that electron can fall into that valence-band state (undergo a direct transition) by emitting a photon. In normal germanium, holes accumulate at the Γ point and electrons at the L point. Accordingly, light emission efficiency is low because these direct transitions do not occur, and instead light is only emitted by less frequent indirect transitions triggered by lattice vibration. On the other hand, it is known that the electronic state changes when tensile strain is applied, making it easier for electrons to accumulate at the Γ point, and that using a high concentration of n-type doping to provide a large number of electrons makes it possible to inject electrons not only at the L point but also the Γ point[(2)]. However, while simple qualitative predictions have been made for these effects, no quantitative predictions have yet been made. Because adequate light emission efficiency has yet to be achieved through experimental methods, Hitachi set out to use first-principles calculations to predict light emission efficiency so that this could be used in materials design to assess the extent to which strain and doping should be used.

Calculation of Light Emission Efficiency

This calculation method is based on the DFT using plane wave basis for describing wave function and pseudopotential method, which treats the nucleus and core orbital electrons as an ion core. A hybrid functional[3] is used as the exchange-correlation term.

The top of Fig. 2 shows the wave function for the Γ point of germanium. The blue and white surfaces are isosurfaces for the wave functions of the valence and conduction bands, with the different colors representing opposite signs. To determine the light emission efficiency, it is necessary to calculate the probability of optical transition between these two levels. This in turn requires obtaining the optical transition matrix elements. That can be calculated by applying the x, y, and z partial differential operators to one of the wave functions, multiplying this with the other wave function and integrating the product.

The bottom half of Fig. 2 shows the distribution of this integrand. The different colors represent opposite signs. This shows that a non-zero value remains for the x component after performing a spatial integration, but that the positive and negative contributions for the y component cancel to zero. This indicates that a transition between these two states is only possible with the emission of light polarized in the x direction. The light emission efficiency can be obtained by performing this calculation for all combinations of electronic states between which transitions are possible and summing them with reference to the occupation of electrons and holes.

Although there is a difficulty in the calculation of optical transition matrix elements using a plane-wave based pseudopotential method by which considerable error arises in the core region, it was solved by incorporating a core-repair term[4], [5] and the calculation was kept accurate.

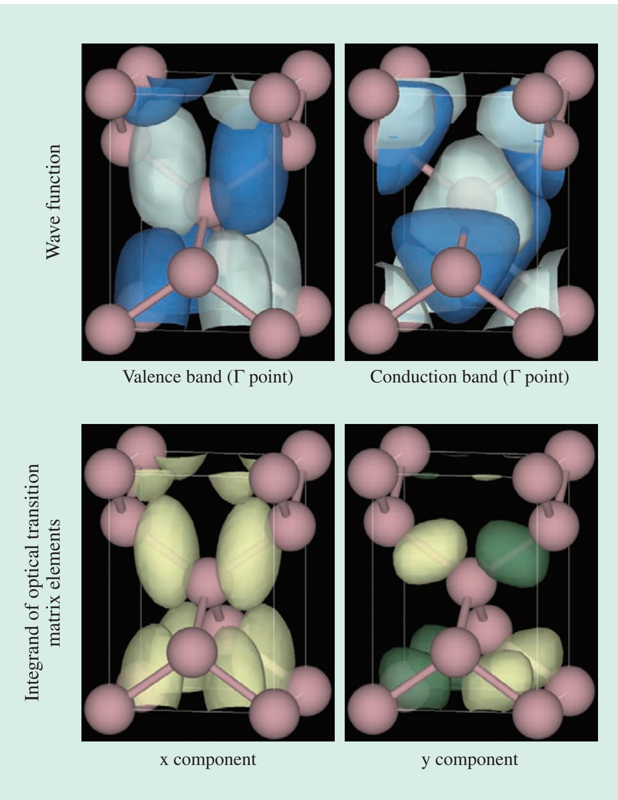

Fig. 2—Germanium Wave Function and Calculation of Optical Transition Matrix Elements.
The different colors of the isosurface represent opposite signs. The higher the optical transition matrix elements calculated from the valence band and conduction band wave functions, the higher the light emission efficiency.

Prediction of Light Emission Efficiency for Germanium Under Strain

The factors that have a major influence on the light emission efficiency of germanium are the injected electron density, hole density, strain, density of crystal defects, and temperature. Fig. 3 shows the calculated result of optical gain for an ideal defect-free germanium crystal at room temperature (300 K) using the electron and hole densities as parameters.

Achieving lasing is an important requirement for obtaining sufficient light output for use as a light source in photonics-electronics convergence systems,

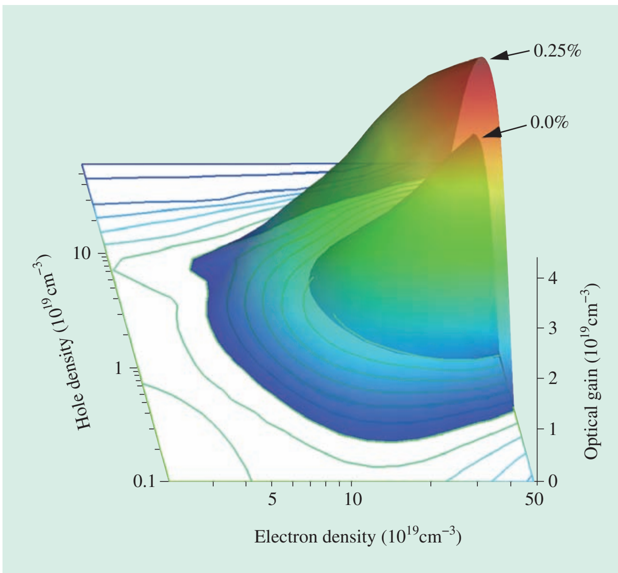

Fig. 3—Calculated Result of Optical Gain.
The results are for no strain (0.0%) and for a biaxial strain (0.25%) parallel to the (001) plane. The gain is negative in regions where no colored surface is shown.

and to realize that, the optical gain of the light-emitting material should be positive. If there are wavelengths at which the net gain (after subtracting the light absorption loss from the light emission efficiency) is positive, lasing is possible at those wavelengths. Fig. 3 also shows the calculated net gains for the cases of no strain and 0.25% biaxial tensile strain parallel to the (001) plane where the vertical coordinate of the surfaces represents the gain (only shown for positive values). Regions where no surface is shown have a negative gain. The figure indicates that a positive gain is available at lower electron and hole densities when strain is present. Put another way, the presence of strain results in a higher gain for the same carrier (electron or hole) density. Looking at the locations where the surfaces are shown also indicates that the minimum necessary electron density is always much larger than the minimum necessary hole density. This is a consequence of the fact that electrons are not injected at the Γ point until they have filled up the region around the L point.

Although inversion of the Γ point and L point levels does not occur until a large strain of about 1.5% is present, as shown in Fig. 1, Fig. 3 indicates that gain improvement can be achieved at a comparatively easily achieved strain of 0.25% by reducing the difference between the two levels. Although positive gain regions also exist when no strain is present, these require impractically high electron densities of about $10^{20}cm^{-3}$. Accordingly, taking advantage of strain to reduce the required density is a more realistic alternative.

While the above describes the calculation of gain at room temperature, heating due to the injected current raises the temperature in an actual device. Fig. 4 shows the gain at a variety of temperatures calculated to determine how the gain changes under such conditions. The figure shows the gains for a germanium crystal n-type doped with an electron density of $4.6 \times 10^{19}cm^{-3}$ and with a strain of 0.25% (same as Fig. 3) when the same number of electron and hole carriers are injected (current injection). Fig. 4 shows that, even if the temperature rises above 100°C (400 K), and the gain falls, there is still an adequate region with a positive gain. Also, because the gain region expands if the temperature falls, it demonstrates that cooling is a useful technique for experimental confirmation of lasing.

These results show that achieving a gain requires carrier injection on the order of $10^{19}cm^{-3}$, a level of carrier density that is not easy to achieve. A small number of defects also inevitably appear during device manufacturing, reducing the crystallinity. These defects shorten the life time of the injected carriers and prevent increases in the carrier density. Because doping and the use of strain to increase light emission efficiency also increase defects, too much of these will have the opposite effect of reducing the light emission efficiency. To find the optimal balance of strain, doping, and crystallinity needed to achieve lasing by theoretical material design will be our next research subject.

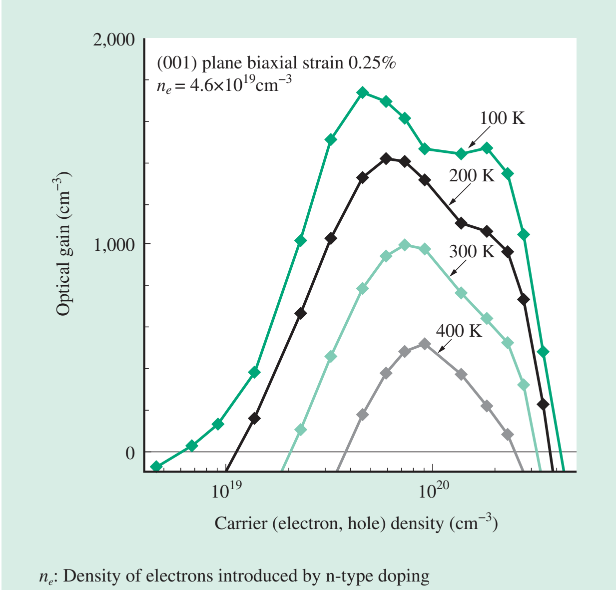

Fig. 4—Temperature Dependence of Optical Gain.
A region in which lasing can occur is still present even if the temperature increases by about 100°C from room temperature. Cooling significantly expands the conditions under which lasing occurs.

FIRST-PRINCIPLES ANALYSIS OF THE CURIE TEMPERATURE OF MAGNETS

High-performance magnets are used in a number of familiar products, such as hybrid electric vehicles (HEVs), air-conditioning compressors, and hard disks. While neodymium magnets ($Nd_2Fe_{14}B$) are the most common type of ferromagnets in current use, their poor high-temperature properties mean they require the addition of dysprosium (Dy), a rare metal. However, there was a sudden disruption in supply of this material in 2010, and this created a need for the development of new high-performance magnets that do not use rare metals. A key point is being able to provide adequate magnetism at product operating temperatures. The operating temperature of an HEV, for example, is about 200°C (473 K) or more. The key to determining the magnetism at non-zero temperatures is the Curie temperature, which needs to be sufficiently higher than the operating temperature. The following sections describe a technique developed by Hitachi for the theoretical prediction of Curie temperature.

Curie Temperature

The electrons in the iron (Fe) and other magnetic atoms present in a magnetic material impart a magnetic moment (spin) allowing the atoms to form a three-dimensional (3D) crystal lattice. Fig. 5 shows the concept behind this phenomenon. The quantum mechanical interaction between these spins causes them to align at low temperatures, forming a ferromagnetic state. At higher temperatures, the spins fall out of alignment, reducing the magnetism to zero (paramagnetic state). The temperature at which this transition occurs is called the Curie temperature (T_C).

Calculation Method

The Heisenberg model is used for the theoretical calculation of Curie temperature. In this model, the Hamiltonian for the energy of the system is written as follows:

$$H = -\sum_{ij} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j - \sum_{i} \mathbf{h} \cdot \mathbf{S}_i \quad (1)$$

Where $\mathbf{S}_i$ and $\mathbf{S}_j$ are the spins (3D vectors) at sites i and j, and the exchange parameters J_{ij} determine the strength of interaction between them. These exchange parameters, which are the critical elements of this method, can be calculated from first principles with high precision. Specifically, the Liechtenstein method(6) that determines J_{ij} from the change in energy when the spins at sites i and j only are varied by an angle θ is used. In this case, Hitachi used the AkaiKKR(7) first-principles calculation (DFT) code to calculate J_{ij}. Once the Hamiltonian is determined, the spin states at non-zero temperatures can be determined from the statistical-mechanical partition function (Z).

$$Z = \sum_{\{\mathbf{S}_i\}} e^{-H/k_B T} \quad (2)$$

Although it is necessary to use an approximation to calculate the partition function, Hitachi used the Monte Carlo method, which provides the highest level of accuracy. Hitachi also tried using mean field approximation, whereby the mean value of the spin is used to minimize the computational load. However, this proved to be impractical because it ignores the effect of spin fluctuation and produces results that overestimate T_C by around 200 K to 300 K.

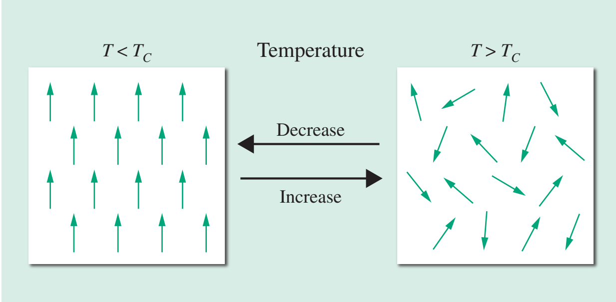

Fig. 5—Concept of Curie Temperature.
In a magnetic material, a lattice is formed by the magnetic moment (spin) of magnetic atoms. The spin orientations become aligned at low temperatures (ferromagnetic state) (left) but lose this alignment at higher temperatures (paramagnetic state) (right). The temperature at which this transition takes place is called the Curie temperature (T_C).

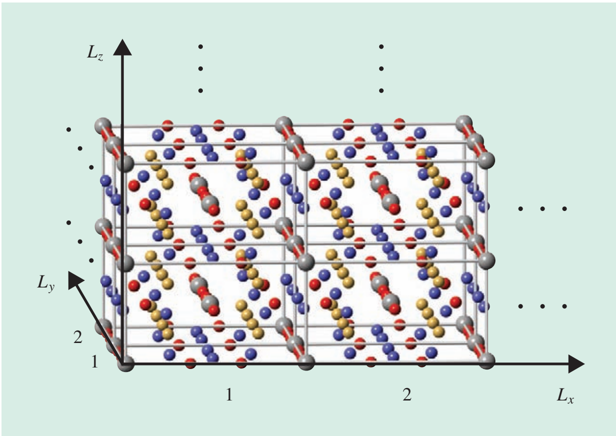

Fig. 6—Crystal Model.
The actual calculation is performed for a three-dimensional lattice consisting of $L_x \times L_y \times L_z$ unit cells (the figure shows tetragonal YFe_{12}). The correct result is obtained when the lattice size (L_x, L_y, L_z) is infinitely large.

The Monte Carlo method uses random numbers for the spin orientation at points in a 3D lattice extending across $L_x \times L_y \times L_z$ (= N) unit cells to generate probabilistic variation (see Fig. 6). The larger the lattice size (L_x, L_y, L_z), the closer this approaches an actual system. While the Monte Carlo method gives a partition function that is more accurate than any other approximation, the problem with it is that, when used to calculate T_C directly, it requires that a sufficiently large lattice be used to approximate reality, and this increases the computational load. Accordingly, Hitachi resolved this lattice size problem by using a method that calculates a quantity known as a "4th order cumulant."

Solution to Lattice Size Problem

The 4th order cumulant (U_L) is defined as follows.

$$U_L = 1 - \frac{\langle M_z^4 \rangle}{3\langle M_z^2 \rangle^2} \quad (3)$$

Here the lattice size is $L_x = L_y = L_z$ (=L). U_L has the property of being equal to zero when treated as a Gaussian distribution for which the mean value of the z-axis magnetization M_z (= $\sum_i S_{zi}/N$) is zero ($\langle M_z \rangle = 0$). This condition is satisfied when the system is above the Curie temperature. Another property of U_L is that, at the Curie temperature, it is not dependent on the lattice size. When calculated for tetragonal yttrium-iron (YFe_{12}), for example (see Fig. 7), as L increases, U_L converges on one of the values $\frac{2}{3}$, 0.38, or 0 (fixed point U^*), depending on the temperature. Here, $\frac{2}{3}$ corresponds to the ferromagnetic state when $T = 0$, and 0 corresponds to the paramagnetic state when $T = \infty$. Similarly, 0.38 corresponds to the Curie temperature and in this case U_L clearly has little dependence on L. Although specifying the spin state at the Curie temperature is difficult, when all spins are aligned and have the same magnitude, and are then rotated at random, for example, the calculation gives $U^* = \frac{2}{5} = 0.4$. It is believed that the value of $U^* = 0.38$ comes about because short-range correlation states have the effect of reducing U^* by a small amount. These three fixed points are generally explained from a renormalization group perspective in terms of the relative magnitudes of the correlation length (ξ) of the magnetization (M_z) and the lattice size (L)[8]. Hitachi has taken advantage of this property to calculate the Curie temperature with high accuracy using a comparatively small lattice.

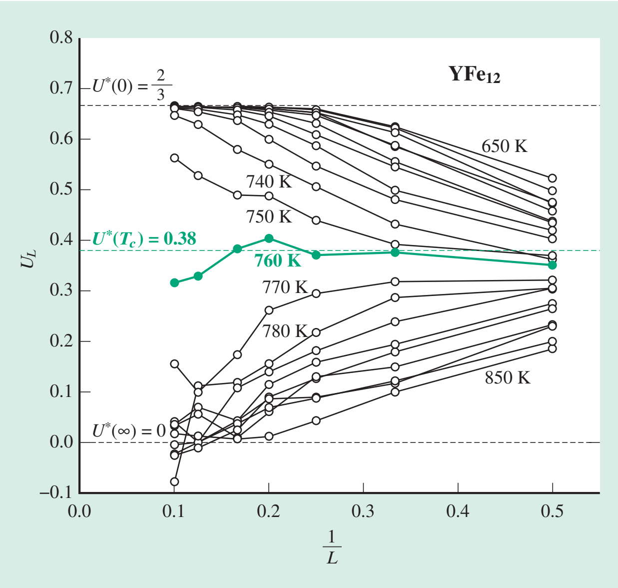

Fig. 7—Dependence of 4th Order Cumulant on Lattice Size.
As the size of the lattice used in the calculation (L) increases, the 4th order cumulant (U_L) converges on one of the fixed points (U^*) (0, 0.38, or $\frac{2}{3}$), depending on the temperature. The graph shows there is no dependence on L at the temperature that gives $U^* = 0.38$. This property can be used to obtain the Curie temperature (T_C = 760 K) with high accuracy.

Testing on Common Magnets

The newly developed technique was used to calculate the Curie temperature of ferromagnetic materials such as body-centered cubic iron (bcc-Fe), body-centered cubic cobalt (bcc-Co), face-centered cubic nickel (fcc-Ni), YFe_{12}, Y_2Fe_{17}, and yttrium-iron nitride ($Y_2Fe_{17}N_3$). Fig. 8 shows a plot of the results, with the vertical axis representing the calculated temperatures and the horizontal axis representing the measured values. The dotted line indicates agreement between the calculated and measured values. The calculations for bcc-Fe and bcc-Co, which have simple structures, match the measured values exactly. Meanwhile, although the calculation slightly overestimates the Curie temperatures for the complex structures of YFe_{12}, Y_2Fe_{17}, and $Y_2Fe_{17}N_3$, the calculated temperatures are in the same relative order as the measured values. The calculation underestimates the Curie temperature of Ni. This can be explained by the low magnetic moment of Ni, which means the Heisenberg model provides a poor approximation. That these calculations reproduce

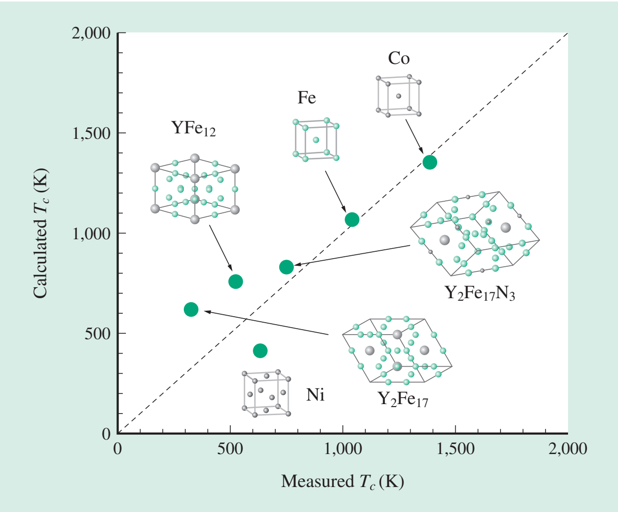

Fig. 8—Curie Temperature of Common Magnetic Materials.
The graph plots the Curie temperature calculated for ferromagnetic materials by this method (vertical axis) against their experimental values (horizontal axis). The Monte Carlo calculation is in good agreement with experiment even for materials with complex structures (YFe_{12}, Y_2Fe_{17}, $Y_2Fe_{17}N_3$).

the measured values with a practical level of accuracy indicates that this technique can be used to predict the Curie temperature of new materials from first principles. Accordingly, the technique will be useful for developing a new generation of magnetic materials that do not use rare elements.

USE OF DFT + U METHOD TO ANALYZE STRONGLY CORRELATED MATERIALS

While the DFT method is recognized as suitable for analyzing the electronic states of most materials, there is one class of materials to which it is not applicable. That class consists of materials with localized electrons, what is known as a "strongly correlated electron system." In addition to the magnets described above, other examples of strongly correlated electron systems include the cathode material used in lithium-ion batteries, high transition temperature (high-Tc) superconductors, metal oxides, and catalysts. Since these materials play an important role in social infrastructure systems, analysis of the electronic structures of strongly correlated electron systems is an important topic for infrastructure materials research.

The DFT method uses the electronic states of a hypothetical system (in which there is no interaction between electrons) as the basis for analyzing actual electronic structures where interactions are present. Accordingly, while the DFT method is suitable for analyzing the electronic structures of materials such as semiconductors and metals with properties determined by free electrons, it is less suited to performing such analyses for strongly correlated electron systems with localized electrons. The solution to this problem with the DFT method is the DFT + U method[(9), (10)]. Fig. 9 shows an overview.

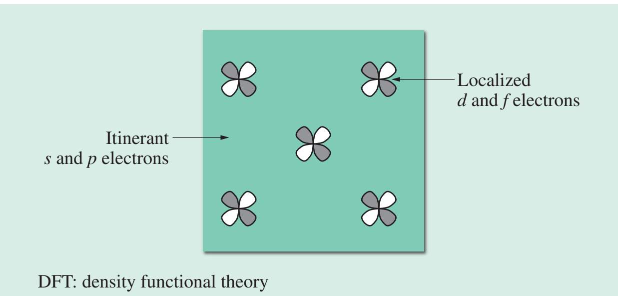

Fig. 9—Overview of DFT + U Method.
This strongly correlated electron system consists of itinerant s and p electrons and localized d and f electrons. The DFT + U method uses the DFT method for the s and p electrons and introduces the concept of on-site energy for the d and f electrons.

The electrons in a strongly correlated electron system can be divided into highly itinerant *s* and *p* electrons (electrons with *s* and *p* atomic orbital components) and highly localized *d* and *f* electrons (electrons with *d* and *f* atomic orbital components). The DFT + U method uses the DFT method for the *s* and *p* electrons and the approximate Hartree-Fock wave function method for the *d* and *f* electrons. The Hartree-Fock wave function method uses an approximation that only considers the on-site (within same atom) electronic interactions. Inter-atomic electronic interactions are ignored. Because consideration for the electronic interactions for *d* and *f* electrons is an inherent part of the DFT + U method, it can take appropriate account of their being localized and correctly specify the electronic states of a strongly correlated electron system.

Theoretical Determination of U_{eff}

The DFT + U method uses the effective interaction parameter (U_{eff}) for the on-site interactions between localized electrons. U_{eff} is obtained from the difference between the parameter for Coulomb interaction between electrons (U) and the exchange interaction parameter (J) ($U_{eff} = U - J$). U_{eff} is typically obtained empirically, and often takes a value of around 5 eV. However, use of an empirical value for U_{eff} is undesirable because it means the calculation is no longer from first principles and therefore confidence in it is undermined.

Accordingly, Hitachi set about performing first-principles DFT + U calculations in which U_{eff} was calculated theoretically. The constraint DFT method[(11), (12)] is recognized as one way to calculate a value for U_{eff} theoretically. This method performs the DFT calculation for different numbers of localized electrons in a strongly correlated electron system to obtain U from the second derivative of energy with respect to the number of localized electrons. This was done using the linearized muffin tin orbital method, which provides an easy way to calculate electronic structures for different numbers of localized electrons, rather than with the more accurate pseudopotential method. This is because it is difficult to use the pseudopotential method to calculate electronic structures for different numbers of localized electrons. To overcome this problem, Hitachi developed a technique for the theoretical calculation of U_{eff} in the DFT + U method based on the pseudopotential method[(13)]. This works by performing the DFT + U calculation for small variations in the value of U_{eff} around 0 eV and using the number of localized electrons and change in energy given by this calculation to obtain the second derivative for energy with respect to the number of localized electrons, and thereby to calculate the value of U. Because the value of J can be approximated as $\frac{1}{10}$ the value of U(11), this can be used to determine $U_{eff} = U - J$. Because the value of U_{eff} obtained by this procedure does not include any empirical parameters, it means that the DFT + U calculation can be performed from first principles.

Electronic State Calculation for Antiferromagnetic Ce_2O_3 and Nd_2O_3

This section describes the application of the first-principles DFT + U method to cerium (III) oxide (Ce_2O_3) and neodymium (III) oxide (Nd_2O_3).

Ce_2O_3 is a catalyst for reducing exhaust emissions and Nd_2O_3 is a material that occurs in crystal boundaries in neodymium magnets and may influence their coercivity. Both have a hexagonal crystal structure and constitute strongly correlated electron systems with localized *4f* electrons in their respective Ce and Nd atoms. Hitachi used the DFT + U method to calculate the electronic states, using the method described above to determine the values of U_{eff} for the *4f* electrons. The U_{eff} values are 8.99 eV for Ce and 8.17 eV for Nd. These values are larger than the empirical value of 5 eV. The generalized gradient approximation (GGA) was chosen as the exchange-correlation term in the DFT part of the calculation. The materials were also assumed to be in an antiferromagnetic state.

Fig. 10 and Fig 11 show the results of calculating the density of states (DOS) for Ce_2O_3 and Nd_2O_3 respectively. To compare the differences between calculation methods, the graphs show the results for both DFT on its own and DFT + U. DOS has both a positive and negative value, representing the up and down spin components. Because the material is in an antiferromagnetic state, there is little difference

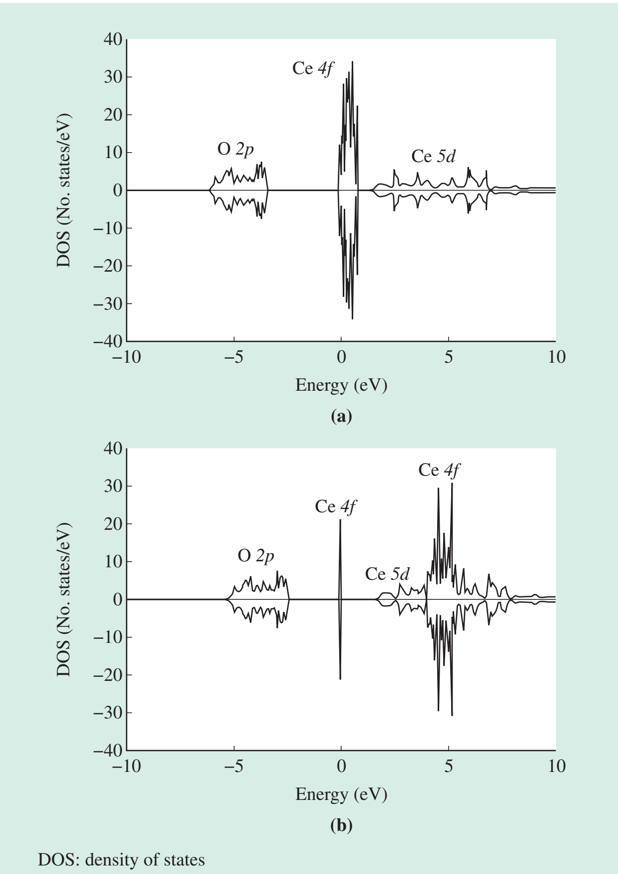

Fig. 10—Density of Electronic States for (Antiferromagnetic) Hexagonal Ce_2O_3.
Graph (a) shows the result calculated using the DFT method and graph (b) shows the result calculated using the DFT + U method. The DFT + U method gives a U_{eff} of 8.99 eV for the 4f electrons of Ce.

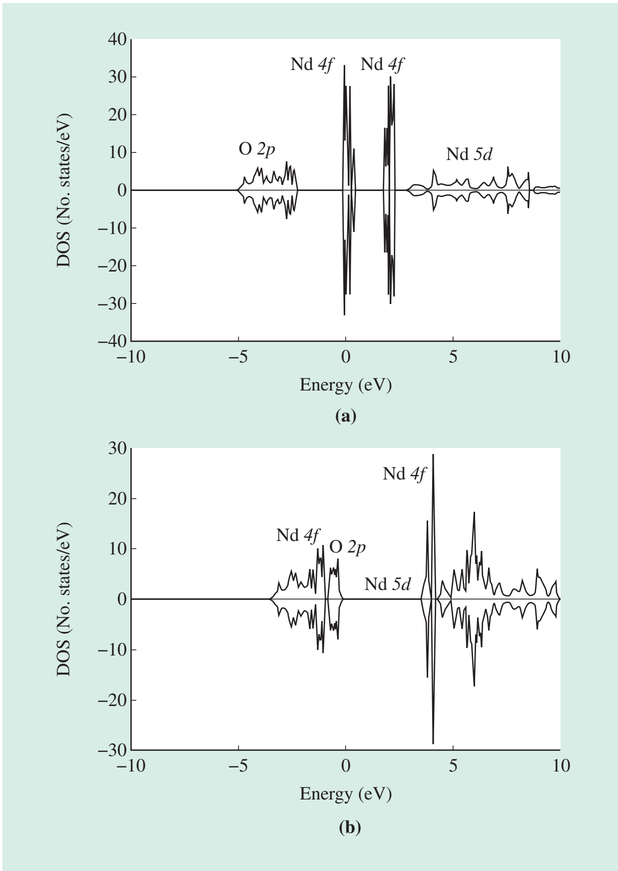

Fig. 11—Density of Electronic States for (Antiferromagnetic) Hexagonal Nd_2O_3.
Graph (a) shows the result calculated using the DFT method and graph (b) shows the result calculated using the DFT + U method. The DFT + U method gives a U_{eff} of 8.17 eV for the 4f electrons of Nd.

between spin components, giving a graph with horizontal symmetry.

States with an energy of 0 eV are at the Fermi level and the DOSs at and around these states have a major influence on the electrical behavior of the material. The results calculated using the DFT method show that both Ce_2O_3 and Nd_2O_3 have non-zero DOSs at and around 0 eV, and since there is no band gap (energy ranges where the DOS is zero) at these energy levels, the electronic states behave like a metal. As these materials are in fact insulators, this indicates that the DFT method has failed to reproduce experimental results. The DFT + U calculation, on the other hand, correctly reproduces experimental results by showing that both materials have a band gap at around 0 eV and therefore behave like insulators.

The size of the gap between the *2p* band (O) and *4f* band (Ce) for Ce_2O_3 calculated by DFT + U is 2.34 eV. This is very close to the measured value of 2.4 eV(14). Similarly, the gap between the *4f* band (Ce) and *5d* band (Ce) is calculated to be 1.49 eV, which is close to the value of 1.29 eV calculated by the GW method(15) (which considers many body effects and therefore is accurate but with a high computational cost). When the same calculation is performed using an empirical value of U_{eff} (5 eV), it gives a band gap of 1.69 eV between the *2p* band (O) and *4f* band (Ce) and 2.19 eV between the *4f* band (Ce) and *5d* band (Ce), indicating poor agreement with the experimental values.

In the case of Nd_2O_3, the DFT + U method calculates a band gap of 3.44 eV, considerably different from the experimental value of 4.7 eV(14). This is because the band gap for this material is determined by the energy difference between the *2p* band (O) and *5d* band (Nd). As U_{eff} is introduced for the Nd *4f* electrons, the *4f* band (Nd) is split into high and low energies and is away from the Fermi level. In contrast, there is no U_{eff} for bands such as the *2p* band (O) and *5d* band (Nd), and therefore these remain close to the Fermi level. It is known that the self-interaction of electrons gives the DFT method a tendency to underestimate the band gap, and the difference in level between the *2p* band (O) and *5d* band (Nd) is underestimated here for the same reason. Accordingly, introducing the U_{eff} for the Nd *5d* electrons also has the potential to improve the calculated value of band gap. Furthermore, when the DFT + U calculation was performed using an empirical value for the U_{eff} for the Nd *4f* electrons (5 eV), it indicated that the electronic states behave like a metal and failed to correctly describe the insulating nature of Nd_2O_3.

These results confirmed the reliability of a first-principles DFT + U method that uses theoretical calculations to determine U_{eff}, and that it has better agreement with experiment compared to past DFT + U methods that have determined U_{eff} empirically. This method, which can be used alongside the accurate pseudopotential method, and which can analyze the electronic states of strongly correlated electron systems at high speed and with a similar computational cost to the DFT method, is an effective tool for designing the strongly correlated materials that underpin social infrastructure systems.

CONCLUSIONS

A decade ago, it was predicted that the thousand-fold improvement in computer speed every 10 years would begin to slow down. In practice, no such slowing has occurred(1), and the trend can be expected to continue for some time yet. Accordingly, the scope and reliability of research based on the use of computer simulation will continue to grow in the future.

Although the value of first-principles calculation technology has already been demonstrated and is widely acknowledged, the details of this technology are not yet complete. Progress continues with a variety of improvements being achieved on a regular basis. Given this situation, if materials research is to be pursued using first-principles calculations to advantage, it is essential to follow up on advanced simulation technology continuously and to take up the challenge of making new improvements as described here. Hitachi intends to continue with these efforts in the future to expand the scope of research, and to work on elucidating the physical properties of new substances and on performing theoretical design of new materials.

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Featured Articles

Light Water Reactor System Designed to Minimize Environmental Burden of Radioactive Waste

Tetsushi Hino, Dr. Sci.
Masaya Ohtsuka, Dr. Eng.
Kumiaki Moriya
Masayoshi Matsuura

OVERVIEW: One of the problems with nuclear power generation is the accumulation in radioactive waste of the long-lived TRUs generated as byproducts of the fission of uranium fuel. Hitachi is developing a nuclear reactor that can burn TRU fuel and is based on a BWR design that is already in use in commercial reactors. Achieving the efficient fission of TRUs requires that the spectrum of neutron energies in the nuclear reactor be modified to promote nuclear reactions by these elements. By taking advantage of one of the features of BWRs, namely that their neutron energy spectrum is more easily controlled than that of other reactor types, the new reactor combines effective use of resources with a reduction in the load on the environment by using TRUs as fuel that can be repeatedly recycled to burn these elements up.

INTRODUCTION

NUCLEAR power generation has an important role to play in both energy security and reducing emissions of carbon dioxide. One of its problems, however, is the accumulation in radioactive waste from the long-lived transuranium elements (TRUs) generated as byproducts of the fission of uranium fuel. The TRUs include many different isotopes with half-lives ranging from hundreds to tens of thousands of years or more. As a result, the radiotoxicity of TRU-containing radioactive waste (a measure of the intensity of radiation in terms of the combined effects on people of all radioactive isotopes in the waste) takes around 100,000 years to fall to a level equivalent to that of naturally occurring uranium ore. If, on the other hand, the TRUs could be burned up to eliminate them from the radioactive waste, this time could be reduced to a few hundred years[(1)].

Work is progressing on the research and development of nuclear reactors capable not only of eliminating TRUs from waste, but also of reducing the consumption of uranium by burning TRUs as fuel. Sodium-cooled fast reactors, which use sodium (Na) to cool the fuel, are one example.

Hitachi, meanwhile, is working on the development of its resource-renewable boiling water reactor (RBWR) based on a boiling water reactor (BWR) design that is already in use in commercial reactors.

This article describes the concept behind the RBWR along with the progress of its development, as well as its specifications and features.

RBWR CONCEPT

Plutonium Breeding Reactor

The original concept on which the RBWR is based was the plutonium generation boiling water reactor (PGBR) proposed by Takeda and others from Hitachi in 1988[(2)]. The PGBR produces fissile plutonium (Puf), a TRU fuel for nuclear power generation containing plutonium-239 (^{239}Pu) and plutonium-241 (^{241}Pu), from uranium-238 (^{238}U), the non-fissile isotope that makes up more than 99% of natural uranium (U). Puf breeding means that more Puf is created during the burning of the fuel than is provided in the initial fuel as a startup neutron source. As it was generally assumed at the time that this could only be achieved using sodium-cooled fast reactors, the PGBR's ability to breed plutonium in a light water reactor made it a ground-breaking proposal.

To achieve the breeding of plutonium, it is necessary to promote the absorption of neutrons by ^{238}U to transmute it into ^{239}Pu. For it to be used in a power reactor, it also needs to be able to sustain a fission chain reaction in the nuclear reactor. That is, a higher number of neutrons than in a conventional BWR is required to maintain the simultaneous transmutation and fission chain reactions. Typically, the higher the energy of the neutrons that trigger fission, the more it encourages neutron absorption by ^{238}U and the higher, in relative terms, the number of neutrons emitted by the fission reaction. Accordingly, breeding plutonium requires that the mean neutron energy in the reactor be raised.

In a BWR, the heat from the fuel rods causes the water (coolant) that flows through the core of a nuclear reactor to boil, thereby removing heat from the fuel rods. Meanwhile, the coolant also acts to moderate the high energy of the neutrons generated by the fission reaction (reduce it down to a low level) through repeated collisions between neutrons and the hydrogen nuclei in the coolant. To minimize this effect, the PGBR reduces the proportional volume of coolant in the reactor core by having narrower coolant channels between fuel rods. Calculations have also demonstrated that the PGBR can achieve a high neutron energy and enable Pu breeding despite being a light water reactor by taking advantage of a characteristic of BWRs whereby the boiling of coolant to form steam reduces the density of hydrogen nuclei.

Intrinsic Safety

Nuclear reactors need to exhibit inherent safety, which means that, when the output of a reactor increases due to some external factor, the nature of its design means it automatically acts to reduce that output. The main mechanisms for inherent safety in a conventional BWR are the effect whereby fission is suppressed by the greater absorption of neutrons as the fuel temperature increases (Doppler effect), and the effect whereby higher temperatures promote more coolant boiling, which raises the proportional volume of steam (void fraction), reduces the moderation of neutrons, and thereby also suppresses fission.

This latter effect is a consequence of the fact that, in a conventional BWR, fission is primarily triggered by low energy neutrons (around 0.1 eV). This is because, at low energies, the fission of fissile ^{235}U and $^{239,241}Pu$ tends to become less likely as the neutron energy increases. An indicator that represents this relationship between void fraction and likelihood of fission is called the void reactivity coefficient. The void reactivity coefficient has a negative value in situations where an increase in void fraction makes fission less likely, as in a conventional BWR.

This relationship reverses at high energies of 100 keV or more, where the higher the neutron energy the more likely fission is to occur. Accordingly, when the proportion of fission reactions triggered by high-energy neutrons becomes large, as in the PGBR which is intended for plutonium breeding, the effect whereby a higher void ratio automatically acts to reduce reactor output becomes attenuated. Although the Doppler

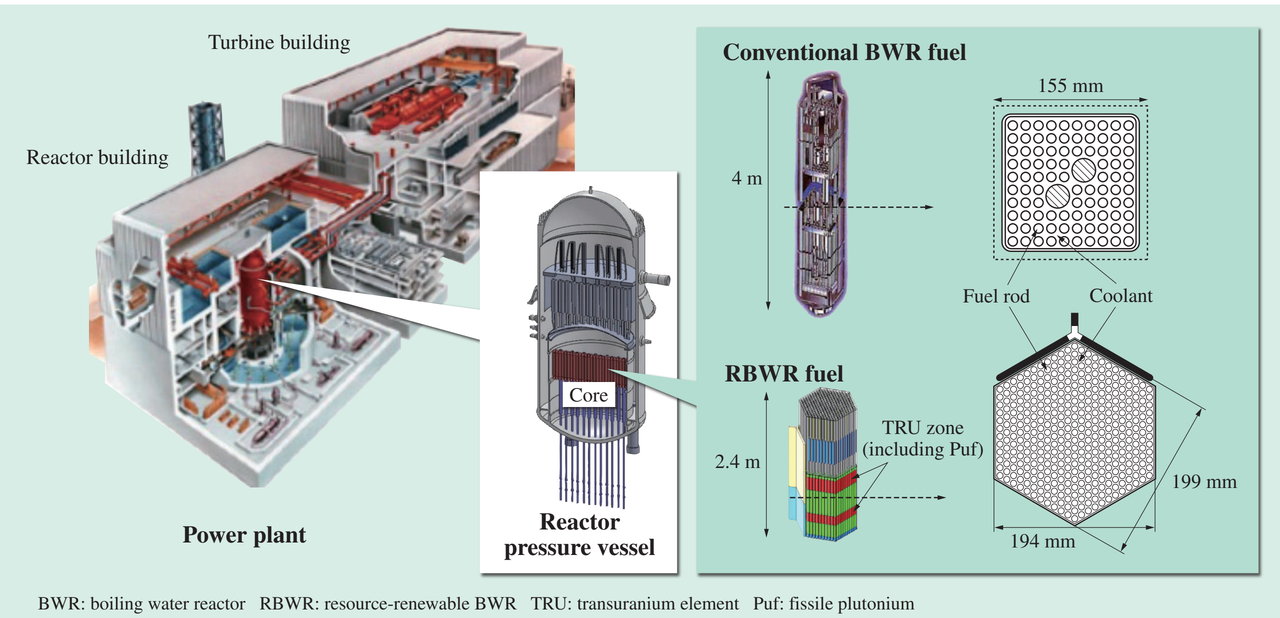


Fig. 1—RBWR Concept.
Apart from the core, the RBWR is largely the same as conventional BWR systems. To achieve effective burning of TRUs, the gaps between fuel rods through which the coolant flows are narrower on the RBWR. Also, the TRUs are contained in two separate zones to ensure inherent safety.

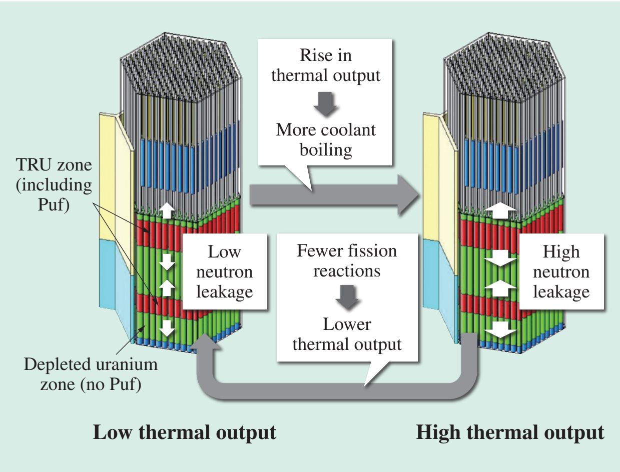


Fig. 2—Inherent Safety of RBWR.
A rise in thermal output leads to more coolant boiling and greater neutron leakage, thereby suppressing fission.

effect still works automatically to reduce output, the PGBR has a positive void reactivity coefficient.

Takeda and his team continued their work, and in 1995 proposed the concept of an RBWR actinide recycler (RBWR-AC) that combined plutonium breeding with a negative void reactivity coefficient(3). The name of the RBWR derives from its ability to recycle not only plutonium but also the other TRUs as fuel. A feature of the RBWR-AC is that Puf is added as a startup neutron source to the fuel in two separate zones (two-zoned core) (see Fig. 1). Because the increase in void fraction as the reactor output rises acts to reduce the probability that neutrons will collide with and bounce off hydrogen nuclei, the probability of the neutrons leaving the fuel increases. The idea behind the two-zoned core was to suppress fission by amplifying this effect whereby an increase in void fraction results in greater neutron leakage (see Fig. 2).

Multi-recycling

Another feature of the RBWR-AC is its multi-recycling capability whereby it can repeatedly recycle the TRUs contained in its own spent fuel (see Fig. 3). The TRUs consumed by the fission reactions that produce the heat needed to generate electric power are created by the operation of the reactor itself through the transmutation of depleted uranium. This means that the operating cycle of the RBWR-AC can be maintained simply by replenishing it with depleted uranium. Being the byproduct left over after the manufacture of the enriched uranium (which contains a high proportion of the fissile ^{235}U isotope) used to fuel conventional commercial light water reactors, depleted uranium is a plentiful resource that can provide the basis of a long-term energy supply.

Multi-recycling requires that the isotopic composition of TRUs in the fuel be kept the same before and after burning them in the reactor. If the proportion of fissile isotopes after use is lower, then the amount of these isotopes will diminish each time the fuel is recycled, ultimately resulting in loss of criticality in the reactor. There is also the risk of compromising reactor design and operation criteria, such as a change in the fuel composition causing the void reactivity coefficient to become positive. In addition to having narrower coolant channels, the RBWR-AC is able to satisfy a variety of criteria as it runs through repeated operation cycles by modifying the coolant flow rate to adjust the neutron energy spectrum during operation and maintain a constant isotopic composition of TRUs in the fuel before and after use.

TRU Burner

One of the advantages of nuclear power generation is that it has a higher energy density than thermal and other forms of power generation, meaning that it requires less fuel to produce the same amount of electric power. On the other hand, when TRUs are used to fuel a nuclear reactor, the percentage of the initial fuel load burned up in each operation cycle is only in the single digits or low teens. Accordingly, the fuel needs to be recycled many times to burn up a large amount of TRUs.

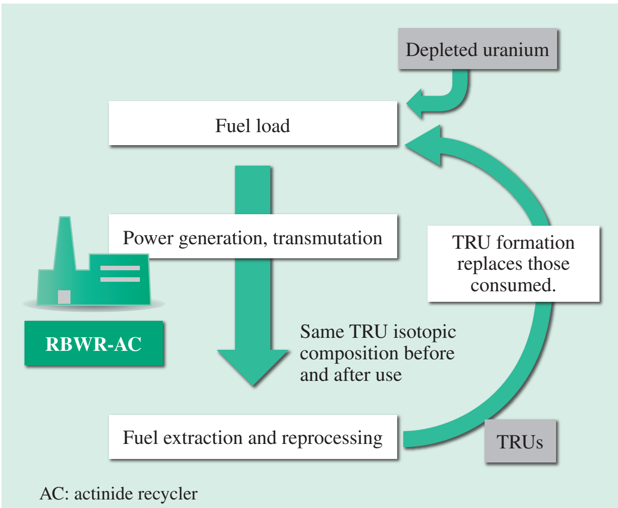


Fig. 3—Fuel Cycle for RBWR-AC.
Each operation cycle of the RBWR-AC forms its own TRUs to replace those consumed during operation while maintaining the same isotopic composition of TRUs before and after use.

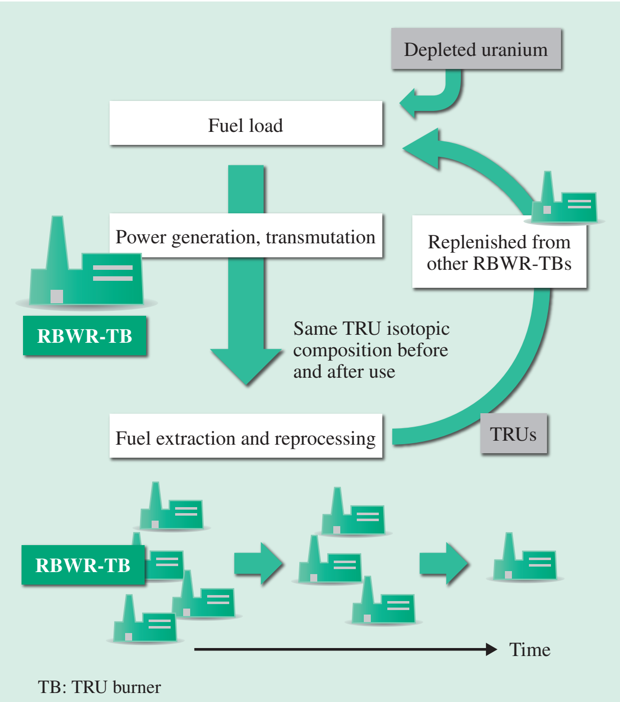


Fig. 4—Fuel Cycle for RBWR-TB.
The TRUs consumed during operation are replenished from the spent fuel of other RBWR-TBs. The fuel is recycled through progressively fewer reactors until all the TRUs are burned up apart from those in the final reactor.

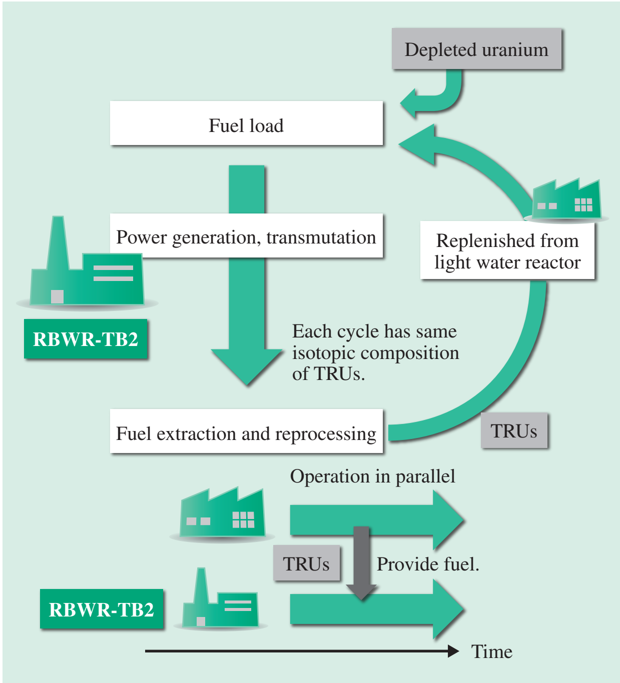


Fig. 5—Fuel Cycle for RBWR-TB2.
The TRUs consumed during operation are replenished from the spent fuel of light water reactors. The RBWR-TB2 operates in parallel with a light water reactor to minimize the buildup of excess TRUs.

Takeda and his team took advantage of the characteristics of the RBWR that allow it to repeatedly recycle fuel while keeping constant its isotopic composition of TRUs and proposed the concept of employing a TRU burner (RBWR-TB), meaning a reactor that could reduce the amount of TRUs by burning them up[(4), (5)]. Although the RBWR-TB shares the RBWR-AC's characteristic of maintaining a constant isotopic composition of TRUs in the fuel before and after use, the process of burning the fuel reduces the absolute quantity of TRUs. The operation cycle is repeated by making up for this loss of TRUs by supplying fuel from another RBWR-TB. That is, the concept behind the RBWR-TB is to run the operation cycle with progressively fewer reactors until all of the TRUs are burned up except for those loaded into the final reactor (see Fig. 4). This presents a scenario under which the fuel is first used for long-term energy production in RBWR-ACs, during which time the TRU fuel is maintained at a constant level. Subsequently, once alternative non-nuclear forms of energy production become available, RBWR-TBs are then used to burn up the TRUs and transition away from nuclear power generation without leaving behind long-lived radioactive waste.

Feasibility Study by US Universities

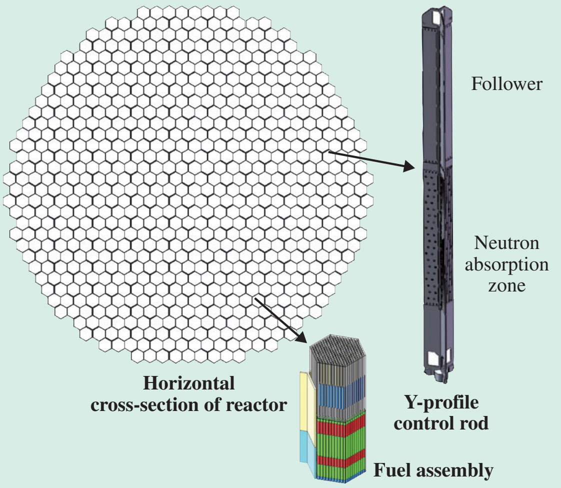
Between 2007 and 2011, three US universities (Massachusetts Institute of Technology, University of Michigan, and University of California, Berkeley) conducted feasibility studies of RBWR reactors under research contracted to the Electric Power Research Institute, Inc. (EPRI)[(6)]. Though some differences between the analysis results obtained by Hitachi and the universities need to be evaluated further, the analyses collectively indicated that the RBWRs appeared to be able to achieve their design objectives.

Part of the contracted study included the proposal of another TRU reactor, the RBWR-TB2, for comparison with sodium-cooled fast reactors. An RBWR-TB2 operates in parallel with a conventional light water reactor and burns the TRUs in its spent fuel (see Fig. 5). An RBWR-TB2 recycles fuel repeatedly, loading a mixture of fuels comprising the TRUs in both its own and the light water reactor's spent fuel. The operation of the RBWR-TB2 serves to minimize the buildup of excess TRUs.

RBWR SPECIFICATIONS

Plant Overview

The rated thermal output, power output, reactor pressure vessel diameter, and core pressure of the



Parameter	RBWR	ABWR
Thermal output (MWt)	3,926	3,926
Power output (MWe)	1,356	1,356
Reactor pressure vessel diameter (m)	7.1	7.1
Core pressure (MPa)	7.2	7.2
No. of fuel assemblies	720	872
Fuel lattice shape	Hexagonal lattice	Square lattice
No. of control rods	223	205
Control rod shape	Y-profile	Cross (+) profile

ABWR: advanced BWR

Fig. 6—Basic Specifications of RBWR Plant.
The rated thermal output, power output, reactor pressure vessel diameter, and core pressure of the RBWR are the same as an ABWR. A follower is fitted to the top of each control rod to prevent water entering the space vacated when the control rod is withdrawn.

RBWR are the same as the advanced BWR (ABWR), the latest commercial BWR (see Fig. 6). The core has 720 fuel assemblies and 223 Y-profile control rods. As the fuel assemblies for the RBWR-AC, -TB, and -TB2 all have roughly the same size, their cores can be swapped between each other by exchanging fuel assemblies. The following section describes the latest specifications for each reactor type(7).

Core Fuel Configuration

Fig. 7 shows the fuel assemblies for the RBWR-AC, -TB, and -TB2 respectively. The fuel assemblies for the RBWR-AC have upper and lower TRU zones (with heights of 280 mm and 193 mm), sandwiched between the upper, central, and lower depleted uranium zones (with heights of 70 mm, 520 mm, and 280 mm). Neutron absorber zones, meanwhile, are located respectively above and below the upper and lower depleted uranium zones. These are provided to enhance the output suppression effect by absorbing neutrons when a rise in output causes the void fraction of the coolant to increase, thereby increasing the leakage of neutrons from the fuel zones (TRU and depleted uranium zones). The heights of the depleted uranium and TRU zones are determined so as to maintain the same isotopic composition of TRUs before and after use.

Because the requirement for TRU breeding is lower on the RBWR-TB and -TB2 TRU burner reactors

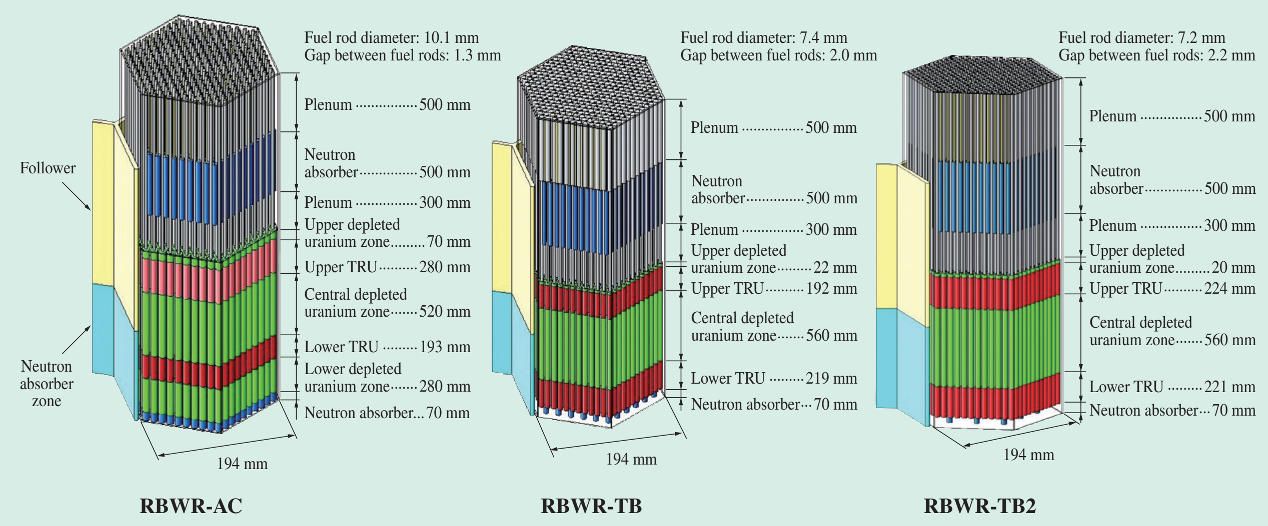


Fig. 7—RBWR Fuel Assembly.
The height of the TRU and depleted uranium zones, the fuel rod diameter, and the gap between fuel rods are adjusted to ensure that the multi-recycling of TRUs can be performed in a way that suits the purpose of each reactor design. As the RBWR-TB and -TB2 TRU burner reactors have less need for TRU formation, their fuel assemblies do not include the lower depleted uranium zone.

than it is on the RBWR-AC, their fuel assemblies do not have the lower depleted uranium zone. As in the RBWR-AC, they have neutron absorber zones above and below the fuel zones. The heights of the TRU and depleted uranium zones for the RBWR-TB are also determined so as to maintain the same isotopic composition of TRUs before and after use, as in the RBWR-AC. In the case of the RBWR-TB2, when the isotopic composition of TRUs in the fuel supplied from light water reactors is the same for each operation cycle, the heights of the TRU and depleted uranium zones are determined such that the isotopic composition that results after combining the RBWR-TB2's own spent fuel will be the same for each operation cycle.

Along with adjusting the heights of the TRU and depleted uranium zones in the RBWR-AC, -TB, and -TB2, the balance between consumption and creation of TRUs is also adjusted by modifying the fuel rod diameter and gaps between fuel rods to adjust the neutron energy spectrum (see Fig. 8). In the case of the RBWR-AC, where not only the isotopic composition of TRUs but also their quantity needs to be kept constant before and after use, it is necessary to increase the mean neutron energy by having the lowest proportion of coolant of the three designs so that the ratio of fissile TRU isotopes before and after use (breeding ratio) will be above 1.0. After the RBWR-AC, it is the RBWR-TB that has the next lowest proportion of coolant. This is because the breeding ratio of fissile TRU isotopes needs to be increased somewhat to keep the relative reduction in fissile TRU isotopes and non-fissile TRU isotopes the same in the RBWR-TB, where the isotopic composition needs to be kept constant even as the quantity decreases as the fuel is burned. The fuel configuration of the RBWR-TB2, on the other hand, has a higher proportion of coolant than the RBWR-TB because it is supplied with TRUs in spent fuel from light water reactors with a high proportion of fissile isotopes.

RBWR CORE CHARACTERISTICS

Burning uranium in a conventional BWR forms both fissile and non-fissile TRU isotopes (see Fig. 9). When using mixed oxide (MOX) fuel that contains plutonium and uranium, the fuel ends up with more of the non-fissile isotopes of plutonium and other TRUs than it had when loaded because, whereas the fissile isotopes of plutonium are consumed, the non-fissile isotopes are not. Calculations have demonstrated that the RBWR-TB and -TB2 TRU burner reactors are able to consume both fissile and non-fissile TRU isotopes at more than twice the rate they are produced by a conventional BWR.

Fig. 10 shows the dependence of the neutron capture rate and fission reaction rate on neutron energy in the nuclear reactor of an RBWR-TB, where the neutron capture rate is the proportion of

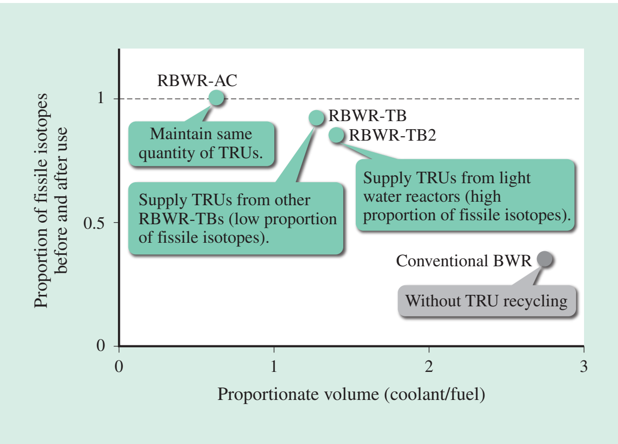


Fig. 8—Proportionate Volume of Coolant in RBWR and Conventional BWR Reactors.
Since the RBWR-AC and -TB need to continue the operation cycle without consuming fissile materials other than those contained in the fuel discharged from themselves, their water-to-fuel volume ratios are set lower than those of the RBWR-TB2 and conventional BWR.

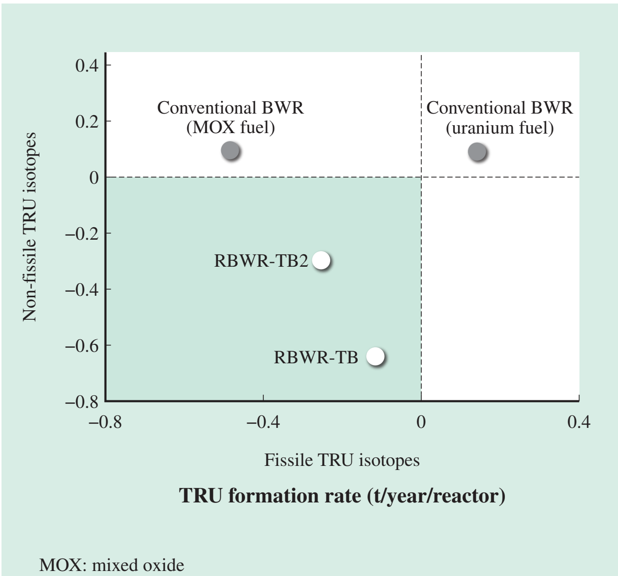


Fig. 9—Rate of Formation and Consumption of TRUs.
A negative value indicates that consumption of TRUs results in a reduction in their quantity. The value for conventional BWRs is from Ando and Takano[8].

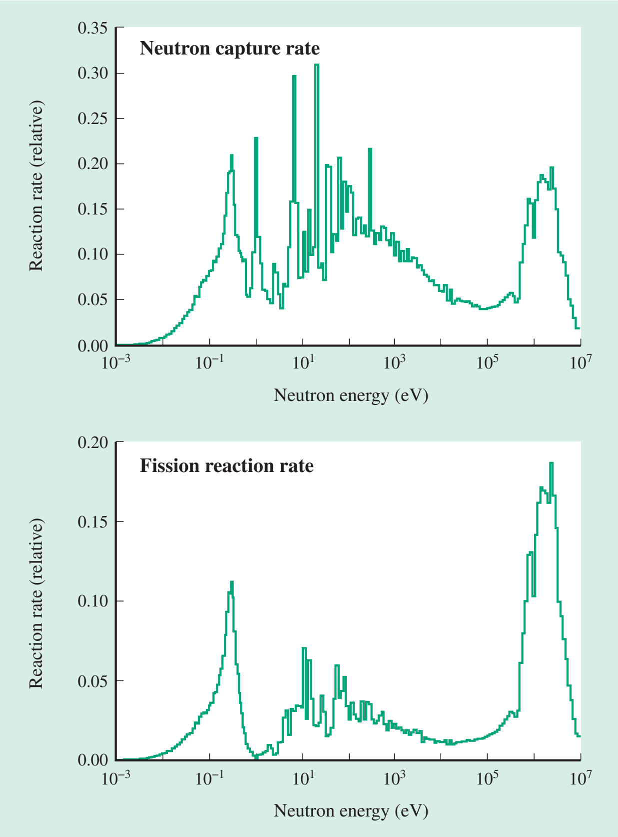


Fig. 10—Dependence on Neutron Energy of Neutron Capture and Fission Reactions in RBWR-TB Core.
Non-fissile TRUs are transmuted into fissile TRUs by the capture of a neutron.

cases in which a transmutation reaction occurs due to capture of a neutron and the fission reaction rate is the proportion of cases in which fission occurs(7). Neutron capture occurs for a wide range of energies, from low energies of around 10^{-1} eV up to high energies on the order of 10^6 eV. Non-fissile isotopes such as ^{240}Pu and americium-241 (^{241}Am) are transmuted by neutron capture into fissile ^{241}Pu and ^{242}Am respectively. Also, the direct fission of isotopes like ^{240}Pu and ^{241}Am occurs at high neutron energies in the vicinity of 10^6 eV. By using this wide distribution of neutron energies to achieve the fission of non-fissile TRUs, both by first transmuting them into fissile TRUs and also through direct fission by high-energy neutrons, the RBWR can burn up non-fissile TRUs in the same proportion as fissile TRUs and maintain the same isotopic composition of TRUs before and after use.

Table 1 lists the isotopic composition of TRUs before and after use and the core characteristics of the RBWR-AC, -TB, and -TB2. When the RBWR-AC and -TB are operated to keep the same isotopic composition of TRUs in the fuel before and after use, the quantity of TRUs increases in the case of the RBWR-AC and decreases in the case of RBWR-TB. When an RBWR-TB2 is loaded with fuel in which the TRUs in its own spent fuel and the spent fuel from a light water reactor are in the same proportion, and

TABLE 1. Change in Isotopic Composition of TRUs during Burning in Reactor
This considers the case when spent fuel is left for three years after removal from the reactor to allow radiation and heat generation to diminish.

Isotope	RBWR-AC		RBWR-TB		RBWR-TB2		
	When fuel loaded	Three years after removal	When fuel loaded	Three years after removal	When fuel loaded	Three years after removal	TRUs discharged from light water reactor
Np237	0.4	0.4	0.1	0.1	1.9	1.4	6.7
Pu238	2.9	2.9	4.7	4.7	6.3	6.7	2.8
Pu239	43.5	43.5	9.5	9.5	27.7	25.5	48.8
Pu240	36.3	36.3	39.5	39.6	38.5	40.1	23
Pu241	5.1	5.1	4.4	4.4	5.5	5.4	7
Pu242	5.1	5.1	25.4	25.4	9.6	10.1	5
Am241	3.6	3.6	4.7	4.7	5.4	5.4	4.7
Am242m	0.2	0.2	0.2	0.2	0.2	0.2	0
Am243	1.3	1.3	4.7	4.7	2.4	2.4	1.5
Cm244	1.1	1.1	4.1	4	1.8	2	0.5
Cm245	0.4	0.4	1.2	1.2	0.5	0.6	0
Cm246	0.1	0.1	1	1	0.2	0.2	0
Cm247	0	0	0.2	0.2	0	0	0
Cm248	0	0	0.2	0.2	0	0	0
Cm249	0	0	0.1	0.1	0	0	0
Puf (t)	1.94	1.96	1.14	1.06	2.06	1.74	0.32
TRU (t)	3.99	4.03	8.18	7.62	6.2	5.63	0.58

Np: neptunium Pu: plutonium Am: americium Cm: curium under conditions in which the isotopic composition of TRUs remains the same in each cycle, the quantity of TRUs decreases as the fuel is burned.

Calculations have also demonstrated that all of the reactor types have a negative void reactivity coefficient(7).

CONCLUSIONS

This article has provided an overview and described the latest specifications of the RBWR, a reactor that can recycle as fuel the TRUs formed in nuclear power generation to provide a long-term supply of energy while also preventing the TRUs from becoming radioactive waste that will continue to emit radiation for a long time.

Hitachi intends to continue development work aimed at commercializing the RBWR, seeing it as a valuable option, based on proven BWR technology, for meeting expectations for the long-term supply of energy from nuclear power while also solving the industry's problem of how to deal with TRUs.

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