RADREMOTE 2018
Proceedings of
The 5th Fukushima Research Conference (FRC) 2018
-Radiation Hardness, Smartness and Measurement in Remote Technology for the Decommissioning of the Fukushima Daiichi Nuclear Power Station-

(Eds.) Masaaki KABURAGI, Tatsuo TORII and Toru OGAWA

Remote System and Sensing Technology Division
Collaborative Laboratories for Advanced Decommissioning Science
Fukushima Research Institute
Sector of Fukushima Research and Development
There is high expectation for advanced remote technology and robotics to reduce the radiation exposure for workers in harsh nuclear environments such as the decommissioning of the Fukushima Daiichi Nuclear Power Station (FDNPS). However, the radiation tolerance of state-of-the-art key components, sensors and electronic devices, for remote operation is still limited. In order to extend the application of robotics in nuclear energy, it is pertinent to develop “Radiation hardness” of components and “Radiation smartness” in operation procedures. Furthermore, developments of “Radiation measurement” and “Technology to recognize the location and to grasp the surrounding environment”, including the radiation imaging of the high dose-rate fields inside the FDNPS and the detection of nuclear fuel debris, are necessary for the future nuclear fuel debris retrieval.

The 5th Fukushima Research Conference aims to share the future vision for advancing the remote technology among experts from diverse fields.

Keywords: Fukushima Research Conference, Remote Technology, Radiation Hardness, Radiation Measurement
福島第一原発の廃炉を始めとした過酷な放射線環境下で、現場作業者の被ばく線量を低減するため、遠隔技術やロボティクスの高度化に大きな期待が集まっている。しかし、ロボットの遠隔制御のための最先端の要素技術やセンサー、電子機器の耐放射線性にも厳しい限界がある。原子力へのロボット技術の応用拡大に向けて、機器の耐放射線性の向上（Radiation hardness）や運用における放射線環境への適応力（Radiation smartness）が求められる。さらに、将来の核燃料デブリの探査と取り出しに向けては、福島第一原発域内の高線量率現場での放射線イメージングや核燃料デブリの検出といった、放射線計測（Radiation measurement）および位置認識・周辺環境の把握のための技術の開発が必要である。

今回の福島リサーチカンファレンスでは、遠隔技術のさらなる進展のため、さまざまな分野の専門化を交えて将来のビジョンを共有することを目指している。
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Organizers

Planning Committee
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Tamio ARAI, International Research Institute for Nuclear Decommissioning
Katsuhiko NARUSE, ATOX Co., Ltd.
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Takayuki TAKAHASHI, Fukushima University
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Hiroyuki TAKAHASHI, The University of Tokyo
Keitaro HITOMI, Tohoku University

Secretariats
E-mail: frc-radremote@jaea.go.jp

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Extreme Energy-Density Research Institute, Nagaoka University of Technology
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Shinji KIHARA, CLADS, JAEA
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人見啓太朗（東北大学）

事務局

E-mail: frc-radremote@jaea.go.jp

小川 徹（日本原子力研究開発機構 廃炉国際共同研究センター、
長岡技術科学大学 極限エネルギー密度工学研究センター）
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古田 禄大（日本原子力研究開発機構 廃炉国際共同研究センター）
1. Program

Monday, 26th November, 11:00–17:00 〈Open Seminar〉
11月26日（月）11:00–17:00 〈一般公開セミナー〉

Venue: Tomioka Town Art & Media Center Manabi-no-Mori
会場：富岡町文化交流センター「学びの森」

11:00–11:40 Opening オープニング
Chair: Takaumi KIMURA (CLADS, JAEA)
司会：木村 貴海（原子力機構廃炉国際共同研究センター）

11:05–11:25
Daniel IRACANE (OECD/NEA)
ダニエル イラカン（経済協力開発機構／原子力機関）

11:25–11:40
Koji OKAMOTO (CLADS, JAEA)
岡本 孝司（原子力機構廃炉国際共同研究センター）

11:40–13:00 Lunch and Exhibitions 昼食・展示

13:00–14:50
Keynote Lecture: Development of Robotic Technology in the Radiation Fields of Fukushima Daiichi Nuclear Power Station
基調講演：福島第一原子力発電所の放射線環境とロボット技術の展開
Chair: Takayuki TAKAHASHI (Fukushima University)
座長：高橋 隆行（福島大学）

13:00–13:40
Hajime ASAMA (The University of Tokyo)
Status and technical issues of remote technologies for Fukushima Daiichi decommissioning – Robotics in radiation environment –
浅間 一（東京大学大学院 工学系研究科）
福島第一原子力発電所の廃炉のための遠隔技術の現状と課題
〜放射線環境下におけるロボット技術〜
13:40–14:20

**William R. HAMEL** (The University of Tennessee)
Past perspectives and future directions of robotics and remote systems in nuclear environments

ウィリアム・ハメル（テネシー大学）
原子力環境におけるロボット・遠隔システムの経験と展望

14:20–14:50

**Hideo HIRAYAMA**
(KEK, High Energy Accelerator Research Organization)

Dose Concepts and Fukushima Daiichi Radiation Field Characteristics

平山英夫（高エネルギー加速器研究機構）
線量概念と福島第一原子力発電所の放射線場

14:50–15:30  **Exhibitions, Demos, and Videos 展示・デモ・映像**

15:30–17:00

**Topics: Challenge to Operations in High-Radiation Fields**

トピックス：高放射線場での運用に向けて

Chair: Hiroshige KIKURA (Tokyo Institute of Technology)

座長：木倉宏成（東京工業大学）

15:30–16:10

**Simon DELAVALLE** (Oxford Technologies)

Design and experiences on remote operation in high radiation field

サイモン・デラバール（オックスフォード・テクノロジーズ）

高放射線場における遠隔技術の設計と運用経験

16:10–16:40

**Shin-Ichiro KUROKI** (Hiroshima University)

Approach to realizing radiation-hardened devices

黒木伸一郎（広島大学）

耐放射線性デバイスの実用化へのアプローチ

16:40–17:00

**Yuki SATO** (CLADS, JAEA)

Development and demonstration of small compact radiation imaging system

佐藤優樹（原子力機構廃炉国際共同研究センター）

小型軽量放射線イメージング技術の開発と実証
Tuesday, 27th November, 9:00–17:00 (Pre-registration Required)
Closed Oral and Poster Sessions, and Panel Discussion

11月27日（火）9:00–17:00

Venue 1: Tomioka Town Art & Media Center Manabi-no-Mori
Venue 2: JAEA CLADS Main Building

会場1：富岡町文化交流センター「学びの森」
会場2：原子力機構廃炉国際共同研究センター 国際共同研究棟

9:00–11:00  Oral Session 1: Experiments in Intense Radiation Field (Venue 1)
Chair: Tadahiro WASHIYA (CLADS, JAEA)

9:00–9:40
Carlo DAMIANI (Fusion for Energy)
Development of rad-hard technologies for ITER Remote Maintenance

9:40–10:20
Kenro TAKAMORI
(International Research Institute for Nuclear Decommissioning)
Experiences and lessons in PCV internal remote inspection in Fukushima Daiichi NPS

10:20–11:00
Kai VETTER (LBNL, The University of California)
3-D gamma-ray imaging and visualization: Enhancing radiation safety and smartness

11:00–13:40  Lunch, Exhibitions, and Poster Session (Venue 1)

13:40–16:40  Parallel Sessions (Detailed Schedules on the Following Pages)
Parallel Session 2.1: Radiation Hardness (Venue 1)
Parallel Session 2.2: Radiation Measurement (Venue 2)
Parallel Session 2.1: Radiation Hardness (Venue 1)
Chair: Masafumi KUMANO (Tohoku University)

13:40–14:20
Paul LEROUX (KU Leuven)
Chips for extreme radiation environments in standard CMOS

14:20–14:40
Junichi H. KANEKO (Hokkaido University)
Development of a diamond radiation detector and a charge sensitive preamplifier based on diamond MESFET

14:40–15:00
Takeshi OHSHIMA
(National Institute for Quantum and Radiological Science and Technology)
Radiation response of SiC-based semiconductor devices

14:20–15:20
Recent topics on radiation-hardened devices

14:20–14:40
Junichi H. KANEKO (Hokkaido University)
Development of a diamond radiation detector and a charge sensitive preamplifier based on diamond MESFET

14:40–15:00
Takeshi OHSHIMA
(National Institute for Quantum and Radiological Science and Technology)
Radiation response of SiC-based semiconductor devices

15:00–15:20
Minoru WATANABE (Shizuoka University)
Radiation-hardened optically reconfigurable gate array

15:20–16:40
Wrap-up Panel Discussion
Facilitator: Toru OGAWA (CLADS, JAEA)

Advanced sensing and robotics for harsh radiation field
Short presentations by Tamio ARAI, Barry LENNOX, and Yasuyoshi YOKOKOHJI, followed by discussions with the floor

Panelists:
Tamio ARAI
(International Research Institute for Nuclear Decommissioning)
Barry LENNOX (The University of Manchester)
Yasuyoshi YOKOKOHJI (Kobe University)
Paul LEROUX (KU Leuven)
Shin-Ichiro KUROKI (Hiroshima University)

16:40–16:50
Break
Parallel Session 2.2: Radiation Measurement (Venue 2)
Chair: Hiroyuki TAKAHASHI (The University of Tokyo)
13:40–14:10 Laboratory Tour on Radiation Measurement Equipments

14:10–14:40
Keisuke OKUMURA (CLADS, JAEA)
Prediction on radiation fields in PCV of Fukushima Daiichi NPS

14:40–15:10
Simon WATSON (The University of Manchester)
Radiation monitoring of a nuclear reactor using a robotic platform

15:10–15:40
Yuki MORISHITA (CLADS, JAEA; University of Michigan)
Detection of alpha particle emitters originating from a nuclear fuel of Fukushima Daiichi Nuclear Power Station

15:40–16:10
David BOARDMAN
(Australia’s Nuclear Science and Technology Organization)
Gamma-ray imaging based on compressed sensing

16:10–16:40
Keitaro HITOMI (Tohoku University)
Development of directional gamma-ray detectors using thallium bromide

16:40–16:50 Move to Venue 1

16:50–17:00 Poster Awards and Closing (Venue 1)
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2. Opening Session
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2.1 The NEA Nuclear Education, Skills and Technology (NEST) Framework

Dr. Daniel Iracane

*NEA Deputy Director General and Chief Nuclear Officer*

**Abstract**

NEA member countries are, collectively, world leaders in the use of nuclear technology and materials for a wide range of industrial, scientific, medical and energy purposes. To ensure the safe, secure and sustainable use of nuclear energy, it is critical that these countries have the scientists, engineers and technologists needed to meet environmental challenges of managing high-level radioactive waste and spent nuclear fuel, as well as finding better ways for decommissioning.

The NEA has recently created the Committee on Decommissioning of Nuclear Installations and Legacy Management that will allow the NEA member countries to continue cooperating on important activities related to decommissioning including the use of robotics.

The NEA is also addressing the concerns of member countries about the potential loss of nuclear expertise and knowledge. It is therefore imperative to create new approaches to retain, nurture and expand this knowledge base, and to build the new expertise needed for innovative nuclear technologies.

The NEST Framework is the NEA’s response to this need. The goal is to enable students, post-docs and young professionals to develop expertise and skills by exposing them to challenging projects and real-world problems, by transferring the knowledge accumulated by the current generation through hands-on training and by encouraging them to pursue careers in the nuclear field.

The NEST Framework is a joint undertaking currently bringing together 15 public and private organisations, such as academia, research centres and industries, from 10 countries: Belgium, Canada, France, Germany, Italy, Japan, Korea, Russia, Switzerland and USA, who wish to cooperate through international exchanges and activities to strengthen nuclear-related education programmes and build technical and non-technical skills in the field of nuclear science, the safe use of nuclear technology and its applications.

The NEST CLADS project on Advanced Remote Technologies, led by JAEA/CLADS, will start with a series of theoretical seminars and practical exercise on the topic of “Radiation Hardness and Smartness in Remote Technology for Nuclear Decommissioning”.

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The Committee on Decommissioning of Nuclear Installations and Legacy Management (created in April 18) will address:

- The decommissioning and dismantling of all nuclear facilities (e.g., fuel cycle and waste facilities) and all reactor types; and
- The development of practical guidance on regulating and managing legacy waste, waste sites, and releases of legacy sites.

The NEA: 33 Countries Seeking Excellence in Nuclear Safety, Technology and Policy

Fostering international co-operation to assist its member countries in maintaining and further developing, the scientific, technological and legal bases — Forging common understandings on key issues, as input to government decisions.

Decommissioning, a growing topic of interest

Total Number of Reactors: 103

Number of reactors in decommissioning normalised to year 2000

Number of reactors in permanent shutdown, Oct 2018 (JAEA, PRIS)
Robotics in the nuclear: to carry out nuclear activities safely & efficiently

- A wide range of applications:
  - Inspection, reactor refurbishment, routine NPP operations, handling in radioactive packages, decommissioning, post-accident management...
- NEA 2014:
  - “The current labour-intensive decommissioning & dismantling of nuclear facilities can benefit from the use of robotics, remote systems and innovative manipulating technologies.”

Building up talented individuals is a long term investment, for every country, requiring strategic vision and involvement

NEA Workshop, Marcoule, France, January 30-31, 2019

THE APPLICATION OF REMOTE AND ROBOTIC SYSTEMS IN NUCLEAR BACK-END ACTIVITIES

- To open an international dialogue to evaluate the applications of remote and robotic systems in waste management and decommissioning projects
- To discuss international cooperation for wider application of robotic in the nuclear back-end

NEA countries shared vision

- Importance of nurturing the next generations of experts and professionals
  - regardless of the current domestic nuclear policies

- Need for international collaboration in the area of Nuclear Education, Skills and Technology
  - to guarantee the worldwide sustainability and availability of necessary skills in the nuclear area
  - to transfer, share and create knowledge for the next generation and address both Explicit and Tacit knowledge
Transferring Knowledge to next generations:
the Explicit Knowledge

- The Explicit Knowledge is easy to codify and preserved
- The Explicit Knowledge is transferred through education, training, books, procedures, conferences...
- The NEA contributes to it via the work of its committees, expert groups, workshops and professional schools

Explicit Knowledge is currently managed by relevant national and international organisations. No critical issues are identified.

Transferring Knowledge to next generations:
the Tacit Knowledge

- The Tacit Knowledge is based on personal experiences, hands-on training, and challenging projects
- The Tacit Knowledge is difficult to codify and to transfer, easily lost, difficult to harvest and to manage
  - To develop innovative expertise the workforce needs to be exposed to challenging projects and real-world problems.

Nuclear energy needs experienced and highly-trained scientists and technologists to support and develop current and future technologies and to manage nuclear legacies.

The NEA Nuclear Education, Skills and Technology Framework (NEST)

is the NEA’s response to this challenge

SKILLS are necessary to address challenging projects

AND

Challenging projects are necessary to develop SKILLS

NEST purposes and criteria

- Attracting young fellows by addressing Demanding and Innovative activities
- Working on Real-world problems alongside experienced practitioners
- Establishing links between Universities, Research Institutes, Industry and Regulatory bodies
- Offering Hands-on activities in Multi-disciplinary and Multi-national contexts
- Complemented by training sessions to get a broad nuclear culture
NEA
10 NEST Countries
15 Parties

NEST projects being developed
• NEST CLADS “Collaborative Laboratories for Advanced Decommissioning Science”, led by Japan
  – This present workshop is part of the theoretical seminars of the NEST CLADS project on Advanced Remote Technologies.
• NEST HYMERES “Hydrogen Mitigation Experiments for Reactor Safety”, led by Switzerland
• NEST Waste management, led by Russia
• NEST Small Modular Reactors, led by Canada
• NEST Molten Salt Reactors, led by the United States

The NEST-HYMERES example

The NEA NEST offers
To address real issues for the society,
on innovative activities,
By working with students from abroad,
Opening better career opportunities
2.2 CLADS Activities on Fukushima Decommissioning Research

Koji Okamoto

Director General,
Collaborative Laboratories for Advanced Decommissioning Science (CLADS)
Japan Atomic Energy Agency (JAEA)
okamoto.koji@jaea.go.jp, okamoto@n.t.u-tokyo.ac.jp

The decommissioning of the Fukushima-Daiichi Nuclear Power Plant has required and will continue to demand conducting many challenging activities, many of which do not have prior experience in the nuclear industry. International decommissioning knowledge and technology advances will be required to support the challenging work. A program of this scale is most effective when performed collaboratively, and has been established by the Japan Atomic Energy Agency (JAEA).

The Collaborative Laboratories for Advanced Decommissioning Science (CLADS) was established by the JAEA in April 2015. The main objectives of CLADS are the management, research and development for decommissioning at the Fukushima-Daiichi site. Not only is the coordination of research and development important to effective decommissioning, but also the management of research activities around the world, and is included in the CLADS program tasks. Major technical areas included in CLADS are: (1) waste processing and disposal, (2) handling and analysis of fuel debris, (3) accident progression and behavior evaluation, and (4) remote control technologies.

The CLADS will cover the basic researches and advanced Research Infrastructures for Fukushima Decommissioning as shown in Figure 1. The activities will continue to more than 30-40 years, therefore the basic research activities are very important to promote the future technologies and future human resources.

The Fukushima Research Conference (FRC) is one of the collaborative work organized by CLADS. Fukushima Decommissioning contains huge research area and fields. The oversight of the Fukushima Research is one of the objectives of CLADS. Also, the detailed research topic should be discussed with world-wide specialists. The FRC intended to focus on the special topics on the Fukushima Decommissioning. We will have several conferences a year to keep the knowledge to Fukushima to be state-of-the-arts.

It is my pleasure to open the FRC on “Radiation Hardness, Smartness and Measurement in Remote Technology for the Decommissioning of the Fukushima Dai-ichi Nuclear Power Station.” The conference focused on the collaboration of two major fields, i.e., radiation technology and remote technology. Both two fields relate to each other, with complicated functions. The fruitful discussions will result in the many useful Research and Development topics for safety Decommissioning.
In April 2015, CLADS was established to accelerate R&D for the decommissioning of the Fukushima Daiichi NPS and human resource development (HRD) by bringing global and domestic knowledge and experience.

CLADS promotes R&D and HRD in a comprehensive manner while establishing a network that facilitates communication among universities, research institutes and industry across multiple fields in Japan and abroad.

Facility available to universities or research institutes in which CLADS conducts R&D and HRD near the Fukushima Daiichi NPS. Experts from Japan and abroad will gather there, bringing together their knowledge and experience.

In April 2017, the CLADS’s Main Building was opened in the Tomioka town, Fukushima to accelerate R&D for the decommissioning of the NPS, and to contribute to the restoration and reconstruction of Fukushima.

Utilizing JAEA’s special facilities for handling nuclear fuels and radioactive materials, and irradiation facilities at Tokai and Oarai in Ibaraki Prefecture.

CLADS as international R&D base

In April 2017, the CLADS’s Main Building was opened in the Tomioka town, Fukushima to accelerate R&D for the decommissioning of the NPS, and to contribute to the restoration and reconstruction of Fukushima.
“Enhancement of Human Resource Development”

- Development of core researchers for Mid-and-Long term
  - Developing human resources program
  - Integrating of analysis technologies from various fields
  - Operating cooperative courses with universities and other institutes

“Research Activities of CLADS”

- Fuel Debris Characterization & Analysis
  1. Fuel Debris Characterization & Analysis Technology
     - Estimate the characteristics of fuel debris in the reactor using simulated fuel debris, and establish methods for handling and analysis of actual debris towards decommissioning work for the removal and storage of fuel debris.
  2. Dose Evaluation & Nuclear Material Accountancy
     - Study on dose evaluation method and nuclear material accountancy for fuel debris with non-destructive assay (NDA) technique.

“Potential Risk Reduction for Decommissioning”

1. Aging Mechanism Analysis on Fuel Debris and Radioactive Micro-particles Behavior
   - Fundamental research on aging mechanism of fuel debris, and analysis of radioactive micro-particles behavior during the retrieval of fuel debris.
2. Analysis of Corrosion Mechanism in Specific Environment
   - Risk of corrosion degradation for plant materials in 1F site have been increasing with time duration and/or environmental changes by decommissioning procedure. Preventing methods for these corrosion risks are developed based on corrosion mechanism.
3. Hydrogen Safety Engineering
   - Development of technology to ensure long-term safe storage of radioactive waste by analyzing hydrogen behavior in a waste storage vessel and by applying mitigation methods to suppress an increase in hydrogen concentration.

“Research Division for Potential Risk Reduction in Decommissioning”

- R&D on Analysis on Fuel Debris Behavior
- Analysis of Corrosion Mechanism in Specific Environment
- R&D on Hydrogen Safety Engineering

“Aging mechanism of fuel debris”

“Fuel Debris Characterization & Analysis”

- Conceptual design of NDA system
- Calculation of 3D-dose rate distribution
- Analysis on Radioactive Particles (ex. Vickers Hardness)
- Dose evaluation method and nuclear material accountancy for fuel debris with non-destructive assay (NDA) technique.
Core Status Evaluation in the 1F Accident

1. Fission Product (FP) chemistry, release/transportation/sorption

Estimation of Cs chemisorption behavior in order to reflect it in the evaluation of Cs distribution and characteristics inside 1F.

Cs distribution is important especially when viewing as radioactive source. The research will also focus on the boron effect on Cs-chemisorption behavior.

2. Core melt/relocation behavior, core support damage/MCCI

Estimation of important element processes on core material relocation behavior (melting and relocation of fuel assemblies/damage of core support plate/damage of lower plenum/MCCI, etc.) reflect on the evaluation of debris distribution and residual core structure situation.

Integrated Radiation Imaging System (IRIS)

3 key components

- Radiation measurement
- Remote control
- Visualization technology

Visualization technology Visualize distribution of radioactive substances and environmental information

Experimental condition

Measurement Time: 39.5 s

Hotspots are clearly visualized inside the FDNPS
The CLADS has been carrying out above research and development encountered 1F decommissioning with concentrating wisdom and expertise from national and international cooperation.

International Cooperation in CLADS

Major international collaboration in CLADS is as follows:

- Radioactive waste management in the decommissioning,
- Characterization of fuel debris and MCCI product, damaged fuel handling and treatment and storage, etc.

Multinational cooperation as IAEA and OECD/NEA are conducting.

- PreADES, TCOFF, etc.
- NEST (Nuclear Education, Skills and Technology)

International Cooperation for 1F Decommissioning

JAEA is conducting R&D to support Fukushima Daiichi NPS (1F) decommissioning with aiming to develop safer and efficiently decommissioning.

Oversight on Fukushima Decommissioning R&D activities are very important.

International collaboration researches between OECD/NEA and CLADS are strongly needed. CLADS has launched several collaborative activities with international communities as bilateral and/or multinational (OECD/PreADES, TCOFF, IAEA/CRPs).

CLADS is aiming to act as a center of excellence for basic and fundamental research for decommissioning.

CLADS contributes on radiation measurement using remote technology, especially on-site environmental identification and Reactor Building, etc.
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3. Keynote Lecture
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3.1 Status and Technical Issues of Remote Technologies for Fukushima Dai-ichi Decommissioning
– Robotics in radiation environment –

Hajime Asama
The University of Tokyo, Japan

Abstract
The Great Eastern Japan Earthquake and Tsunami occurred in 2011, and the accident of Fukushima Daiichi Nuclear Power Plant occurred. Utilization of remote-controlled machine technology including robot technology was essential for accident response and decommissioning of Fukushima Daiichi Nuclear Power Station to accomplish various tasks in the high-radiation environment. In this presentation, the robot technologies which have been developed and utilized for the disaster response and the decommissioning are introduced, and technologies and its societal dissemination, which are demanded for disaster prevention and disaster response including decommissioning of Fukushima Daiichi NPS in the future, are discussed.

Biography
Hajime Asama received his B. S., M. S., and Dr. Eng in Engineering from the University of Tokyo, in 1982, 1984 and 1989, respectively. He worked at RIKEN (Institute of Physical and Chemical Research) in Japan from 1986 to 2002 as a research scientist, etc. He became a professor of RACE (Research into Artifacts, Center for Engineering) of the University of Tokyo in 2002, and a professor of School of Engineering of the University of Tokyo since 2009. He received SICE (The Society of Instrument and Control Engineers) System Integration Division System Integration Award for Academic Achievement in 2010, RSJ (Robotics Society of Japan) Distinguished Service Award in 2013, JSME Award (Technical Achievement) in 2018, etc. He was the vice-president of RSJ in 2011-2012, an AdCom member of IEEE Robotics and Automation Society in 2007-2009. Currently, he is the president-elect of IFAC since 2017, the president of International Society for Intelligent Autonomous Systems since 2014, and an associate editor of Control Engineering Practice, Journal of Robotics and Autonomous Systems, and Journal of Field Robotics, etc. He is a member of Science Council of Japan from 2014 to 2017, and a council member since 2017. He is a Fellow of IEEE, JSME and RSJ.

Hajime ASAMA
Dept. of Precision Engineering, The University of Tokyo, Japan
Agency for Natural Resources and Energy (ANRE) and TEPCO:
Council for the Decommissioning of TEEPCO’s Fukushima Daiichi NPS, member
Nuclear Damage Compensation & Decommissioning Facilitation Corp. (NDF):
Fuel Debris Retrieval Expert Committee, member
Decommissioning R&D Partnership Council, member
International Research Institute for Nuclear Decommissioning (IRID), TC member
Japan Atomic Energy Agency (JAEA): Working Committee on Remote Control Equipment and Device Development Facility (Mock-up facility), Chair
Fukushima Innovation Coast, Framework Promotion Committee, member

Mid-and-long-Term Roadmap Summary (TEPCO)

Present (Completion of Step 1)
Within 3 Years

Phase 1
- Remove debris conditions
- Conduct experiments in toxic environment
- Develop support of robots

Phase 2
- Euthanasia of debris
- Remove debris conditions
- Develop support of robots

- Complete the removal of fuel debris
- Complete the removal of fuel debris
- Complete the removal of fuel debris
- Complete the removal of fuel debris

Within 10 Years

After 30-40 Years

Current Situation of 4 Units

Accident of Fukushima Daiichi Nuclear Power Station

- Earthquake (14:47)
- Loss of Power Supply
- Activation of Emergency Diesel Generator
- SCRAM
- Stop Reactors
- Tsunami
- Damage of Fuel Tanks and Generators
- SBO (Station Black Out) (15:39)
- Failure of Cooling System of Reactors and Fuel Storage Pool
- Loss of Cooling Water
- Melt down
- Hydrogen Explosion (Mar. 12-15, Unit 1, 3, 4)

Fuel Debris (Melt-down Fuel)
Spent Fuel and New Fuel in Spent Fuel Pool

3P: meeting of Japanese Government and TEPCO; Council for the Decommissioning of TEEPCO’s Fukushima Daiichi NPS
Needs (Tasks) for Remote Technology

- Water injection
- Removal and transportation of rubbles, fuels (including fuel debris), and contaminated water, etc. (Cutting, suction, handling)
- Investigation, measurement, and mapping (images, radiation, etc.)
- Sampling (dust, contaminated water, concrete core, fuel debris, etc.)
- Decontamination and Shielding
- Fixing of contaminated water leakages
- Handling, transportation, removal, setup of devices, instruments, equipments, etc.
- Waste and contaminated water management
- Dismantling of facilities

Missions depending on phases

- **Phase 1: Emergent Situation**
  - Cooling down of reactors

- **Phase 2: Stabilization**
  - Containment, systems reconstruction, for aftershocks

- **Phase 3: Decommission**
  - Fuel removal

- **Reduction of radiation exposure of workers**
Phase 3
New development (for specific use)

Inspection inside PCV in Unit 2
(operated by IRID/Toshiba and TEPCO)
Feb. 2, 2017

Inspection inside PCV in Unit 2
(operated by IRID/Toshiba and TEPCO)
Feb. 9, 2017

PCV internal robot inspection (1st phase)
○ Shape change-type robot (B2 phase)
X-100B/NE

PCV internal inspection (2nd phase)
X-6 PE phase

PCV internal inspection (3rd phase)
**Inspection inside PCV in Unit 3**
(operated by IRID/Toshiba and TEPCO)
July 19-22, 2017

- Structures
- Melt
- Deposits

**Remotely controlled machines utilized for**
the response of accident of nuclear power plant
(Foreign Machines)

**Remotely controlled machines utilized for**
the response of accident of nuclear power plant
(Domestic Machines)

**What have achieved so far**
(Successful)

- Exploration, investigation & measurement
  - States, Spatial Radiation Dose (Level & Distribution), 3D data, etc.
- Rubble removal
  - On Site Field (Outdoor), Inside R/B, Inside Spent Fuel Pool, on Operation Floor
- Sampling
  - Dust, Contaminated Water, Core Samples
What have achieved so far  
(Insufficient or on-going)

- Decontamination
- Water Leakage Fixing
- Sampling
  - Fuel Debris
- Fuel Debris Removal and Transportation

Factors of failures

- Direct factors
  - Communication failures
  - Misoperation
  - Malfunctions by radiation
- Indirect factors
  - Prototypes (not products)
  - Unknown environment

Unrecoverable Robots

Measures for Direct Factors

- Communication failures
  - Combination of wired & wireless communication
  - Implementation of wireless com. infrastructure
- Misoperation
  - Training
  - Improvements of Human Interface (situation awareness)
- Malfunctions by radiation
Outcome of the Project

Bird-eye View Image

Narrow Passage (Maze)

Generation of robot view from arbitrary viewpoints

Concept of Bird-eye view Display

Production of virtual bird-eye camera image by integrating multiple fish-eye cameras

Obstacle detection by LiF

Application to Robot for Decommissioning of NPS

MH1 Super Griffe
Radiation effects on semiconductors

- Total Ionizing Dose (TID) Effect
- Single Event Effect (SEE)
- Displacement Damage Dose (DDD) Effect

Strategies for Countermeasures against Radiation

- Shielding
  - Shield by lead/steel/tungsten (not realistic)
  - Lead glass
- Radiation-hardened devices/components
  - Radiation-hardened(resistant) Semiconductor
  - Camera tube(Namatsu Photonics) 245V dose
  - Radiation-hardened Camera(SW) 1000V dose
- Mechanical systems
  - Wire-driven(Tendon-driven)
  - Hydraulic drive(Water)
- Robust design(Fault-tolerance/Maintainability)
  - Redundant and functionally degradable
  - Modular design and easy replace

Gamma irradiation experiment

- The gamma irradiation was conducted in the Technology Development Center of ATOX Co., Ltd.

Camera model: AXIS M8007-PV

Radiation source (56Co)

Experimental environment

- 5G
- 500 mm
- 800 mm
- 600 mm
- 600 mm

Box made with aluminum frames
Gamma irradiation experiment: Movie

- After 23 min irradiation

Camera 1 (malfunction after 23 minutes)

Camera 2

Camera 3

Camera 4

Bird's-eye view generation corresponding to camera malfunction

Gamma irradiation experiment: Result(1)

- Camera 1 malfunctioned after 23 min irradiation (Integral dose: 192.1 Gy)

Camera 2 Camera 1

4 cameras

Proposed method

Camera 1 malfunctioned

Camera 2

Proposed method

Camera 3 Camera 4

Camera 2 malfunctioned after 54 min irradiation (Integral dose: 141.3 Gy)

Camera 2

Proposed method

Camera 3 Camera 4

Camera 2

Camera 3 Camera 4

Camera 2 malfunctioned

Proposed method

Camera 3 Camera 4

Gamma irradiation experiment: Result(2)

- Camera 4 malfunctioned after 82 min irradiation (Integral dose: 224.1 Gy)

2 cameras

Camera 4 malfunctioned

Proposed method

Camera 3 Camera 4

- Camera 3 malfunctioned after 94 min irradiation (Integral dose: 162.9 Gy)

Camera 3

Measures for Other Factors

- Prototypes (not products)
  - Risk assessment for failures
  - Testing
- Unknown environment
  - Advance investigation
  - Assumption of various situation
For Fuel Debris Retrieval and Decommissioning

- Development of diverse technology (Portfolio)
  - Devices and robots for specific and general use
  - Cutting devices, manipulators, handling devices (Sampling, leakage fixing, contaminated water processing, retrieval of fuel debris)
  - Endoscope-type Robot
For Fuel Debris Retrieval and Decommissioning

- Development of diverse technology (Portfolio)
  - Devices and robots for specific and general use
  - Cutting devices, manipulators, handling devices (Sampling, leakage fixing, contaminated water processing, retrieval of fuel debris)
  - Endoscope-type Robot
- Water proof devices
- Radiation-tolerant devices
- Autonomy and intelligence of remotely controlled systems
- 3D reconstruction from movies
  - Structure from Motion

Coming soon

- Removal of spent fuel of unit 3
- Dismantling of exhaust pipe of unit 1-2
- Investigation inside PCV of unit 1
- Retrieval of fuel debris of unit 2

3D Reconstruction of Unit 3 Pedestal

- 3D Reconstruction by Structure from Motion

Removal of spent fuel of unit 3
(2018.11-)

(Toshiba, R&D)
Dismantling of exhaust stack of unit 1-2 (2018.12-)

Investigation inside PCV of unit 1 (2019-)

Retrieval of fuel debris of unit 2 (2019-)


Main Contractor: The University of Tokyo
Project Leader: Prof. Koji Okamoto (The University of Tokyo)
Subcontractor: Fukushima University, Kobe University
Goal of the project

Human resource development for decommissioning of Fukushima Daiichi NPP

- Development of specialists on robotics and nuclide analysis based on the basic research
- Development of on-site/off-site analysis system
- Development of generalists who understand total risk

On-site/Off-site analysis system

**On-site**: Gamma-ray CT with a mobile robot
**Off-site**: Microanalysis of sampled fuel debris

Radioactivity Distribution Mapping Using a Mobile Robot Equipped with a Radiation Detector

放射線検出器を搭載した移動ロボットによる放射線分布マップ生成
Concept of proposed method

1. CT scan using a mobile robot equipped with a radiation detector
2. Multiple observation of radiation surrounding region of interest
3. Alternative detector pose at the observation point
4. Need of estimation of detector pose

Framework of proposed method

Reconstruction of radioactivity map

| Mobile robot localization | Coordinate transformation | MLEM |

- Finding best radioactivity distribution $\hat{\lambda}$ based on all the radiation measurement data $D$
- Maximum likelihood expectation maximization (MLEM)

$\hat{\lambda} = \arg \max L(D|\lambda)$

- Start with a guessing image
- Finite iterations over images
- Robust for the uncertainties on the data

Experiment setting 1/2

- Experimental environment
  - $5 \times 5$ m size of environment
  - $1 \times 1$ m size of small room
- Radiation source inside the small room
  - invisible from outside
- Observation points with green marks (8 points)
- Each observation time: 30 min
Experiment setting 2/2

- Localization of robot pose
  - Experimental environment map acquired in advance
  - Localization of robot pose using environment map and Laser range finder
- Ground truth of robot pose and radiation source location
  → Motion capture system

Experiment result 1/2

- The result of 3D radioactive distribution map using Compton camera data and estimated robot pose

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Voxel size</td>
<td>0.05 m</td>
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<tr>
<td>Voxel dimension</td>
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<tr>
<td>Total voxels</td>
<td>64,000</td>
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<tr>
<td>Detected radiation numbers</td>
<td>562</td>
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<tr>
<td>Number of iterations</td>
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</tbody>
</table>

For Future Development

- Make use of the failure experience
- Utilization of available technology
  - SLAM, SfM, Drones, AI (Deep Learning), IoT, etc.
- Efficiency: Systematic and drastic design for repeating use
- Common platform
  - From specific system development to standardized components
Summary

  - System integration
  - Derivation of solutions
  - Intelligent (not just mounting AI)
- Needs to concentrate the wisdom of the world
  - Nuclear accidents do not happen often
  - International cooperation in knowledge sharing and technology transfer
- Dissemination of the developed technology to other sites and applications
- Develop young human resources
  - OECD NEA NEST (Nuclear Education, Skills and Technology)

Thank you for your attention!

Hajime ASAMA
Dept. of Precision Engineering
The University of Tokyo, Japan
asama@robot.t.u.tokyo.ac.jp
3.2 PAST PERSPECTIVES AND FUTURE DIRECTIONS OF ROBOTICS AND REMOTE SYSTEMS IN NUCLEAR ENVIRONMENTS

Professor William R. Hamel  
*Mechanical, Aerospace, & Biomedical Engineering*  
*University of Tennessee, USA*

This presentation will cover three aspects of robotics and remote systems technology as it applies to decontamination and decommissioning (D&D) of nuclear systems and sites. First, an overview of the history of remote operations and the various types of tools and equipment that have been used over the years in D&D type operations will be reviewed and discussed. Second, given this previous experience and the knowledge base it represents, thoughts about how rapidly emerging modern robotics and artificial intelligence technologies may be merged into the next generation of nuclear robotics and remote systems will be given. Today’s robotics and remote systems technologies contain sophisticated electronics, embedded computers, sensing devices, materials, etc. that are susceptible to damage and malfunctions due to nuclear radiation exposure. So in the third part of the presentation, various design approaches to reduce and management the negative effects of nuclear radiation exposure on system operations will be presented.
Past Perspectives and Future Directions of Robotics and Remote Systems in Nuclear Environments (D&D)

- Professor William R. Hamel

Outline

- Brief History of Remote Operations, including D&D
- Potential of Robotics and AI in Future Remote Operations such as D&D
- Issues Regarding Radiation "Hardening"

- Extended Reach Tools:
  - Long handled tools to place worker between worker and radiation source
  - Direct tool handling and operation—manual
  - Direct viewing
  - Shielding materials: water, concrete, steel

D&D…taking things apart and cleaning up

- Characterize
- Plan
- Dismantle
- Decontaminate
- Segregate/sort
- Size reduce
- Package
- Store/transport
- Clean
- Characterize/verify

Dirty and Dangerous

- Dust
- Contamination control
- Payloads: kg to Tonnes
- Reaches: m's to 10's of meters
- Dexterous to coarse
- Aggressive tools:
  - Cutters/shears
  - Saws
  - Decon
  - Manipulators
  - Cranes
  - Construction-like machines

Range of radioactivity issues

Extended Remote Handling

- Early Remote Handling

- Overview
- Dismantle
- Decon
- Manipulation
- Package
- Store/transport
- Clean

- Characterize

JAEA-Review 2019-031
Remote Crane and Impact Wrench

Early Large Facility Remote Handling

- One degree of freedom (up/down) plus X-Y resulting in large floor space requirements for equipment
- Generate large handling forces with no force feedback
- Very slow: 100's > contact operations
- Crane operator in a shielded cab

Better Dexterity – First Mechanical Master-Slave Manipulator (MSM)…1948-49

Bilateral MSM’s are key to Hot Cell operations since the Early 50s

- Anthropomorphic
- Sensitive ~ 100 grams
- Glassware
Unilateral Power Manipulators
• multi-dof kinematics
• remote volumetric range
• high payload
• no force reflection

MSM-like capabilities in large work volumes...circa 1950's

Remotely maintainable servomanipulators...first modularized robot

Fuel Reprocessing...Ultra high levels radiation/contamination
• Reduce repair and exposure risk
• Enhance group productivity through off-line maintenance
Shortfalls...

- Remote work efficiency
  - Best: direct/teleoperations ≥ 10
  - Worst: direct/teleoperations ~ 100s
- Power supply and transmission; cable handling
- 3D remote viewing

Key Lessons Learned...applicable to D&D as well

- Anthropomorphism and dual arm
- Focus on Human-compatibility
  - Anthropomorphic size and kinematics
  - Human-like motion in master and slave
  - No bad surprises ~ 3 yrs
  - Some features (e.g., fingers) have been achieved
- Tweeze controls and display ergonomic
- Maintain high-fidelity sensory feedback
  - Vibration motor-seeing senses
  - Auditory feedback
- Microphone and tactile feedback through master controller
- Tooling-centric: Use common tools

Aging Plants brought focus to D&D in the 1980’s

- Generally lower radiation levels but not always
- More use of commercial systems where possible
- Solutions that save money (e.g., lighter design) as much as possible (can never have from all at once)
- Further human operation where possible
- Add automation where helpful
  - Research in automated systems for remote operation go back to the mid-1980s
  - Most human systems are still fully human controlled
  - Most fully automated systems are not sufficiently reliable for unstructured environments
  - Value focus on dual arm systems capabilities in human or controlled system.
The Dual Arm Work Platform was used to size reduce and package radiologically contaminated reactor vessel and containment components.

- The DAWP was used to remotely remove:
  - 60,000 pounds of graphite,
  - 2,000 pounds of carbon steel,
  - 1,700 pounds of aluminum,
  - 1,400 pounds of lead, and
  - 620 pounds of boral from the CP-5 reactor.

Modern Robotics & AI are about 25 years old...

Can Subtask Automation Be Useful...Telerobotics?

- Telerobots?
  - Telepresence & Telemanipulation
  - Telerobots: 2° of freedom
  - Telerobots: 6° of freedom
  - Telerobots: 5° of freedom
- Human interaction
- Computer assisted supervision
- Subtask automation – a form of semi-autonomy
Model & Plan, 6 minutes Execute, 23 minutes

Modern Robotics & AI are about 25 years old. Possibilities to “disrupt” remote operations are endless!

• Drones
• Mobile Platforms
• Manipulators
• Humanoids
• Perception, Sensing
• Machine Learning
• Cooperative Autonomous Systems
• Data Commo and Energy Storage? https://www.youtube.com/watch?v=H0ds54G53kI

JAEA-Review 2019-031
Goal: Predictable system operability in a given radiation environment

- What are the most sensitive components and materials?
- What are the upper limits of rad hardening?
- "Systems" level considerations?
- High Rad D&D different than space/military space applications.
- What are the engineering application options?

Factors

- Radiation spectra, dose rate and total accumulation > damage and malfunctions
- Dose rate
  - Proximity (monitoring)
  - Exposure time (position and retreat)
  - Auxiliary radiation shielding
- Total Accumulation
  - Total dose tolerance > hardening
  - Exposure control

Factors in High Rad D&D RRS Systems

- Long chain molecules – polymers, plastics, electrical insulations, etc.
- Lubricants
- Batteries
- Active electronic components and systems, particularly high resolution integrated circuit components, e.g. CPU’s, memory, printed circuit board assemblies, etc.
- Imaging systems, e.g. remote cameras

Qualitatively speaking:

- Dose Rate & necessity of remote operations
- Proximity to Fission Products (fuel debris)
Basic Systems-level Approaches

- Maximal radiation hardening
- Replacement based on Exposure; Combinations of:
  - COTS
  - Radiation hardening
  - Modularization and operational replacement

Pervasive Rad Hardening

- $10^3$ by design, $10^8$ by hardening
- Careful selection of systems, components and materials
  - Expensive, limited suppliers
  - Design limits: latest IC chips seldom available (years)
  - Tolerance no better than weakest link.

Accumulated Dose Management Approach

- Use COTS
  - With Selective component and materials selections
  - With shielding
  - Dose rate and total accumulation sensing
  - Treat sensitive system elements as replaceable consumables

Accumulated Dose Management Approach

- Smart design and operations
  - Dose rate and total accumulation sensing
  - Treat sensitive system elements as replaceable consumables, design for repair/replacement
  - Tradeoff COTS and Rad Hardening
  - Shielded and sealed
  - Decontaminable to manageable levels
  - Modularized
    - Hands-on replacement with humans and PPE
    - Hot cell replacement with MBE's
Opinion

- Avoid (expensive) rad hardening where possible.
- Use combination of:
  - Material and component selection (best COTS)
  - Shielding
  - Design for decon and contact/remote replacement
  - Manage dose accumulation
3.3 Dose concepts and Fukushima Dai-ichi radiation field characteristics

Hideo Hirayama
High Energy Accelerator Research Organization

Abstract

Dose concepts related radiation fields, radiation protection and radiation damage are presented together with brief introduction of radiation fields inside Fukushima Dai-ichi Nuclear Power Station.

Contents of talks are
1. Radiation field
2. Dose related to radiation protection
3. Dose related to radiation damage
4. “Dose” measurement
5. Fukushima Dai-ichi (1F) radiation field characteristics
Dose concepts and Fukushima Dai-ichi radiation field characteristics

November 26, 2018
High Energy Accelerator Research Organization
Hideo Hirayama

Introduction

• The “dose concept” of radiation to be introduced in this talk, especially the “dose concept concerning radiation protection” is complicated and difficult.
  – Even those engaged in radiation management seem to have someone who does not understand properly.
• However, knowing the basic idea of various “doses” used in the “dose related to radiation protection” is necessary to avoid “misunderstanding” and “confusion” with respect to “dose”.
• Although it is hard to understand, I would like you to listen as a lecture to deepen your understanding of “basic way of thinking”.

Contents

1. Radiation field
2. Dose related to radiation protection
3. Dose related to radiation damage
4. “Dose” measurement
5. Fukushima Dai-ichi (1F) radiation field characteristics

1. Radiation fields

• Information necessary to know radiation fields
  – Type of radiation
  – Energy distribution of each type of radiation (Energy spectrum)
  – Angular distribution of each type of radiation
• Many information are necessary to define the radiation field and it is difficult to know the difference with other fields (other source).
  – It is desired to express as one amount.
Dose for radiation field

- Dose for radiation field is used mainly for X-ray and γ-ray (use “photon” from now on) which are most common radiation.
- It is necessary to define object for dose for radiation field different from the case of photon spectrum.
- As the object, air is used as the most common material.
- Type of dose is different depending on the quantity to see.
  - Exposure
  - Air kerma (kinetic energy released in air)
  - Air absorbed dose

Air absorbed dose

- The air absorbed dose is the amount per unit weight of the energy applied to the air by photons in the air of Δm.

\[ D = \frac{\Delta E}{\Delta m} \]

- Although the absorbed dose is a concept that can be applied to any radiation, it is limited to photons here. Also, although the absorbed dose is a concept applicable to any substance, air is targeted as “air absorbed dose”.
- The size of Δm
  - It is sufficiently large that it contains so many interactions that the energy given to Δm has meaning as an average value.
  - Δm is small enough that photons can be regarded as uniform.

2. Dose related to radiation protection

- Dose related to radiation protection is introduced for person to be present in the radiation field.

Relation between 3 quantities related to radiation protection
Dose related to radiation protection

• 1990 recommendation of ICRP: Equivalent dose, Effective dose
• Equivalent dose
  \[ H_T = \sum_R w_R \times D_{T,R} \]
  - \( w_R \): Radiation weighting factor
  - \( D_{T,R} \): Average absorbed dose of organ T due to radiation R
• Effective dose
  \[ E = \sum_T w_T \times H_T = \sum_T w_T \sum_R w_R \times D_{T,R} \]
  - \( w_T \): Tissue weighting factor
• Same unit “Sv” is used for equivalent dose and effective dose.

System for radiation protection quantity

Radiation weighting factor ( Introduced from viewpoint of convenience at the field of radiation protection )

<table>
<thead>
<tr>
<th>Radiation weighting factor</th>
<th>Photon</th>
<th>Electron and muon</th>
<th>Proton and charged pion</th>
<th>Alpha particle, fission</th>
<th>Other than heavy particle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.0</td>
<td>0.5</td>
<td>2.0</td>
<td>20</td>
<td>Below</td>
</tr>
</tbody>
</table>

It is a factor used for the purpose of calculation of the equivalent dose which is the protection amount multiplied by the average absorbed dose of tissues and organs in order to express the difference in effect by the radiation quality regardless of internal or external radiation exposure and is similar to the quality factor. Although it is a concept, it differs greatly from being separated from the concept of the function of LET.
Calculation of effective dose

- Calculation of Equivalent dose using human body phantom and Monte Carlo code
  - Detailed phantom
    - “Voxel phantom” based on CT
  - No matter how detailed it is “standard model of human body”.
  - From the viewpoint of convenience at the site of radiation protection, it is determined by the type and energy of radiation incident on the human body
- Tissue weighting factor
  - In many ways, a large uncertainty factor
  - Difference in exposed form, difference in dose rate, etc.
Operational quantity like ambient dose equivalent
- It is not an amount that can be measured based on the principle. (dose equivalent cannot be measured)
- Depending on the irradiation geometry, the effective dose varies depending on whether the field dose is the same or different (angle spectrum is different)
  - Dosimeter can not respond
  - Ambient dose equivalent was determined as “amount” that can be evaluated as “safety side” (larger) of the effective dose in what kind of irradiation geometry.

Relation between ambient dose equivalent and effective dose or air absorbed dose
- The relationship between these “dose” differs depending on the energy of photons.
  - Unless we know the main photon energy, we can not convert from field dose (air absorbed dose) to ambient dose or effective dose.
- Even with the same photon energy, the effective dose differs depending on the irradiation geometry.
  - Effective dose must be shown together with the irradiation geometry.
  - Treatment of air absorbed 1 Gy is corresponding to 0.8 Sv as the effective dose
  - Assume an effective dose of ISO irradiation geometry
  - As a countermeasure at the time of the accident, 1 Gy = 1 Sv corresponds to the evaluation on the safe side from 1 Gy = 0.8 Sv.
Dose in Sv

- Sv is used for various "doses" related to radiation protection.
- When "dose" in Sv unit is used, it is necessary to indicate the kind of dose and its condition.

Radiological protection quantities
- Effective dose (irradiation condition)
- Equivalent dose (organ)

Operational quantities
- Ambient dose equivalent (1 cm dose equivalent)
- 70μm dose equivalent
- 3mm dose equivalent

3. Dose related to radiation damage

- When there is an object in the radiation field, it becomes the subject of "radiation damage".
- Radiation damage due to photons and electrons is basically proportional to "absorbed dose" which is energy imparted to a target substance by radiation.
  - In the case of neutrons and the like, it is necessary to consider displacement of atom (DPA) due to reaction.
- The absorbed dose varies depending on the target substance even in the same radiation field.
  - In the case of photons, it depends on the mass energy absorption coefficient of the target substance.
  - In the case of electrons, it depends on the mass collision stopping power of the target substance.

Relationship between dose related to damage and dose related to radiation protection

- The dose related to radiation protection is related to the probabilistic influence by radiation exposure to the last, it does not lead to radiation damage of the substance.
- In the dose of radiation protection, the internal organs of the human body are targeted, but the damage of the equipment is often the most severe near the surface and the influence of the following radiation is large.
  - photons with relatively low energy
  - neutrons near the surface
- It is meaningless to apply the protective dose to the dose related to damage, but if it is "absorbed dose" such as "air absorbed dose", it can be correlated with the influence of difference of the target substance, so it is possible to use as an index.
  - When using the absorbed dose of substances other than the target substance, it is necessary to indicate the dose (Gy) with the substance name.

4. “Dose” measurement

- Measurement of air absorbed dose by cavity ionization chamber
  - It has a cavity of gas of near composition of air in a substance having a composition close to air and measures the absorbed dose of air from the ionization amount in the gas.
  - Although some corrections are necessary, measurements based on definitions are possible.
- Measurement of air absorbed dose by methods other than ionization chamber
  - Measurements made by various corrections such that the energy response (the absorbed energy of air per unit photon) is close to the response of air. Not measurement based on definition.
- Measurement of dose related to radiation protection
  - "Operational quantity" defined for measurement is not a "dose" that can actually be measured.
  - Similarity to the air absorption dose measurement by a method other than the ionization chamber, measurement is made so that the energy response becomes close to the response of the operational quantity by various contrivances.
  - Depending on the spatial method, the energy range that can be measured with relatively high accuracy is different.
- Measurement of dose related to radiation damage
  - Because radiation damage is in much higher dose range than dose for protection, it is considered that "absorbed dose" in which damage occurs is often "estimated" from the degree of damage of the substance being grouped to some extent.
  - In general, caution is necessary because the composition and size are actually different from the target device.
5. Fukushima Dai-ichi (1F) radiation field characteristics

- Apart from fuel debris etc. to be handled in the future, the main sources of worker’s external exposure and equipment damage at 1F are Cs-137 and Sr-90/Y-90.
- For a while after the accident, the contribution of Cs-134 was greater, but due to the difference in half-life now, the contribution of Cs-137 is dominant.
- The most important property of the radiation field caused by the accident is that the source area is very wide.
  - Although so-called hot spots are conspicuous, from the perspective of exposure, even if the density is low, the influence of widely distributed sources is greater.
  - It should be noted that even though Cs-137 is the main source, the primary photons of the 1F radiation field are not 0.662 MeV γ-rays emitted with the decay of Cs-137.

Importance to know radiation field

- It is very important to know the situation of the radiation field for conducting radiation protection and radiation damage.
  - Even if the γ ray emitted from the radiation source is 0.662 MeV, the contribution of photons of 0.2 MeV or less, whose energy is low due to scattering, is large in the 1F site other than the reactor building, and the dose rate (peripheral dose equivalent) can be reduced easily with 2 mm lead.
  - If there is Sr-90/Y-90 in the vicinity, there is a possibility that it may cause exposure of the skin and the lens of eyes, or damage of the equipment, but if it can be confirmed, these effects can be reduced easily.
    - The effects of β-ray can be shielded by about 2 mg/cm² plastic in the case of Sr-90 or Cs-137 with low β-ray energy and 1 g/cm² plastic even with Y-90 with high β-beta ray energy.
Radiation field inside reactor building and correspondence (1)

- There are many places where the ambient dose equivalent rate is high inside the reactor building and the situation of the radiation field is not sufficiently grasped.
- When the ambient dose equivalent rates is high, it is difficult to measure the pulse height distribution of photons, and it is difficult to obtain photon energy information.
- It is necessary to grasp basic information “contribution ratio to scattered radiation” and “presence or absence of β ray contribution”.

Radiation field inside reactor building and correspondence (2)

- Response to external radiation exposure
  - The main radiation of external radiation is γ ray, scattered ray from Cs-137 and β rays.
  - γ ray and scattered photons
    - Since ease of shielding varies depending on the ratio of scattered photons, grasp the “contribution ratio of scattered photons”, and in places where the proportion of scattered photons is high, it is possible to reduce the dose rate by utilizing a screen or the like containing lead of several mm.
  - β rays
    - β rays are important when surfaces contaminated with Cs-137 and Sr-90/Y-90 are exposed.
    - The β ray of Cs-137 is low in energy, so it stops at about 1 - 2 mm of polyethylene.
    - It is necessary to grasp whether there is Sr-90/Y-90 pollution including Y-90 that produces high energy β rays
      - When the contaminated surface is exposed, the full mask acts as shielding, so always wear it.
    - As a β ray stops with a small amount of substance, the direction of the dosimeter is important.
      - That is why the orientation of the APD and the glass badge is checked before starting work.

Scattered photons are dominant

The dose rate at B is about half of A.

Since the scattered photons from Unit 1 Operational Flow etc. is the main component and the photon coming from the front is dominant, it attenuates with the human body.
Radiation field inside reactor building and correspondence (3)

• Response to internal
  – In internal radiation countermeasures, it is most important not to incorporate radionuclide into the body.
  – It is essential to have necessary equipment properly.
    • Attach the full mask exactly.
    • Wear rubber gloves properly so that there is no exposed surface.
  – Confirmation that no radionuclide is attached to the body.
    • Contamination inspection after work
  – Unlike “external radiation exposure” where radiation exposure is inevitable with work, “internal radiation exposure” can be prevented unless radioactive nuclides are taken into the body.

Summary

• In efforts towards the decommissioning of 1F facility, it seems that it will correspond to the harsh “radiation field” that has never been experienced before.
• Under such circumstances, in order to make the damage of the worker (individual and whole) and equipment less than the standard, it is important to clarify information on the necessary radiation field and to collect in a manner that can be reliably acquired. It is important to set up countermeasures based on the obtained results.
  – Based on the degree of precision and what kind of information is required, we will make effective use of the methods established so far.
4. Topics
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4.1 Design and experiences on remote operation in high radiation field

Simon Delavalle
*Oxford Technologies (Veolia Nuclear Solutions UK)*

**ABSTRACT**
Since 2000, Oxford Technologies has delivered complex remote handling equipment to some of the most challenging environment in the world. The company has worked with sites where various level of radiation exists, such as JET (UK), ITER (France), Dounreay (UK), Sellafield (UK) and Fukushima (Japan).

Whilst many constraints create the challenges of achieving these designs and delivering functional remote handling equipment, some are unique to this industry.

This presentation will cover some specific requirements due to these environment:
- An overview of the impact of high level of gamma radiation on the selection of technologies and materials
- The importance of viewing the remote unmanned operation and the additional constraints that creates, as well as the use of real time digital twins 3D models (or virtual reality) as an complementary technology.
- The challenge in designing equipment to be recoverable in these inaccessible environment

All the above drive inherent complexity into achieving a suitable design of remote handling equipment. One common consequence is the impact on the required number of services and their management across complex range of motion; this will be illustrated in a simple example.

Finally a summary discussion will highlight some of the R&D currently being progressed and how they will alleviate some of these challenges.
Design for remote handling equipment in high radiation field

Remote handling experience

FUKUSHIMA

Radiation hardness

- Typical technologies level of radiation sensitivity
  - Concrete
  - tyres
  - electronic devices
  - electronics processor
  - semiconductors
- Typical technologies level of radiation sensitivity
  - polymer
  - motor windings
  - cable insulation
  - plastic components
  - seals
- Organic material
  - epoxy, resin
  - hydraulic fluid
  - grease and lubricant

Summary of some experiences and lessons learnt from designing complex electromechanical equipment for high radiation environment

- High radiation field (Gamma)
- Undeclared / uncertain environment
- No manned access

Constraints:
- High radiation field (Gamma)
- Undefined / uncertain environment
- No manned access
Radiation hardness

- Design for radiation hardness:
  - Shielding / radiological protection
  - Investigation of off the shelf components
  - Testing of specific materials / components
  - Development of new technologies
  - New materials
  - Semi conductor technologies
  - Camera technologies

Vision System

- The only views AND lighting available are the one deployed by the remote handling equipment!

Vision System

- Environmental condition

Vision System

- Virtual reality system – Digital Twins:
  - Design development taking in consideration information from expected operation and environment
  - “Offline” planning and rehearsal of operations
  - Real time 3D information from equipment status and operation progress
How to retrieve a failed remote handling equipment in a state that can be recovered for repair, where there is no manned access?

Recovery strategy

Recovery strategy

Design and experiences on remote operation in high radiation field

Redundancy:
- Secondary motors / sensor to enable the completion of task

Recovery:
- Auxiliary system to enable retrieval of equipment out of operational environment

Rescue:
- Assistance from external systems to retrieve equipment

Development and integration of recovery solutions / technologies for remote application:
- Separable joint
- Manual overdrive
- Latching system
- Breakable joints
- Slipping joints
- Etc.

Design for remote handling equipment in high radiation field

Illustrative example:
- Articulated arm (1 joint) for camera inspection
- 1 servo motor + 1 camera
Design for remote handling equipment in high radiation field

Example:
- 2 additional servomotors?

In summary:
- Many factors drive the complexity of remote handling equipment. This is why systems have to be kept as simple as practical for the tasks.
- The selection of the appropriate technologies is key to the suitability to operate successfully in high radiation environment.
- Whilst many challenges exist for the design of remote handling equipment, one common limitation is usually the number of services required (electrical cables, hoses, fibre optics, etc.) and their management across the range of motion.

Project example: 480 cores!

Research and Development:
- We are working on critical areas with international partners to develop key technologies to simplify remote handling equipment for high radiation field:
  - Radiation tolerance of sensitive electronics
  - Radiation tolerance of digital cameras and vision systems
  - New cable construction for high density service routing
  - Use of advanced VR techniques for real time integration of plant and intervention technologies
Any questions?
4.2 Approach to realizing radiation-hardened devices

Shin-Ichiro Kuroki1) *, Hiroshi Sezaki2), Takeshi Ohshima3), and Yasunori Tanaka4)  
1) Research Institute for Nanodevice and Bio Systems (RNBS), Hiroshima University  
1-4-2 Kagamiyama, Higashi-Hiroshima, 739-8527, Japan  
2) Phenitec Semiconductor Corp., 150 Kinoko-cho, Ibara, Okayama, 715-8602, Japan  
3) National Institutes for Quantum and Radiological Science and Technology (QST)  
1233 Watanuki, Takasaki, Gunma, 370-1292, Japan  
4) National Institute of Advanced Industrial Science and Technology (AIST)  
1-1-1 Umezono, Tsukuba, Ibaraki, 305-8568, Japan  
*skuroki@hiroshima-u.ac.jp

Radiation-hardened electronics have been required for human activities in space, accelerator, and for decommissioning of nuclear power plants. For the harsh environment applications, silicon carbide (SiC) with wide energy band gap is one of the promising semiconductor [1-4]. Our objective is to realize the SiC harsh environments electronics, which consist of SiC CPU, sensor systems, motor drivers, etc as shown in Fig.1. 4H-SiC BJTs logic circuits were demonstrated after high gamma-ray exposure of 3.32 MGy [5]. 4H-SiC n/pMOSFETs were also demonstrated in a high temperature of 450°C and high gamma-ray exposure of 1.13 MGy [6,7]. For radiation-hardened image sensor, 4H-SiC/SOI-Si hybrid pixel device was suggested and demonstrated [8]. This pixel device consists of three 4H-SiC MOSFETs and one Si photodiode as shown in Fig.2. The Si photodiode was fabricated on the 4H-SiC substrate with 4H-SiC MOSFETs after direct bonding of 4H-SiC and SOI (Silicon-On-Insulator) substrates.

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Fig.1 SiC radiation-hardened electronics. Fig.2 SiC/SOI-Si hybrid pixel device [6].
Approach to realizing radiation-hardened devices
耐放射線デバイスの実用化へのアプローチ

Shin-Ichiro Kuroki1), Hiroshi Sezaki2), Takeshi Ohshima3), and Yasunori Tanaka4)

1) Research Institute for Nanodevice and Bio Systems (RNBS), Hiroshima University
2) Phenitec Semiconductor Corp.
3) National Institutes for Quantum and Radiological Science and Technology (QST)
4) National Institute of Advanced Industrial Science and Technology (AIST)

Outline

1. Introduction
2. SiC Power Semiconductor Devices
3. Wide-Bandgap Semiconductor & Harsh Environment Electronics
4. Summary
Our Requirements

**SiC CPU**

- Sensors
- OpAmp
- ADC
- Motor Driver

**Memory**

- Image Sensor
- Gamma-ray Neutron
- Temp.

Goal:
- Radiation-Hardness (TID): > 2 MGy (200 Mrad)
- Temperature: 300°C
- Operation Frequency: 100 MHz
- Base Device: 4H-SiC MOSFETs (Normally off)

Outline

1. Introduction
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4. Summary

**From Silicon to Silicon Carbide(SiC)**

<table>
<thead>
<tr>
<th>Material</th>
<th>Si</th>
<th>4H-SiC</th>
<th>vs. Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandgap (eV)</td>
<td>1.12</td>
<td>3.26</td>
<td>×3</td>
</tr>
<tr>
<td>Breakdown Electric Filed (MV/cm)</td>
<td>0.3</td>
<td>2.8</td>
<td>×10</td>
</tr>
<tr>
<td>Thermal Conductivity (W/cmK)</td>
<td>1.5</td>
<td>4.9</td>
<td>×3</td>
</tr>
</tbody>
</table>

Schottky Barrier Diode

- Silicon
- Electric Field $E_B$ (Si)
- $n$-layer
- $n^+$
- Depletion layer ~ 1/10 $N_D$~100X
- Low ON-resistance ~ 1/300
- Low power consumption

4H-SiC Wafer

- 4H-SiC
- 4 inch
- 6 inch
- 3 inch
- 2 inch
- Manufactured with high Temperature of ~ 2200°C
Development in Hiroshima Univ.

**Prototype Fabrication**

- 14 Prototype Fabrications in Hiroshima University from 2012 to 2015.

**ES Production**
- From Dec. 2015

**Rapid Prototyping**
- Mask-less Litho@RNBS
- EB Litho@RNBS

**Digital Mirror System**

**Conventional**
- With Mask

**Mask**
- Limiting Factor For Fabrications
- Import the Technologies from July, 2014

**Prototype Fabrication**
- 2012.05 - 2014.05

Outline

1. Introduction
2. SiC Power Semiconductor Devices
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4. Summary

**Hybrid / Electric Cars**

- Electric Cell
- Power Module ~ Power Semiconductor Devices
- Generator
- Motor
- Gate Driver Circuits

**SiC**
- Maximum Operating Temp. < 125°C

**Gate Driver Circuits**
- are strongly required!
Why Wide-Bandgap Semiconductor?

Energy

\[ E_c: \text{Conduction Band} \quad e^- \quad \text{Electron} \]

\[ E_v: \text{Valence Band} \quad h^+ \quad \text{hole} \]

Bandgap

\[ \sim \text{Intrinsic Property of Material} \]

High Radiation

Si: Silicon

\[ E_c \quad \text{Bandgap} \quad 1.12 \text{eV} \]

SiC: Silicon Carbide

\[ E_c \quad \text{Bandgap} \quad 3.26 \text{eV} \]

At High Temperature > 150°C

Si: Silicon

\[ E_c \quad \text{Bandgap} \quad 1.12 \text{eV} \]

SiC: Silicon Carbide

\[ E_c \quad \text{Bandgap} \quad 3.26 \text{eV} \]

Typical Wide-bandgap Semiconductors

<table>
<thead>
<tr>
<th></th>
<th>Si</th>
<th>4H-SiC</th>
<th>GaN</th>
<th>Ga_2O_3</th>
<th>Diamond</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandgap</td>
<td></td>
<td>1.12</td>
<td>3.26</td>
<td>3.39</td>
<td>4.5-4.9</td>
</tr>
<tr>
<td>Relative Permittivity ( \epsilon )</td>
<td>11.8</td>
<td>9.7</td>
<td>9</td>
<td>10</td>
<td>5.9</td>
</tr>
<tr>
<td>Electron Mobility ( \mu_e ) (cm²/Vs)</td>
<td>1500</td>
<td>1000</td>
<td>900</td>
<td>200</td>
<td>1800</td>
</tr>
<tr>
<td>Breakdown Electric Field ( E_b ) (MV/cm)</td>
<td>0.3</td>
<td>2.8</td>
<td>3.3</td>
<td>7-8</td>
<td>5.6</td>
</tr>
<tr>
<td>Electron Saturation Velocity ( V_{sat} ) (×10⁶ cm/s)</td>
<td>10</td>
<td>20</td>
<td>25</td>
<td>-</td>
<td>27</td>
</tr>
<tr>
<td>Thermal Conductivity ( \kappa ) (W/cmK)</td>
<td>1.5</td>
<td>4.5</td>
<td>1.3</td>
<td>0.11-0.27</td>
<td>20.9</td>
</tr>
</tbody>
</table>

For CMOS Fabrication

- CMOS (nMOS and pMOS)
- Direct Oxidation
- Dicing (Easy to Cut)
Device Structures

MOSFETs
- Self-Alignment S/D Trench MOSFETs
- No need for gate oxide
- ~ Rad-hard

JFETs
- Planar structure
- Good for integration
- No need for gate oxide
- ~ Rad-hard

BJTs
- Stops structure
- No need for gate oxide
- ~ Rad-hard

Feature

Structure

4H-SiC MOSFETs and its Circuits

4H-SiC MOSFETs
- Radiation-Hardness [1]
- High-Temp. operation [1,2]
- ~ 450

4H-SiC nMOS
- 4H-SiC pMOS


4H-SiC/SOI-Si Image Sensors

3T Image Sensor


4H-SiC/ SOI-Si Pixel Device [1]


- Si photodiode and 4H-SiC MOSFETs for Radiation-Hardness
- Add. SIC epilayer for radiation-hardness
Outline

1. Introduction
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4. Summary

Summary

1. SiC Power Semiconductor Devices is now in practical use.

2. SiC Harsh Environment Electronics is under development.
   - Radiation-Hardness ☑ > 1 MGy
   - High Temperature Operation ☑ ~ 500°C

Space Exploration

Gate Driver Circuits for Automobile

Decommissioning

Hiroshima Castle
~ was originally build in 1599, was destroyed by the atomic bomb in 1945, and was rebuilt in 1958.
Acknowledgements:

Part of this work was supported by

- the Special Coordination Fund for Promoting Science and Technology
  of the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan,

- The program for Strategic Research on Nuclear Energy, Culture, Sports, Science and Technology (MEXT), Japan.

Thank you very much for your kind attention.
4.3 Development and demonstration of small compact radiation imaging system

Yuki Sato
Collaborative Laboratories for Advanced Decommissioning Science, Japan Atomic Energy Agency, 790–1, Motooka aza Ohtsuka, Tomioka-machi, Fukushima, 979–1151, Japan
E-mail: sato.yuki@jaea.go.jp

The Fukushima Daiichi Nuclear Power Station (FDNPS), operated by Tokyo Electric Power Company Holdings, Inc., went into meltdown after the large tsunami caused by the Great East Japan Earthquake of March 11, 2011. Measurement and visualization of the distribution of radioactive substances inside the site of the FDNPS are indispensable to execute the decommission tasks because the information would be important to predict risk to workers and to decrease the amount of radiation exposure. We have developed a radiation imaging method based on a compact Compton camera and conducted demonstration tests for visualization of radioactive substances inside the site of the FDNPS. In March, 2018, we conducted a radiation imaging experiment inside the reactor building of Unit 1 by using the Compton camera mounted on a crawler robot [1]. As a result, we succeeded in remotely visualizing the gamma-rays streaming from deep inside the reactor building. We also drew a radiation image obtained using the Compton camera onto the 3D structural model of the experimental environment created using photogrammetry. This visualization technique helps workers easily recognize high-dose regions and decrease their own exposure. In the future, we contribute to the survey in the deep part of the reactor buildings by integrating the environment recognition technologies such as SLAM and photogrammetry and the robot control technology into the radiation imaging technology.

Real-time visualization of radioactive substances inside the 1F building

- Location: Turbine building of Unit 3
- RS plate installed on the top and bottom, left and right, and back of the gamma-ray sensor (1 cm-thickness)

1F建屋内における放射性物質のリアルタイム可視化

- 現場項目: 3号機タービン建屋内
- 1cm厚のアルミシートをカバー
- センサーの上、下、左、右に設置

1F建屋内にて、ホットスポットを“その場”で確認可能

Hot spot can be observed in situ in the 1F building

Development of small and lightweight Compton camera

Conventional gamma cameras weigh several tons of kg

Compact Compton camera (by JAEA)

- Total weight less than 1 kg
- Power consumption < 3 W
- Operated by 128 Ibus power

小型軽量化コンプトンカメラの開発

小型・軽量コンプトンカメラ

(by JAEA)

Compact size

Measurement of a 3D-model data of the 1F building

Laser rangefinder

Scan laser light on the structures and construct a 3D model of working environment

Hokuyo YV-3002(3D)

小型測域センサーを用いた1F建屋内部3次元データの取得

測域センサー

Hokuyo YV-3002(3D)

レーザー光を基点し

作業環境の3次元モデルを構築する
Radiation image + 3D-model data

- It is possible to observe the distribution of radioactive substances from an arbitrary viewpoint.
- Discussion taking into consideration the building structure is possible.

放射線イメージ + 3次元モデルデータ

- 任意の視点から汚染分布を観察可能
- 建築構造を考慮した議論が可能となる

Acknowledgments

We would like to thank everyone who cooperated in achieving this result.

- ATOX CO. Ltd
- Visible Information Center, Inc.
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- Tokyo Electric Power Company Holdings, Inc.
- Hamamatsu Photonics K.K.
- Waseda University

謝辞

本成果を達成するためにあたり、ご協力いただいた皆様に深く感謝申し上げます。

(JAEA-Review 2019-031)

Conclusion

- We developed a 3D radiation imaging system based on a compact Compton camera.
- Succeeded in 3D visualization of high dose regions in 1F building.
- By combining with a robot, it is possible to measure the distribution of radioactive substances remotely. (In March of 2018, we carried out measurement test of radioactive substances using a crawler robot equipped with the Compton camera in Unit 1 reactor building [1].)
- It is a remote radiation imaging system integrating radiation measurement, remote equipment, environment recognition technology. We would like to contribute to the survey of the deep part inside the reactor buildings in the future.

まとめ

- 小型・重量コンプトンカメラを積載した3次元放射線イメージングシステムを開発した。
- 1F建物内において高濃度箇所の3次元的可視化に成功
- ロボットと組み合わせることにより、遠隔にて放射性物質の分布を測定することが可能（2018年3月に、一部機の原発建物内にて、コンプトンカメラを積載したクレーアロボットを用いた放射性物質の測定試験を実施）。
- 放射線測定・測定機器の環境認識技術を組合した遠隔放射線イメージングシステムであり、今後、原子力建物内深い部の調査に貢献したい。
5. Oral Session 1
This is a blank page.
5.1 Development of rad-hard technologies for ITER Remote Maintenance

C. Damiani
Fusion for Energy, Torres Diagonal Litoral B3, Josep Pla 2, 08019 Barcelona, Spain

For a first-of-a-kind nuclear fusion reactor like ITER, remote maintainability of neutron-activated and contaminated components is one of the key aspects of plant design and operations, hence a fundamental ingredient of its success, as well as of the demonstration of long-term viability of fusion as an energy source. The whole ITER Remote Maintenance System is of unprecedented complexity and includes specifically developed technologies. Its procurement and start of operation will represent a major innovation to maintenance in hostile environments.

Europe is a key contributor, with three remote handling (RH) systems, a.k.a. packages, plus a robotic inspection and metrology tool, currently under design. Among others, there is the challenge of performing complex handling sequences (which include transporting and installing multi-tons components with millimetric accuracy) under intense gamma radiation fields, up to several hundreds of Gy/h. Due to the amount of time required to perform a complete shutdown in ITER, which includes thousands of hours of in-vessel maintenance, 1 MGy-rated rad-hard components are needed for the RH systems. The field of operation for these systems is space-constrained; because of this, viewing capabilities in narrow spaces and challenging cable management of the RH systems require specific development of novel rad-hard technologies: compact digital cameras and multiplexers (to reduce the number of cables to be routed through the umbilical harness). For both components, we have performed some basic design and R&D activities, including irradiation tests (1 MGy-scale), which have confirmed there is the potential to fulfil our needs with innovative electronics. For cameras we have designed, manufactured and tested 256x256 image sensor, Analog to Digital Converter, led-based illumination and fixed optics. For the multiplexer we have designed, manufactured and tested application specific integrated circuits (ASICs) able to amplify, digitise and multiplex signals from strain-gauge based pressure sensors, temperature sensors and resolvers. There is a second stage of development on going, aiming at designing, manufacturing and testing the key electronic components for a 640x480 sensor for the camera, and the integration of communication modules for the multiplexer. After this, we should enter in the industrialisation stage, with the ultimate objective of integrating these
components in the various nuclear-grade RH systems to be manufactured, assembled, tested, installed and operated in ITER.

The presentation to the Fukushima Research Conference will cover the following topics:
- introduction to ITER as nuclear fusion plant; radiation maps and need for remote maintenance
- overview of the remote maintenance scenario and of the main RH systems that will operate in ITER
- justification for the need of 1 MGy rated rad-hard components
- identification of critical rad-hard technologies for ITER remote maintenance
- progress on the development of rad-hard digital cameras and rad-hard electronics
- outlook to the future steps in the industrialisation of rad-hard components
Development of rad-hard technologies for ITER Remote Maintenance

Carlo Damiani
F4E RH PT Manager
27th November 2018

Outline
• Introduction to ITER and justification for the need of 1 MGy rated rad-hard components
• Overview of the remote maintenance scenario
• Identification of critical rad-hard technologies for ITER remote maintenance
• Progress on the development of rad-hard digital cameras and rad-hard electronics
• Outlook to the future steps in the industrialisation of rad-hard components
During ITER operation, in the burning D-T plasma, the fusion reactions generate high energy neutrons and alpha particles (He nuclei).

In a typical ITER plasma pulse, lasting 400 s, with 500 MW fusion power, almost $10^{23}$ neutrons (and same number of $\alpha$-particles) are produced.

The neutrons carry 80% of the fusion energy and are mostly captured by the shielding blanket modules and the divertor cassettes.

Why ITER needs remote handling?

• Introduction to ITER and justification for the need of 1 MGy rated rad-hard components
• Overview of the remote maintenance scenario
  • Identification of critical rad-hard technologies for ITER remote maintenance
  • Progress on the development of rad-hard digital cameras and rad-hard electronics
• Outlook to the future steps in the industrialisation of rad-hard components

A closer look to ITER radioactivity - 1

During ITER operation, $n$ and $\alpha$ make the tokamak building largely inaccessible.
During ITER maintenance, the in-vessel radioactivity is several 100 Gy/h.
Components to be maintained - 3

- Removal and installation of massive blanket modules implies complex remote handling tasks, like:
  - Gaining access to the component
  - Cutting/welding water cooling lines
  - Unlocking/locking the component from the vessel
  - Lifting and transporting it/to from the transfer casks

Such tasks require the overall permanence in highly radioactive environment for 1000s of hours (overall shutdown duration max 6 months).

Considering the calculated dose rates, this implies the RH components must be 1 MGy rated.
Divertor Remote Handling System - 1

- The lower portion of ITER hosts 54 divertor cassettes (dimensions 3.4x1.2x0.6 m, weight 10 tons)
- At the divertor level there is the extraction of plasma ashes and other impurities
- Given the very high thermal loads, it is foreseen to exchange the whole divertor 3 times during ITER lifetime

Divertor Remote Handling System - 2

- The 54 cassettes are removed and installed by utilizing 3 RH ports at the lower level in the tokamak
- The remote handling is performed by movers equipped with end-effectors, force feedback manipulator arms, special tooling, cameras etc.
- The cassettes must be unlocked from the vessel rails and the cooling pipes must be cut before they can be taken away and transported toroidally up to the RH port and radially along such port (reverse sequence during installation)

Divertor Remote Handling System - 3

- RH Port 8
- RH Port 2
- RH Port 14

Divertor Remote Handling System - 4

- Divertor Remote Handling, JAEA, Japan, test facilities, Naka, Japan
- Blanket module handling, JAEA, Japan, test facilities, Naka, Japan
The cassette movers, tooling, pipe isolators, replace the 54 divertor cassettes during a 6-month shutdown.

(Divertor Remote Handling System - 4)

Cassette Toroidal Mover

Pipe cutting tool

Pipe welding tool

Wrench tool

High torque bolting tool

Jacking tool

Pin tool

(Cassette Mock-up)

Divertor region mock-up with CMM + cassette operations capabilities (non-nuclearised)

Integrated operations demonstrations - Virtual Reality + Command & Control + Equipment Controllers (real HW) + Operations Management System

Accurate VR (Structural Simulator – Accuracy improved from 60-70mm to 5-10mm)

Last tests: full sequence on 2nd cassette; 1st (aka central) cassette including tests with improved locking system

Complementary activities on digital water hydraulic valves, remote diagnostics and computer-aided teleoperation

(Cask and Plug Remote Handling System - 1)

It is a fleet of 15 mobile casks, whose primary function is the remote transport of components between Vacuum Vessel and Hot Cell Facility, for maintenance and rescue operations (total max 100 tons – 8.5x3.7x2.6m max size).

Each cask unit consists of: 1) a leak tight cask envelope (equipped with double door system); 2) a mobile platform (with double door system to ensure connection of the casks to the vessel and to the hot cell).

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DRHS: the DTP2 in Finland

DTP2 Facility

Divertor region mock-up with CMM - cassette operations capabilities (non-nuclearised)

Integrated operations demonstrations - Virtual Reality + Command & Control + Equipment Controllers (real HW) + Operations Management System

Accurate VR (Structural Simulator – Accuracy improved from 60-70mm to 5-10mm)

Last tests: full sequence on 2nd cassette; 1st (aka central) cassette including tests with improved locking system

Complementary activities on digital water hydraulic valves, remote diagnostics and computer-aided teleoperation
Cask and plug remote handling system

Moving along the corridors of the ITER buildings…

Delivering a divertor cassette to the Hot cell

Delivering a divertor cassette to the Hot cell

... to the Hot cell

Cask variants

Transfer technologies

Summary: the CPRHS consists of a fleet of 15 casks of different typologies, travelling across TMX and HC buildings for confined transportation of activated/contaminated components and other RH systems.

Cask hosting the BRHS

Cask hosting an equatorial plug

Cask variants

Transfer technologies

Cask variants
Neutral Beam cell Remote Handling System

The RH system is basically composed of a special monorail crane, a beam source-accelerator handling device, mast, swing rails and manipulator arm, and a special tooling.

New NBRHS pipe tool test snapshots

Full-scale RH tests at CCFE in October 2015 to demonstrate the functions of the pipe tooling. The operator operates the tools (in this case the alignment tool made of twin tool mockups in the two halves of the mockup) from behind a wall with only camera-based viewing info and force feedback by through-the-wall manipulators.

New series of pipe tool tests have been launched in 2018.

In-Vessel Viewing System

- Primary Function: Inspection of blanket first wall and divertor plasma facing components looking for damage; in-vessel viewing and metrology
- Main Components:
  - Probes + control / processing units (6x)
  - Deployment system
  - Plug housing + neutron shielding
  - Spares
- System highlights
  - UHV, operation temp. up to 120°C (baking 200°C), gammas 5-6KGy/h, neutron fluence up to 2.3·10¹⁷ n/cm² (wide spectrum), up to 8T magnetic field, space constraints…
  - Viewing performance: spatial resolution <1mm (0.5 – 4m target distance), <3mm (>4m target distance)
  - Metrology performance better than millimetric (next slide)
  - Self-illumination
- Critical functions: wall erosion/damage of in-vessel components
- Managed from CODAC control room

The In-Vessel Viewing System (IVVS)
Recent developments:

- Design of the IVVS-cask interfaces and insertion/removal sequence (by OTL)
- Optical tests covering:
  - Testing of piezoelectric actuator technology for scanning and focusing
  - Upgrade of detection electronics allowing ~10x improvement in distance measurement precision (precision <15 μm at 1-4 m, <50 μm at 10 m)

Lab tests at ASE Optics Barcelona (OTL subcontractor)

Material release rate is 10x lower than the dose rate in the IVVS port cell.

Neutronic analyses:

- Neutron flux inside IVVS during plasma operation
- Shut-down dose rate in the IVVS port cell

Target: 6·10⁴ neutrons/cm²/s.
ITER remote maintenance is a complex, integrated and diffused system embedded in the nuclear plant (it includes many subsystems). The field equipment, in particular, interface in vessel components, diagnostics plugs and heating systems, tokamak and hot cell buildings.

Outline

- Introduction to ITER and justification for the need of 1 MGy rated rad-hard components
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Two specific issues that need attention in terms of rad-hard technologies relate to viewing in space constrained environments and to umbilical cables:

- 1 MGy-rated tube cameras are available on the market, but their dimensions are not compatible with some RH tasks where space for viewing devices is very limited. In particular, there are pipelines in narrow spaces that require small cameras installed on board of pipe tooling and/or the manipulator arm(s) holding these tools (left image).
- Due to high number of sensors/actuators, cable number in the umbilical harness (right image) is problematic. Multiplexing on board would greatly reduce the number of signal cables.
Outline

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Rad Hard Camera development

Market survey

- **Smallest** (dimensions diam 29x79, total dose 1kGy)
  Mirion- IST-REES DOTCAM HR

- **Lightest** (0.2 kg), (diam 43.5 x 80, total dose is 70 kGy)
  VISATEC VT CMOS RC2 Video Camera

- **The non-tube most tolerant**, total doses are 100 kGy
  Diakont RAD-HARD SOLID STATE / STAR CAMERA (diam 100 x 380)
  ECA VS 390 N APS (diam 90 x 200)

- **The smallest x most tolerant** (>100kGy, diam approx. 30mm) (but tube):
  Centronic Raditec CR224 (3MGy, diam 34 x 200)
  IST-REES R95 MX3 (2MGy, diam 40.5x217)

Rad Hard Camera development

Phase 1

- **Technology chosen**: UMC CIS 180 nm process
- Image sensor:
  - Photosensitive area: 256x256 pixels
  - Split in 8 main areas:
    - 4 pixel types to test different Radiation Hardening Techniques
    - With and without colour filters
  - Analog read-out chain
    - ADC
      - Evaluation circuit
      - Simple ramp architecture
      - 10 bits
    - 20 LEDs MC-PCB for thermal management
    - Monochrome and Colour Versions

Demonstrator:

- Working distance: 100 mm
- Field of view: 20mm
- Monochrome system (3 lenses):
  - Wavelength: 595 nm
  - Glass: Suprasil pure-silica
- Colour system (3 lenses):
  - Glass: Suprasil pure-silica (2 lenses), Schott SF6G05 (1 lens)
Rad Hard Camera development

Phase 1
• Demonstrator sub-component design
• Manufacture
• First X-ray irradiation (Fig. below)…
• Then irradiation up to 1MGy (Co60)

Capturing images of an ITER relevant weld after 1MGy irradiation

Fukushima Research Conference 26-27 November 2018 – Carlo Damiani

Rad Hard Camera development

Phase 2
• CIS Chip design 75%
• Digital chip design Feb 2019
• Manufacture Jul 2019
• Validation Nov 2019

These ASICs are intended to amplify, digitise and multiplex signals from strain-gauge based pressure sensors, temperature sensors and resolvers and to withstand the Maydose levels that are foreseen at ITER e.g. for Divertor RH system.

Fukushima Research Conference 26-27 November 2018 – Carlo Damiani

Rad Hard electronics development

Preliminary and Phase 1 activities
These ASICs are intended to amplify, digitise and multiplex signals from strain-gauge based pressure sensors, temperature sensors and resolvers and to withstand the Maydose levels that are foreseen at ITER e.g. for Divertor RH system.

Fukushima Research Conference 26-27 November 2018 – Carlo Damiani
Rad Hard electronics development
Preliminary and Phase 1 activities

- ASIC design using CMOS technology
- Manufacture
- Test procedure revised by IO (cf. EEE NRC HB Working Instructions)
- Characterization, irradiation @1MGy and post-irradiation tests

Setup for irradiation tests

At the end of Phase 1, we identified the need to incorporate a communication interface to allow its integration into the Remote Handling Control System.

Phase 2

- Selection of a communication standard and interface validation
- Development of a new ASIC
- Implementation of the communication interface

Introduction to ITER and justification for the need of 1 MGy rated rad-hard components

Identification of critical rad-hard technologies for ITER remote maintenance

Progress on the development of rad-hard digital cameras and rad-hard electronics

Outlook to the future steps in the industrialisation of rad-hard components

Outline

- Introduction to ITER and justification for the need of 1 MGy rated rad-hard components
- Identification of critical rad-hard technologies for ITER remote maintenance
- Progress on the development of rad-hard digital cameras and rad-hard electronics
- Outlook to the future steps in the industrialisation of rad-hard components

ASIC architecture:

- Selection of a communication standard and interface validation
- Development of a new ASIC
- Implementation of the communication interface

TID tolerance: >1 MGy
SEL: >100 MeV·cm²/mg
SET/SEU: >60 MeV·cm²/mg

Designed using a commercial CMOS technology
### Rad Hard Camera development

**Future steps**

<table>
<thead>
<tr>
<th>Phase</th>
<th>Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Market survey, Camera sensor, preamps, ADC, spectral measurements, prototype testing for ITER</td>
</tr>
<tr>
<td>2</td>
<td>Camera integration (including power supply, communication, cabling)</td>
</tr>
<tr>
<td>3</td>
<td>Gamma irradiation, Neutron testing/particle testing (TBC), Camera integration (including power supply, communication, cabling), Qualification</td>
</tr>
<tr>
<td>4</td>
<td>Series production</td>
</tr>
</tbody>
</table>

**2nd generation (TBC):**
- HD camera
- Integration of the digital chip (1-chip camera)

### Rad Hard electronics development

**Next and future steps**

<table>
<thead>
<tr>
<th>Phase</th>
<th>Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Construction of test bench that covers motion control of electrical actuators using position sensors transmitted over BISS. To validate:</td>
</tr>
<tr>
<td></td>
<td>- Phase 1: selected BISS architecture &amp; cable length</td>
</tr>
<tr>
<td></td>
<td>- Phase 2: ASICs integration</td>
</tr>
<tr>
<td></td>
<td>- ASIC manufacture &amp; validation:</td>
</tr>
<tr>
<td></td>
<td>- ASIC 1, 2 and 5</td>
</tr>
<tr>
<td></td>
<td>- ASIC 3 and 4</td>
</tr>
<tr>
<td></td>
<td>- Phase 3 Radiation tests (X, Y)</td>
</tr>
<tr>
<td></td>
<td>- ASIC 1, 2 and 5</td>
</tr>
<tr>
<td></td>
<td>- Phase 4 series production (TBD)</td>
</tr>
</tbody>
</table>

### Summary

- Among the various challenges linked to the procurement of the ITER RH systems, there are those specific to the development of rad hard technologies.
- In particular, space constraints require small cameras and reduced-size umbilical cable.
- Development of 1 MGy digital cameras and multiplexers has been launched by F4E.
- The results so far have confirmed there is the potential to meet the requirements of the ITER project.
- After the current phase of design and R&D, we should move towards industrialisation with specialised suppliers.
- The final design of our RH devices will take on board these new technologies.
- We are keeping an eye on other developments for other projects.
5.2 Experiences and lessons in PCV internal remote inspection in Fukushima Dai-ichi NPS

Kenro Takamori
International Research Institute for Nuclear Decommissioning (IRID)

Content: IRID is currently undertaking two major research and development (R&D); “R&D for Fuel Debris Retrieval” and “R&D for Treatment and Disposal of Radioactive Waste.” As to technology development of investigation inside the primary containment vessel (PCV) to identify the fuel debris conditions, several on-site verification tests of the investigation device for Unit 1, 2 and 3 were performed since 2015. They were successful to obtain the image information of inside the PCV including reactor pressure vessel (RPV) pedestal. Specifically, the device for the unit 2 achieved the RPV pedestal lower and captured images that deposits have spread at the RPV pedestal bottom. Previous investigations inside the PCV including the verification test were mainly intended to obtain the image information. Currently, IRID has undertaken development of new investigation devices for further information (Project for Development of Detailed Investigation Technology). They are necessary to enlarge the investigation devices to install sensors for collecting the shape data and for measuring radiation to understand the distribution of fuel debris. The important development factors are technique for establishing access routes to safely insert a larger investigation device into the PCV and various sensors with radiation resistance capability. Prototype devices are being produced for on-site verification tests.
Experiences and lessons in PCV internal remote inspection in Fukushima Dai-ichi NPS

Fukushima Research Conference
“Radiation Hardness and Smartness in Remote Technology for Nuclear Decommissioning”

Nov. 27th, 2018
© Manabinomori, Tomioka, Fukushima, Japan

Kenro TAKAMORI
International Research Institute for Nuclear Decommissioning (IRID)

The results are obtained under the Subsidy Project of Decommissioning and Contaminated Water Management (A) by the Ministry of Economy, Trade and Industry, JAPAN.

Organizational Information of IRID
Research and development of technology for the current, most urgent challenge,
- The decommissioning of the Fukushima Daiichi NPS -

1. Name
International Research Institute for Nuclear Decommissioning (IRID)
http://www.irid.or.jp/en/

2. Date of Establishment
August 1, 2013

3. Membership (18 organizations)
- 2 Research Institutes
  JAEA etc.
- 4 Manufacturers
  Toshiba, Hitachi-GE, MHI etc.
- 12 Electric Utilities, etc.
  TEPCO HD, JNFL etc.

Boiling Water Reactor (BWR) Mark-I

Contents

1. Introduction

2. R&D for Investigation inside PCVs
   (1) Results of completed investigation
   (2) R&D plan for next investigations
Fuel assemblies that constitute the nuclear reactor core, and core support structures had melted due to extreme temperatures of nuclear fuel (residual heat + decay heat) caused by the radioactive cooling function loss. Parts of molten fuel and core structures might have flown out of the RPV and fallen to the PCV.

1. Introduction

2. R&D for Investigation inside PCVs
   (1) Results of completed investigation
   (2) R&D plan for next investigations
An example of required specifications for the PCV investigation

<table>
<thead>
<tr>
<th>location, condition</th>
<th>inside PCV</th>
<th>outside PCV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brightness</td>
<td>dark</td>
<td>–</td>
</tr>
<tr>
<td>Water level</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Gamma dose rate</td>
<td>inside pedestal</td>
<td>outside pedestal</td>
</tr>
<tr>
<td>pressure</td>
<td>1~6 kPaG</td>
<td>atmosphere</td>
</tr>
<tr>
<td>temperature</td>
<td>17~35°C</td>
<td>–8~40°C</td>
</tr>
<tr>
<td>humidity</td>
<td>100 %RH</td>
<td>10~100 %RH</td>
</tr>
</tbody>
</table>

Remote operation

- **Prevention of the spread of PCV contamination**
- Inputting and retrieval of survey equipment is possible only when the boundary secured.
- Utilization of the existing PCV penetration.

- **Reduction of the work exposure**
- Large boundary work results in more exposure.
- The survey equipment must be operated from outside the reactor building.

- **For the initial quick look, a 100mm spare PCV penetration was used.**
- less work exposure
- easier to maintain the boundary
- small ROV <100mm dia.
- Limit of spec.
- Power supply, control and communication by cables.
- less run ability, range of access, loading capacity

Investigation experiences using robots inside PCV

- Investigating spreading of fuel debris and damaged conditions in the PCV.

  - **Outside pedestal in Unit 1 PCV**
    - Investigating by moving on the grating to install dosimeter with camera under water

  - **Inside pedestal in Unit 2 PCV**
    - Direct entry of pedestal opening through CRD rail

  - **Inside pedestal in Unit 3 PCV**
    - Applying a submersible robot due to high water levels
    - Landing on the water and then submersing from inlet of pedestal into the PCV

Investigation inside PCV (Robots)

- **Outside pedestal unit #1**
  - Shape-changing robot
  - In going through a pipe
  - In moving on a plane surface
  - Camera & lighting

- **Inside pedestal unit #2**
  - Self-righting mechanism
  - Shape-changing robot
  - Inside pedestal opening through CRD rail
  - Camera & lighting
  - Dosimeter
  - Thermometer
  - Crawler

Requirements for radiation resistance

- 100 Gy/h
- Cumulative 1 KGy
**Unit #2, inside pedestal (A2 robot)**

- **Video observation**
- **Jan-Feb, 2017 (Planned)**

### Process

1. Pre observation
   - Camera overview
   - Lighting
2. CRD rail clean up
   - Camera, backward
3. Access
   - Crawler

---

**Investigation at Unit #2**

**Inside the pedestal (after processing image data)**

**Viewing angle:** 80

**Image list:** 

**Image index:**

Pedestal area below RPV

**Before the accident**

---

**A2D extension rod with cameras**

**Overview of the tip of investigation device**

- Tilt axis
- Pan axis
- Tamper / jamming prevention skirt
- Camera
- Lens assembly
- Illumination
Investigation Results on January 19, 2018

- Pebble and/or clay-like deposits were confirmed at the whole of the pedestal bottom.
- Deposits were confirmed at the pedestal bottom where parts of fuel assemblies (upper tie plates) had fallen. The deposits were estimated to be fuel debris.

Overview of unit 3 submersible ROV (mockup device)

- Thruster for driving
- Neutral buoyancy cable

Item Specifications

- Outer size: d129mm
- Overall length: approx. 300mm
- Weight: approx. 2000g (in air)
- Radiation resistance: 2000 Gy
Investigation of Unit 3 inside the pedestal

- Investigation method: Photo shoot by camera
- Commencement: July 2017

1. Access from a piping penetration (X-53 penetration) to enter the pedestal. Confirm damage conditions of the platform and the lower CRD.
2. Confirm the access route to the basement of the pedestal.
3. Confirm conditions of debris accumulated at the pedestal bottom and spreading from the access opening for workers to outside of the pedestal, if it is possible to enter the basement floor.

Penetration of unit #3 ROV entry

Guide pipe cable sending device
Isolation valve
Guide pipe
PCV shell

Mock up test

Mock up test
Investigation at Unit 3: Pedestal and Underwater

- Molten materials were confirmed, which may have been solidified at the lower part of the pedestal and on the structures inside the pedestal.


Robot Investigations inside PCV: Example of Technical Issues

- High radiation environments management
  - ~ several + Gy/h, accumulated dose ~ several hundred Gy
  - High-radiation-resistant electric device, measurement device and applicable camera
  - Confirmed by an irradiation test and verifying measurement errors

- Ensuring the primary containment vessel (PCV) boundary
  - Size of robots < Diameter of a penetration opening (running performance and restrictions of mounted equipment)
  - Additional installation of isolation valve, sealing mechanism and nitrogen pressurization control
  - Cable feeding mechanism unitized in chamber, robots
  - Connection with on-site construction and reduction of work dose rate at the installation site of the PCV outside device.
Robot Investigations inside PCV: Example of Technical Issues

- **Cable and cable management**
  - Random winding prevention, interference avoidance and robot management in case leaving it inside.
  - Cable weight < Traction force of robot (restricting the scope of investigation)
  - Cable size / properties [power, control and communication]
  (Restricting mounted equipment)

- **Operation**
  - Running performance adapted environments (damaged)
  - Self-location confirmation method, bird’s eye camera, rear camera and utilizing landmarks
  - Complete training and actual mock-up test

Primary Containment Vessel (PCV) Investigation in the Future

- Previous investigations mainly focused on obtaining images.
- A larger access device has been developed to obtain more information.

- Future needs
  - Work and removal of obstacles
  - Identification and Sampling of fuel debris
  - Radiation resistance for longer time

Example of Investigation Needs for Design

- **Debris retrieval design**
  - Access/transport design, cutting method and collection method
  - Location of fuel debris: Extent of spread, distribution and amount
  - Hardness, cutting properties
  - Distribution of dose rate and intensity of radiation

- **Retaining sub-criticality**
  - Sub-criticality retaining design
  - Fuel debris properties: Nuclear fuel concentration, distribution and amount
  - Neutron absorbent concentration: B, Gd concentration
  - Moderator distribution: Water levels and water content in debris

- **Radiation dust control/purification**
  - Leakage control design
  - Fuel debris properties: Process cutting) dust ability, solubility, collecting property and concentration of radioactive materials
**Investigation Technology**

- **Debris detection technology**
  - CdTe semiconductor
  - B10 detector
  - ...

- **Shape measurement technology**
  - Scanning ultrasonic distance meter
  - Laser light cutting method
  - ...

**Boat Type Access Device**

- A boat type access device has been developed, which can move on a wide range of the water surface in the primary containment vessel (PCV).

  Example: Guide ring installation
  - Diameter: ø2.5m
  - Length: Approx. 1.1m
  - Thrust: Over 25N

**Fuel Debris Detection Technology**

- Developing radiation measuring technology for detecting depositions of fuel debris that was confirmed by the previous investigations.

- Ensuring fuel debris detection, using both of Eu-154y rays detector (CdTe semiconductor detector) and thermal neutron detector (B10 detector).
Shape Measuring Technology

- Development of shape measuring technology (scanning ultrasonic distance meter)

![Image of shape measuring technology]

PCV Penetration Hatch Opening

- PCV penetration (X-6 penetration) opening
- Technology for X-6 penetration opening has been developed to insert the arm access device.
  - Confinement function during a hatch opening.
  - Remote-operated hatch opening

![Image of PCV penetration hatch opening]

PCV investigation summary

- Success, obtained
  - Maintain boundary
  - Remote operation
  - Function under high gamma dose rate
  - Cable managing
  - PCV, pedestal video acquisition
  - Retrieval of ROVs

- Subjects
  - Identification of fuel debris
  - Limit of spec, Run ability, Range of access,
  - More loading

- Expectations for next investigations
  - Larger penetration for larger ROV, wider range of access and more variety of measurement instrument

Arm Type Access Device

- An arm type access device has been produced, which can access on a wide range through the penetration of the primary containment vessel (X-6 penetration) for control rods maintenance.
  - Total length of the arm: Approx. 22m
  - An investigation device up to 10kg can be loaded.

![Image of arm type access device]
Recent developments in radiation detection and imaging in combination with the enormous advances in sensing technologies and associated data processing capabilities enable unprecedented and “smarter” ways to detect, map, and visualize radiation to ultimately enhance safety for operators, the public, and the environment. The accident at the Fukushima Dai-ichi Nuclear Power Plant (FDNPP) and its immediate and persistent impact and challenges locally and globally clearly illustrate the need for more effective means in the assessment and mapping of radiological materials: In the immediate assessment to inform the emergency response and in the long-term assessment to inform the decontamination, decommissioning, and remediation efforts. The assessment of highly radioactive materials which can be found within the reactor buildings and pressure vessels pose additional challenges requiring technologies that can operate in very high dose rates and harsh environmental conditions. In all these circumstances we need to ensure to utilize all available knowledge, to be able to adapt and learn from the accident and actions taken (or not taken), to exploit scientific and technological advancements across all relevant areas, and to integrate all these aspects to create smarter systems and processes. We introduce the recently developed concept of 3-D Scene Data Fusion (SDF) which utilizes advancements in radiation detection and imaging and computer vision that provides smarter means specifically for the assessment of complex radiation fields which are inaccessible to human operators. Not only can SDF be utilized with any radiation detection and imaging systems, it can be deployed on almost any platform, including unmanned ground systems – i.e. robots – and unmanned aerial systems - i.e. drones.

### Introduction

The assessment, clean-up, and decommissioning of the Fukushima Dai-ichi Nuclear Power Plant (FDNPP) remain an enormous challenge, even now, 8 years after the accident induced by an unprecedented combination of the Tohoku Earthquake and the subsequent tsunami. One of the main challenges is associated with the enormous radiation dose-rate levels that can be found in the three damaged reactor buildings and particularly in the Pressure Containment Vessels (PCVs) which contain the fuel debris. Location, shape, and composition of this debris is still not known. New and more radiation hard sensors and deployment platforms are required that can be remotely operated to assess the debris. In addition to radiation hardness, smarter systems and processes need to be developed and utilized to enhance the effectiveness and safety as well as to reduce the costs and duration for the decommissioning of the three reactor units and ultimately, the whole FDNPP facility.

In this paper, we will discuss the meaning of radiation smartness and will discuss the concept of 3-D Scene-Data Fusion (SDF) which we developed at Lawrence Berkeley National Laboratory (LBNL) over the last several years and demonstrated in diverse environments, ranging from
Radiation Smartness

Smartness is the capability of independent and apparently intelligent action and is characterized by quickness and ease in learning. Being smart can mean bright, witty, or clever but always knowledgeable [1]. In contrast to intelligence, smartness is an earned status requiring study and learning. Common examples range from objects to subjects: Smart cars, cards, electrical grids, bombs or missiles, sensors, or animals and humans. Being smart enables the achievement of specific goals and objectives more effectively, or in other words in a faster, more accurate, safer, and cheaper way.

Radiation smartness does not refer to the smartness of radiation – radiation is the physical phenomenon describing the propagation of energy - but refers to the goal of developing smarter systems to sense and process radiation and smarter methods to enable the utilization of these systems for challenging problems, such as the assessment and decommissioning of FDNPP and its complex technological but also societal and political challenges.

In order to achieve smartness, one has to be cognizant of what has been observed and learned in the past and to apply this knowledge to adapt and utilize new findings and predictions across multiple fields of science and engineering. In the following, we will discuss the development and demonstration of a technology that allows the effective utilization of advanced technologies enabling smarter ways to assess complex and hazardous radiation environments in faster, more accurate, and most importantly, in safer ways. SDF combines recent developments in radiation detection, such as Elpasolite scintillators [2], room-temperature operational semiconductor detectors [3], and hand-portable gamma-ray imaging systems, including commercial systems such as Polaris from H3D [4] and GeGi from PHDs [5], as well as advanced laboratory prototypes such as HEMI and PRISM developed at LBNL [6,7] and the enormous advances in computer vision that enable autonomous or remotely controlled operation of unmanned platforms. For example, smart autonomous or driver-less cars are based on advanced sensor technologies that provide large amounts of data about the local environment and the state of the car and computer processing power to utilize the data to estimate and predict the location of the car in this environment, as well as to classify objects in the car’s environment to inform continuous autonomous decision making (i.e. obstacle avoidance). However, not only do these developments allow advanced sensing and computer processing capabilities for autonomous systems, they also enable new means to fuse and visualize data products through augmented or virtual reality technologies. Radiation smartness is based on these advances as well, enabling new means to operate and track ground-based, aerial, or even underwater platforms and to sense, map, classify, and visualize complex and hazardous radiation environments. 3-D Scene Data Fusion utilizes these concepts to provide new means to operate platforms and to map and visualize scenes, as well as fuse radiation fields into the scenes in three dimensions and in real time. This smart way to use radiation detection and imaging systems provides unprecedented means in radiological search and characterization scenarios, as well as for emergency response, consequence management, decommissioning, and remediation applications in complex environments. SDF increases the efficiency, effectiveness, and safety of the operation.
of radiation detection systems, and provides detailed and visual data products that can streamline communication with all stakeholders, including general members of the public.

3-D Scene Data Fusion

Most radiation mapping systems in use today consist either of non-imaging radiation detection instruments equipped with a GPS or of a radiation imaging instrument that is deployed statically, i.e. not moving. The former method is limited because it only measures the radiation levels at or on the detector itself, while the latter is limited due to the lengthy set up and extended measurement times and limited range that can be covered as a result. These mapping systems also only produce two-dimensional (2-D) images or 2-D radiation projections. The left side of Fig. 1 illustrates a state-of-the-art 2-D image overlaid with a visual image obtained in 2014 in a parking lot in an evacuated area of Fukushima Prefecture. The LBNL-developed, hand-portable High-Efficiency Multi-mode Imager (HEMI) produced this image of Cs-137 contamination concentrated in bushes from a stationary measurement. The 2-D heat map produced by HEMI provides useful information about higher radiation levels on the ground, with lower radiation levels towards the sky and the high concentration of radiation levels that can potentially be associated with a bush. However, the 2-D map is limited in that it is not clear where the Cs-137 is concentrated; it could be concentrated within, behind, or in front of the bush or on the ground underneath the bush. In contrast, on the right side of Fig. 1 an image is shown that was also produced by HEMI but in combination with the 3-D SDF during a mobile measurement (i.e. white line in the figure indicates the path the user walked around the container) [8-16]. It shows a reconstructed scene in 3-D with a Cs-137 source localized also in 3-D within a container in the middle of the room. Instead of only being able to determine the 2-D location, SDF provides 3-D coordinates of objects and is based on the ability to

![From conventional static 2D imaging to dynamic 3D volumetric imaging](image)

*Figure 1 Illustration of current approach of “planar” gamma-ray imaging with gamma-ray visual overlay in two dimensions (left) and “volumetric” gamma-ray imaging or scene-data fusion based with full fusion of contextual and gamma-ray image data in three dimensions. The three coordinates represent the location of the detected source in the container with regard to an arbitrary but fixed coordinate system provided by the localization and mapping algorithms utilized.*
move the gamma-ray imaging instrument, such as HEMI, freely through a scene, to map and reconstruct the scene, to track the position and orientation of the instrument automatically, and ultimately to fuse the scene data with the radiation data in 3-D in real-time, while the instrument is being moved through the scene.

The SDF concept enables gamma-ray imaging to be performed from a moving platform without requiring the lengthy setup needed to co-register (or sync the location of) the instrument and the scene, resulting in faster and more accurate measurements of 3-D environments with real-time observations and almost instantaneous feedback. Fig. 2 shows the hardware components that have been used for the development and demonstration of SDF for measurements in Japan, Ukraine, and across the U.S. SDF can be employed in combination with commercial radiation detectors and radiation imagers or in combination with custom-made gamma-ray imagers, such as HEMI and PRISM. The contextual sensing and mapping of the scene can be performed with a variety of sensors, as well, including the MS-Kinect, LiDAR range finding instruments, or visual cameras. These sensors can be complemented with GPS/IMU to support the mapping and tracking of the instrument.

![Figure 2: Examples of hardware components and platforms that can be used with the 3-D SDF concept.](image)

SDF is characterized by its versatility and flexibility with regards to the ability to integrate with various combinations of radiation detection or imaging instrument, contextual sensor, and deployment platform. As illustrated in Fig. 2, SDF-enabled systems can be operated in a hand-
portable format, on Unmanned Ground Vehicles (UGVs), Unmanned Aerial Vehicles (UAVs) or on manned cars, trucks, and helicopters. In this way, SDF can be widely applied for scenarios ranging from search of nuclear materials to consequence management and decommissioning. While the former is generally associated with weakly and potentially shielded sources where radiation backgrounds impact the detection capabilities, the latter is generally associated with very high and complex 3-D radiation fields where background radiation is irrelevant. It is important to note that SDF can be deployed for gamma-ray detection and mapping as well as for neutron detection and mapping.

Figure 3 Steps in the creation of fused 3-D scenes, from the actual cluttered scene (left) to the mapped 3-D scene model with the reconstructed path of the instrument (middle) and the 3-D scene fused with the reconstructed radiation data (right). For this demonstration a HPGe-based gamma-ray imaging instrument mounted on a cart equipped with the MS Kinect was used. List-Mode Maximum Likelihood Expectation Maximization image reconstruction was used with the reconstruction constrained to the point cloud created by the structured light sensors.

The major advances underpinning the development and realization of 3-D SDF can be found in computer vision, radiation (image) reconstruction, and data fusion algorithms, altogether enabling real-time mapping and visualization in 3-D. Fig. 3 illustrates the data processing steps employed to produce the 3-D image of the scene, to estimate the position and orientation of the instrument, and to reconstruct gamma-ray events and fuse the complementary data to represent the fused 3-D scene. Being able to restrict the reconstruction to point clouds and only occupied voxels reduces the image reconstruction time and improves the accuracy in the reconstruction. It is worth mentioning that the reconstruction does not have to be constrained to specific points, pixels, or voxels and can therefore reconstruct source locations inside or outside of objects. Fig. 4 shows the hand-portable HEMI instrument which consists of two planes of coplanar grid (CPG) CdZnTe (CZT) semiconductor detectors in combination with a contextual sensor for range finding. The backplane consists of a fully populated 8x8 array of 64 1cm³ detectors, while the front plane consists of a half-populated array of 32 detectors with gaps in between forming a pseudo-random coded aperture mask built of active detector elements. In this configuration, HEMI can be operated in coded-aperture based gamma-ray imaging mode for gamma rays below 400 keV and in Compton imaging mode for higher energies [17]. It represents a very compact and light-weight yet very sensitive gamma-ray detection and imaging instrument that is hand-portable. The weight of the instrument, including a battery to operate the radiation detection instrument for several hours, is about 3 kg.
To illustrate the power of source localization with SDF in comparison with static imaging, two measurements were performed with the goal to localize a 20 uCi Cs-137 source in our lab (Fig. 5). HEMI integrated with SDF and a MS Kinect sensor was walked through our lab and within 45 s, we were able to detect and localize the source in the correct location in 3-D. Only 95 events were required for localization within 10 cm which, represents the voxel size used for this experiment. A second spot can be seen in the 3-D image, which reflects some image noise induced by the small number of reconstructed events. In contrast, placing HEMI in the middle of the 8x8 m² area and taking measurements in this static configuration, after one minute, we only produce a blurry image. It takes about 20 min to obtain a clear image with the correct location. Instead of 95 events, 985 events were needed, ten times more than in the mobile implementation. The main reason for this gain in sensitivity is due to the ability to move the instrument closer to the source during the measurements and - albeit only temporarily – to overcome the 1/r² flux dependence. The ability to reduce the image space to 3-D voxels reduces the number of events needed to achieve high accuracy. In addition, static measurements only provide a two-dimensional angular location.

The discussion so far has introduced the concept of 3-D SDF based on measurements with HEMI and the MS-Kinect. We will in the following show more relevant examples from measurements around the world performed with HEMI and other radiation detection and imaging instruments in combination with other contextual sensors, particularly LiDAR. While we initially developed the concept with MS-Kinect due to its low cost, capabilities, and available open software to access the data from the structured light and visual camera, all measurements we have been performing since 2015 are either with LiDAR or with visual camera-based photogrammetry, as the MS-Kinect is limited to indoor environments and a tracking range of 1-6 m.
Figure 5 Top right: Detection and 3-D localization of a single Cs-137 point source in our lab. Shown is the final reconstruction from walking around in the scene. The estimation for the Cs-137 source location improves as more data is collected. The blue arrows are the Compton events used in the reconstruction, the line is the path of the detector in the scene, and the white circles are the location of the cone vertex. The total measurement time was about 40 seconds and only 95 events were used for the gamma-ray reconstruction. Lower row: Illustration of static 2-D Compton images of the Cs-137 source with a visual overlay of the lab scene. The left image shows the image after one minute with 58 events. The right image shows the image after 20 minutes and 985 events.

SDF Demonstrations in Real-world Environments

In the following, we will discuss a few examples of SDF from demonstrations and measurements in various real-world environments within the U.S., in Fukushima, Japan and in Chernobyl, Ukraine. A wide variety of measurements have been performed, specifically for nuclear safeguards and radiological search applications, however, we will focus on a selection of examples which further illustrate the power of SDF, including mapping of contamination in Fukushima Prefecture and Ukraine. SDF allows the effective mapping of contamination, the verification of decontamination activities, and the monitoring and detection of potential re-contamination in different urban and non-urban environments and the contamination on objects such as vehicles.

While we focus in this section on the mapping of extended sources associated with the accidental releases of radioactivity into the environment, we start with an example to illustrate the ability of SDF to detect and localize sources in container stacks in 3-D (Fig. 6). Detecting and localizing radiological sources in transport containers, for example at ports, represents an important challenge in nuclear security. While the sources can be detected with a non-imaging system by walking around the containers, the ability to determine the location of the container with the source and the location of the source within the container will significantly reduce the secondary inspection time required to search for and remove the source from the container; this will significantly minimize
disruption to port operations and reduce impacts to U.S. commerce. Utilizing SDF in combination with HEMI and a LiDAR sensor, the container stack consisting of 16 containers were mapped and the three sources were detected and accurately localized within 2 minutes by walking around the containers.

Figure 6 The detection, identification, and localization of 3 point sources in an outside scene with a stack of cargo shipping containers (left). All three sources were detected and localized in their 3-D locations by employing SDF with HEMI and a visual camera. The visual camera was used to create the point cloud and to estimate the pose of the instrument during the path around the containers as indicated by the white line. The containers were voxelized and the gamma-ray images reconstructed into the 3-D voxels providing the accurate localizations of the sources.

Figs. 7 and 8 show results of contamination mapping measurements around and inside a home in Fukushima Prefecture in 2015. These results were obtained with HEMI in a hand-portable configuration in combination with a visual camera. The house is located several km northwest of FDNPP and became contaminated due to the wind direction and precipitation during and after the releases of radioactive materials at FDNPP in March 2011. Most of the radioactive contamination was Cs-137 at that time with Cs-134 still easily detectable; however, with lower activity as expected by the shorter half-life.
In Fig. 7, we show different perspectives of the contaminated home reconstructed from the measurement while walking around the house, including the colorized point-cloud reconstruction and the fused Cs-137 intensity reconstruction onto the point cloud. The decontaminated front of the house is clearly visible, as well as the remaining contamination behind the house and on the roof. Specifically, the hot spot on the roof is of interest, as it had a dose rate of about 6 μSv/hr at this location (associated with an annual dose of about 50 mSv), clearly indicating the need for further decontamination efforts. The higher dose at this location may be explained by the foliage on top of a gutter which accumulated the Cs-137 from the rain that fell after the releases. This measurement illustrates several important aspects: SDF can be used to effectively map contamination at levels that are relevant to inform clean-up and resettlement both in the short and long-term, as it can be used to map and identify contamination even years after an event and allows the visualization of radiation fields in a way that is easier for residents and non-scientific officials to understand. One of the challenges in these environments with distributed contamination is the lack of ground-truth, i.e. the lack of quantitative activity distributions of Cs-137. Our measurements only indicate measured intensities with uncertainties in the quantification of actual surface emission rates, masses of Cs-137, or dose-rates in remote locations. We are currently developing improved methods to estimate relevant quantities of radioactivity and associated uncertainties.

Fig. 8 shows a reconstructed bedroom in the same house. The Cs-137 radiation map serves as a visual guide that makes it possible to see and track the location of contamination inside this room. Specifically, the radiation map on the left indicates increased radioactivity in a hole in the ceiling.
where it is likely that contaminated rain water leaked into the room, flowed down the walls or dripped down to the floor and accumulated in the mattress on the floor. This figure also shows that even four years after the FDNPP accident, we are still able to reconstruct the contamination and possible flow pattern of the radioactivity.

![Indoor 3D nuclear radiation mapping](image)

**Figure 8** Reconstruction of a bedroom in the contaminated and evacuated home in Fukushima Prefecture. Left: Colorized point cloud from the MS Kinect indicating the cluttered environment in this room reflecting the impact of the earthquake and the hurried evacuation of the residents. Right: Fused image showing the reconstructed distribution of Cs-137 in this room. The orange contour at the top of the image indicates a higher concentration of radioactivity from a potential leak in the ceiling. Based on this distribution, one can assume that rain water contaminated with Cs-137 leaked through the damaged ceiling and flowed along the walls to the floor ultimately accumulating in the mattress in the middle of the room.

Fig. 9 shows results of measurements from other locations in the exclusion zone within Fukushima Prefecture to illustrate the utilization of SDF to map radiological contamination over larger areas. All the measurements were performed with HEMI in combination with a LiDAR sensor in hand-portable configuration while walking around buildings and parking lots. The figure on the left includes – similar to Fig. 8 – the decontaminated area in front of a house composed of three buildings with dose-rate levels <0.4uSv/hr and the area behind these buildings which was not decontaminated with radiation levels of up to 4 uSv/hr. The middle figure shows the ability to effectively detect and identify hot spots in a large area encompassing front and rear parking lots around a building which had been previously decontaminated. The figure on the right side also illustrates the ability to map contamination quickly over large areas.
Figure 9  Top-down views of 3-D point clouds and radiation maps in evacuated urban areas in the Fukushima Prefecture. The contaminated and decontaminated areas are clearly visible. The measurement times in these areas were always less than 20 min with the hand-portable HEMI system.

While the mapping and visualization of contamination inside and outside of homes or more broadly in urban and residential areas is critical to inform decontamination and verification activities before residents return home, it is also important to map radioactivity in environments adjacent to urban areas that are accessible to humans and animals and therefore of risk to increased radiation exposure or cross-contamination. For example, it is important to assess forested and other undeveloped areas to estimate potential contamination from these areas flowing into urban and residential areas and potentially recontaminating these areas. Fig. 10 shows an example of mapping contamination in a bamboo forest, also located within the exclusion zone in Fukushima Prefecture. The mapped area represents a slice of about 80x20 m² and shows the reconstructed trees and ground with the Cs-137 contamination localized predominantly on the ground. It shows a contiguous contamination with higher contamination in some areas, specifically towards one end and in depressions. It is important to note that the advantage of using a 32-beam LiDAR sensor is the creation of dense point clouds resulting in the mapping and registration of all trees in this forest. The whole measurement at walking speed took less than 15 min and required two paths.
Figure 10 Fused nuclear scene maps in a contaminated bamboo forest in the Fukushima Prefecture. The bamboo trees with 10-20 cm diameter as well as bushes and ground structures are clearly discernible. Contamination can be identified to be Cs-137 and Cs-134 in some areas on the ground. The original full map includes buildings located on one side of the forest but was removed to enhance the visibility of the contamination in the forest. The measurement took less than 15 minutes walking back and forth through the forest.

An additional advantage in this specific measurement and in the creation of 3-D digital maps is the ability to remove objects which would limit the visualization of specific areas of interest. For example, buildings on one side of the forest were removed digitally to provide an unobstructed view of the forest.

Figs. 6-10 were produced using a mobile and hand-portable gamma-ray imaging system in combination with a LiDAR sensor. Fig. 11 shows an example where a portable gamma-ray imaging system was fused with a 3-D surface created by photogrammetry – or more specifically stereophotogrammetry – utilizing the visual camera on board of the SDF system. While photography is inherently a 2-D imaging modality, utilizing many different angles or projections of an object enables the creation of a 3-D digital model of this object. The object shown in this figure is a large crane claw located close to the Chernobyl Nuclear Power Plant (ChNPP) in the Exclusion Zone in Ukraine where a major nuclear accident happened on April 26, 1986. This claw was used to remove the fuel debris from the reactor unit 4 shortly after the accident. The dose-rate levels inside and underneath of the claw are still in the order of 100’s of uSv/hr, mainly driven by Cs-137. The left-hand side of the figure shows the reconstructed 3-D model of this claw, including the radiation sign and truck tires behind the claw. The right-hand side shows the fused image based on the Cs-137 gamma-ray reconstruction at 662 keV. Most of the Cs-137 radioactivity can be seen inside and underneath the claw, consistent with separate dose-rate measurements. These 3-D fused images demonstrate the ability to detect and map contamination on 3-D objects which could be utilized for contamination mapping and monitoring on other objects in Chernobyl or in Fukushima, specifically in the assessment of contamination of vehicles on the FDNPP site.
Figure 11 Model of the crane claw located close to the ChNPP in Ukraine. The left model was reconstructed via photogrammetry using visual camera data and served as the basis for the right model, which shows a fused model with the reconstructed gamma-ray imaging data provided by a commercially available and hand-portable instrument integrated with SDF. The image was created for 662 keV associated with Cs-137. One can easily see that most of the Cs-137 radioactivity is inside and underneath the claw. Behind the claw, two stacked truck tires are clearly visible.

All the measurements discussed so far were performed with gamma-ray imaging instruments, such as HEMI, in a hand-portable configuration. Over the last two years, we have integrated SDF with a range of other laboratory prototype and commercial radiation detection and imaging systems such as the CZT-based Polaris system manufactured by H3D or the HPGe-based GeGI system manufactured by PHDs. All the 3-D fused scenes were obtained by walking the instrument through the environments of interest. However, in many missions and environments, human operation should be avoided to prevent hazardous levels of exposure to radiation or other risks. In addition, in many circumstances, radiological search and mapping needs to be conducted in physically inaccessible areas. Deploying SDF-integrated systems on unmanned platforms will enable safe and efficient operation in such areas.

We conclude this section of examples for 3-D SDF with two specific implementations on a ground robot and on an UAS, highlighting the versatility of this concept and the ability to map 3-D radiation fields fused with 3-D scenes in real-time on remotely operated, unmanned platforms. The left-hand side of Fig. 12 shows the Localization and Mapping Platform (LAMP) equipped with 4 CsI detectors and mounted on a Talon IV UGV. LAMP is a compact, self-sufficient package that contains a single-board computer, batteries, data storage, power control, and interfaces, that can be connected to internal and external sensors, including various configurations of radiation detectors and contextual sensors. It provides an autonomous and platform independent realization of 3-D SDF [18]. As shown in Figs. 12 and 13, LAMP with the attached detectors and sensors can easily be mounted and operated on various unmanned platforms. Mapping, tracking, image reconstruction, and data fusion calculations are performed on the computer in LAMP and only...
data products are transferred via WiFi or other means of wireless communications to the user in near real-time. This figure shows a top-down view of the reconstructed outline of a building with a detected and localized Cs-137 point source. The right-hand side shows the LAMP system equipped with the same contextual sensors, e.g. LiDAR, visual camera, and GPS/IMU but equipped with a single LaBr gamma-ray detector. The LaBr allows operations and gamma-ray energy measurements, i.e. gamma-ray spectroscopy – at rates of $>10^6$ cps, which can be associated with a dose rate of 10’s of mSv/hr on the detector. The specific measurement shown was a deployment in a tunnel with the objective to find and localize radiological sources within the tunnel. The Co-57 and Cs-137 sources were accurately detected and localized within the reconstructed 3-D model of the tunnel.

The final example in Fig. 13 illustrates the operation of LAMP with 4 CsI detectors on board on an UAS, specifically the Matrice-600 manufactured by DJI. The man-controlled flight around the three-story building took about 13 min and resulted in the reconstruction of all buildings in the vicinity of up to 100 m consistent with the range of the LiDAR and the accurate detection and localization of a Co-60 source in the corner room of the 3rd floor in one of the buildings. Other means of ground-based deployments would have taken significantly longer than the 13 min flight time and only SDF enables the integration of the radiation field and the location of the source in 3-D within the building. Similar to the deployment of LAMP on the UGV, the deployment of the UAS was done with non-imaging radiation detectors, still resulting in the localization of the sources in 3-D. This is enabled through proximity imaging or localization utilizing the underlying $1/r^2$ dependency of the distance between the source and the moving detection platform. While the
use of gamma-ray imaging systems provides higher resolution and sensitivity in the localization of radioactive sources, even non-imaging instruments can be used to localize compact sources, particularly when SDF is being used in the reconstruction.

Figure 13 Figure 14 LAMP in combination with a 2x2 CsI array mounted on a DJI Matrice-600 while flying around a building. The data product on the right shows the reconstructed model of the building (and other buildings) and the reconstructed radiation field fused with the surface of the building pointing to the location of the Co-60 source in the correct corner of the building. The blurred image reflects the overall radiation field which is dominated by the scattered radiation in the concrete wall and the limited spatial resolution of the instrument which localized based on proximity and not based on properly imaging.

Recent Advances
We have been pursuing improved ways to realize compact gamma-ray imaging systems to overcome some of the limitations of HEMI and other commercial gamma-ray imaging instruments. Conceptually, HEMI represents a “smart” way to realize a compact system that provides gamma-ray imaging over a broad band of energies, e.g. from about 50 keV to several MeV only using active detector elements. This is due to the arrangement of the 1 cm³ CZT detector elements in two planes providing coded-aperture imaging for low energies and Compton imaging for high energies. All commercial instruments which provide low-energy imaging capabilities are based on passive, heavy metal masks which reduce the overall detection efficiency and add to the weight of the instrument. One of the drawbacks of HEMI (and all the other passive coded-aperture-based imaging instruments) is the limited Field-of-View (FOV) for coded-aperture imaging as the radiation can only be modulated from the side of the mask due to the parallel arrangement of mask and detector array. In contrast, the Portable Radiation Imaging Spectroscopy and Mapping system (PRISM) – a laboratory prototype recently developed and fabricated at LBNL – is based on a spherical arrangement of the same CZT detector elements and provides unprecedented omni-directional coded-aperture imaging with only active elements. It maintains the advantage of only active detector elements associated with the best possible sensitivity-to-weight ratio like HEMI but enables omni-directional gamma-ray imaging for all energies. Fig. 14 shows the rearrangement of the HEMI detector elements onto a sphere using the same number of 96 1 cm³ detector elements and the associated increase in the FOV. The basis for this realization is the ability to utilize all detector elements as mask and detector element simultaneously so that any incident direction can produce a unique pattern on the opposing side of the incomplete set of detectors.
Figure 14 Left: “Morphing” of HEMI to PRISM; The rearrangement of 96 cubic detector elements from two planes to a sphere enabling $4\pi$ coded aperture imaging and improved $4\pi$ Compton imaging performance as well due to the isotropic distributions and the increased mean distance of the detector elements. Right: Illustration of the increase in the FOV of the spherical PRISM arrangements in comparison to HEMI.

Fig. 15 shows components and views onto and into of the spherical arrangement of the detector modules and the fully functional prototype PRISM which contains all necessary parts and components for 3-D SDF in a stand-alone package. The number of detectors in the arrangement can be adjusted to optimize the trade-off between image resolution and overall detection sensitivity. Currently, PRISM is populated and operated with 120 CZT detectors in coplanar grid configuration and depth-of-interaction (DOI) readout. DOI is obtained by the ratio of the anode and cathode signal amplitudes. Other means to determine the DOI are possible, such as using the time difference of these two signals or only by using specific combinations of the coplanar grid signals. DOI significantly enhances the coded-aperture imaging performance since it provides additional information about the potential incident direction of the gamma radiation. The spherical arrangement of the detector elements and the DOI readout improves the angular resolution and imaging efficiency for Compton imaging, as well. We recently demonstrated the ability of PRISM to map low-energy gamma-ray sources in 3-D with SDF [7].

In summary, recent advances in computer vision along with developments of compact gamma-ray imaging instruments enable new and smart ways to assess radiation fields that are relevant for a wide range of challenges, including nuclear security and safety, and particularly in the search and mapping of radiological materials. Not only do these advances enable smarter ways for detection and mapping in itself, they enable the introduction of smarter processes in the assessment and monitoring of radioactivity in areas of interest, specifically when combined with unmanned ground and aerial platforms. For the decommissioning of FDNPP, these advances provide smarter means and more effective and safer ways to assess the high radiation fields that can be found in the PCVs, as well as in the reactor units and turbine buildings. It also provides more effective means to
monitor radiation fields and dose rates across the whole site and in the assessment and monitoring of contamination of objects on site, such as the fleet of vehicles which currently cannot be moved because of the concern of cross-contamination.

**Current and Future Developments**

While the basic concept of 3-D SDF has been demonstrated in a range of environments and on a range of deployment platforms, more developments are needed to enhance radiation detection and mapping capabilities to enable the deployment of such systems in high radiation fields (>10 mSv/hr on instrument) and to more accurately estimate quantities such as emission rates, material masses, or dose-rates and associated uncertainties. We need to emphasize that 3-D SDF or similar technologies are required for quantification of emission rates from reconstructed surfaces, as the distance between surface and instrument as well as the relative orientation of the instrument needs to be known, in addition to the complete detector and imaging response of the instrument. What makes the estimation particularly challenging is the motion of the instrument in changing environments and radiation fields, particularly in complex and high radiation fields found inside the damaged reactor buildings of FDNPP. However, already with the current state of the technology important insights can be gained and visualized.

We have recently developed and demonstrated a more compact gamma-ray imaging system as compared to PRISM – called mini-PRISM, which is based on the three-dimensional arrangement of the same 1 cm³ CPG CZT detector elements within a cube rather than on the surface of a sphere. Instead of about 120 detectors, only about 60 detectors are arranged within a cube of (8 cm³) resulting in a smaller footprint and lower weight. The detector elements are arranged in three dimensions to enable omni-directional imaging in the coded-aperture as well as in the Compton imaging modalities, as with PRISM. Due to its lighter weight it can be easily integrated with the LAMP package and mounted on UGVs and UASs, such as the DJI Matrice-600. However, this compact, broad-energy gamma-ray imaging system provides improved localization and mapping performance as compared to the non-imaging systems composed of CsI or LaBr detectors, which primarily rely on the aforementioned proximity imaging.

Without a doubt, sensing, computer vision, and data processing technologies will continue to advance quickly, providing even more data about local environments with more compact and lighter weight implementations and platforms and with reduced costs. The computer vision technologies will provide more accurate information that can be utilized in augmented reality (AR) or in virtual reality (VR) environments. Both will become important tools for mapping complex and high radiation fields to enhance the effectiveness and efficiency of operations, to reduce costs, and ultimately, to substantially increase the safety of operators. Additional progress in data processing, specifically in machine learning, will provide new means to assess complex environments and to optimize operations in these complex environments, particularly when done by unmanned systems.

In parallel, radiation detection and imaging technologies will continue to advance linearly providing improved ways to map and monitor radiation fields and processes, specifically relevant in the decommissioning of FDNPP. All of these advancements will result in even smarter systems providing the basis for more effective and safer operations in the future.
Challenges in the assessment and monitoring of high and complex radiation fields as needed for the decommissioning of FDNPP require smarter approaches to enhance effectiveness, reduce cost, and increase safety. Smarter systems need to be able to integrate advancements in knowledge and technologies from a broad range of fields and to adapt and learn from new observations and insights.

The 3-D Scene-Data Fusion concept reflects such an integration enabling smarter and more effective ways in the assessment and visualization of radiological materials as compared to conventional radiation detection and imaging methodologies. It leverages the enormous advances in computer vision – which underpins the realization of autonomous vehicles – and lessons learned from accidents and deployments to enhance not only the ability for detection and visualization for operators and experts but also for the communication with the general public. Now, almost eight years after the accident, after years of often heroic efforts by operators and workers, it has become apparent that both, a.) the ability to quickly and accurately assess and b.) to effectively communicate and visualize radiation is critical in order to minimize the impact of such events, locally and globally.

3-D Scene Data Fusion enables fast and accurate mapping of radiation fields fused into scene data in three dimensions and in real time. The Localization And Mapping Platform (LAMP) realizes this concept via the utilization of contextual sensors such as LiDAR or visual cameras that can be combined with almost any imaging and non-imaging radiation detectors. We have demonstrated it with hand-portable gamma-ray imaging systems such as HEMI and PRISM and non-imaging instruments based on CsI or LaBr detectors. LAMP can be deployed on any platform, including unmanned or manned ground or aerial vehicles, and it can be hand-carried or operated remotely. The data processing for the mapping, instrument tracking, image reconstruction, and data fusion is performed onboard LAMP. We have demonstrated SDF and LAMP in search and localization measurements as well as in contamination mapping and decontamination verification scenarios. While current systems can be operated in dose rates of up to several mSv/hr, we have developed concepts to deploy SDF in very high radiation fields in excess of 1 Sv/hr as they exist in the FDNPP reactor vessels.

In this paper, we provided an overview of the SDF concept and its implementation with a range of radiation detection and imaging instruments illustrating smart ways to map and visualize radiation fields in three dimensions, in real time, and color – i.e. radio-isotope specific, relevant for the assessment and decommissioning of FDNPP and any other nuclear (power) facility.

Acknowledgments
The work presented here reflects contribution of many scientists and students, all members of the Berkeley Applied Nuclear Physics program. In addition, we want to thank our collaborators at the JAEC in Japan, T. Torii, Y. Sanada, and Y. Shikaze who made the measurements in Fukushima possible and L. Hixson from the Clean Futures Fund who made the measurements in the Chernobyl Exclusion Zone in Ukraine possible. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Berkeley National Laboratory under Contract DE-AC02-05CH11231. It has been supported by the US Department of Homeland Security, Domestic Nuclear Detection Office, under competitively awarded contract 2011-DN-077-ARI049-03 as well
as under Grant Award Numbers ECCS-1140069 and IAA HSHQDC-11-X-00380. In addition, it is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number(s) DE-NA0000979, Office of Defense Nuclear Nonproliferation Research and Development (DNN R&D), and in collaboration with the Japan Atomic Energy Agency under the Work-For-Others agreement FP00002328. The LAMP and PRISM efforts were supported by the Defense Threat Reduction Agency under contract numbers 10027-21370, -23334, and -25522 and 10027-26768, -21804, and -19346, respectively. Part of the work was also supported by the Lawrence Berkeley National Laboratory LDRD program.

References


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6. Parallel Session 2.1
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6.1 Chips for extreme radiation environments in standard CMOS
Prof. dr. ir. Paul Leroux

Abstract

The talk starts with an introduction of the research group ADVISE at KU Leuven (University of Leuven) where Prof. Leroux focuses on radiation hardened integrated circuit design for harsh radiation environments such as the nuclear fusion reactor ITER, high energy physics experiments, space, nuclear safety, and medical nuclear instrumentation. Next an overview is given of radiation effects in electronics, with an emphasis on their impact on CMOS integrated circuits. The distinction is made between cumulative total dose effects and single-event effects. A brief overview is given on radiation hardness assurance testing with a specific focus on the use of two-photon laser absorption to determine a full 3D single-event sensitivity map with sub-micrometer resolution. The main part of the talk will be on the measures that can be taken during IC design stage to make the circuits tolerant to the impact of ionizing radiation. Layout measures, such as enclosed gate layout, are presented as well as several analogue circuit design techniques to limit the impact of device degradation on overall circuit performance. In terms of digital circuits, radiation hardening techniques are presented for SRAM memory cells to avoid single-event upsets, as well as both spatial and temporal triple modular redundancy techniques to suppress single-event transients. Finally some state of the art examples of radiation hardened designs are discussed including a bandgap reference circuit, a laser driver, a transimpedance amplifier, a time-to-digital converter and a phase-locked loop.
Chips for extreme radiation environments in standard CMOS

Prof. dr. ir. Paul Leroux
http://www.kuleuven.be/advise

Overview

- Introduction
- Radiation effects in CMOS
- Radiation hardness testing
- Radiation hardened IC design
- Conclusion

Radiation hardened electronics

Application fields
- ITER: Nuclear fusion
- CERN: CMS experiment
- Reactor safety
- SCK-CEN: MIR/RNA
- Deep space missions

Expertise
- RF, analog and mixed-signal radiation IC design
- Modeling radiation effects
- FPGA and board level prototyping
- Radiation hardened digital IC design & synthesis

Radiation Levels

Feasible with...

10 kGy
100 Gy

...current technology

10 MGy
2.10^{16} n/cm^{2}
10^7 ion/cm^{2}
60 MeVcm^{2}/mg

...current limits

COTS
space grade

SCK-CEN:
ITER:
CERN:
Reactor safety
SCK-CEN:
ITER:
CERN:
Reactor safety

Radiation hardened electronics
ADVISE RELY LAB facilities

 Radiation Effects in CMOS

The MOS field-effect transistor

- **Digital**: MOS behaves as switch
  - $V_{GS}$ high (low for PMOS) → switch closed
  - $V_{GS}$ low (high for PMOS) → switch open

- **Analog**: MOS behaves as a transconductor (voltage controlled current source)
  - $V_{GS}$ modulates the drain-source current

The MOS field-effect transistor input characteristic

MOS transistor current in saturation regime:

$$I_D = \frac{\mu C_w W}{L} (V_{GS} - V_{TH})^2$$

- Oxide capacitance
- Width of the device
- Charge carrier mobility
- Threshold voltage
- Length of the device
The MOS field-effect transistor
Sub-threshold current

\[ I_D = I_0 \exp \left( \frac{V_{GS} - V_{TH}}{\frac{kT}{q}} \right) \]

Total Ionizing Dose (TID) effects

- Radiation energy is thermalized through electron-hole pair generation
- In Si but also in SiO₂
- Charges may get trapped in dielectric layers (e.g., oxides or nitrides) either in the bulk of the dielectric, or at or near the interface with the semiconductor
- Changes device characteristics
- Mostly by high-energy photons but also secondary ionization from charged particles

Radiation effects in CMOS

Total ionizing dose (TID) effects

- Displacement damage
- SEU ... Upsets
- SEB ... Burnout
- SET ... Transient
- SEGR ... Gate Rupture
- SEFI ... Functional Interrupts
- SEL ... Latchup
- SESB ... Snapback

Total Ionizing Dose (TID) effects

- Shift in threshold voltage (Vₜ)
- Trapped in gate oxide
- Trapped between bulk Si and oxide
- Interface charge for NMOS
- Interface charge for PMOS

Picture © Martin Dentan
TID effect in MOS transistors
Threshold voltage and mobility

- Radiation-induced charges
  - Translate curve (threshold shift)
  - Stretchout from interface traps
- Mobility degradation

TID effect in MOS transistors
STI charge causes leakage

Intra-transistor leakage

Inter-transistor leakage

TID effects in MOS devices

- Shifts in the threshold voltage
- Changes charge carrier mobility
- Decreases subthreshold slope
- Leakage current
- Increases 1/f noise
- Worsens mismatch
Single-event effects

Induced by even a single high-energetic particle traversing the chip

Single-event transients

-SETs in logic and masking

- The transient pulse generated by the charge deposition might not be controllable, especially in latch circuits, because it could be logically masked, or propagating to latch.
- Loop inhibit masking: pulse propagating to latch
- Electrical window masking: pulse width
- Latch-window masking: pulse width

Ion Trajectory

Drift

Diffusion

Single-event effects
Overview of radiation test

- TID:
  - X-ray (~keV photons, X-ray tube, no radioactive elements)
  - $^{60}\text{Co}$ gamma (~MeV photons, under water or in a bunker)

- SEE testing
- Heavy ions
- Ions accelerated in cyclotron
- e.g., UCL (Belgium), RADEF (Finland)
- Protons (Accelerator, Irradi@CERN)
- Neutrons (Fast neutrons and slow, thermal neutrons)
- Alpha (Americum, ...)
- Two-Photon Absorption laser testing (KU Leuven)

Radiation effects and IC technology scaling

Thicker oxides in older transistors have now reduced single event effects.

Reduced feature sizes have resulted in increased single event effects.

JAEA-Review 2019-031
Laser SEE testing

- Generate electron-hole pair track in Si
- SET, SEU, SEFI, ...
- Alternative to heavy-ion testing
- Single-photon absorption (SPA) and two-photon absorption (TPA)
- Locate sensitive regions in the chip (2D and 3D for TPA)
- No ionizing radiation needed
Radiation-Hardening-by-Design

System-level RHBD
Selection of robust structures

Circuit-level RHBD
Techniques for mitigating radiation effects

Transistor-level RHBD
Enclosed-layout, guarding ring

Enclosed Layout Transistor (ELT)

Leakage path
No leakage path

Current mirror masks TID effects

Output current only dependent on reference current and geometrical parameters

Analogue circuit level mitigation
Differential design

- Exploit charge sharing by interdigitated layout
- Radiation induced charge captured on both outputs
- Thus, voltage transients appear as common mode
MGy tolerant solid-state laser driver

- Optical transmitter
- Send pulsed current to laser diode
- Diode current should be independent of TID

With feedback:
- Current drops by 10% after 3.5 MGy

Without feedback:
- Current drops by 90% after 10 kGy

[IEEE Transactions on Nuclear Science - 2010]

Embedded SRAM memories

Single-event effects
SEU in SRAM
Embedded SRAM memories
Capacitive hardening

Embedded memories
Capacitive hardening

Embedded memories
Dual Interlocked storage CELL (DICE)

Radiation hardened digital circuits
Triple Modular Redundancy (TMR)
Radiation hardened digital circuits
Temporal redundancy

Radiation hardened TDCs and PLL
**Time-to-Digital Converters (TDC)**
- Time-interval → Digital
- Intervals of picoseconds!

**Phase Locked Loops (PLL)**
- Clock/Frequency generator
- Build a high-frequency → Locked to a reference
- 40 MHz → 2 GHz
- Jitter levels < 1 ps!

TDC with 4 ps resolution and SET recovery

[IEEE TCAS 2015]
Low noise radiation hardened clock synthesizers
motivation and architecture

- How do ring oscillators compare to LC oscillators?
- How can LC oscillators be made radhard (TID and SEE)?

Low noise radiation hardened clock synthesizers
Single-event experiments

Low noise radiation hardened clock synthesizers
Improved oscillator

Low noise radiation hardened clock synthesizers
Radiation experiments

- Heavy ion tests at UCL
  - LC1: large cross section
  - Ring: smaller cross section
  - LC2: No errors measured
- Confirmed with TPA tests

[IEEE TNS 2018]
Conclusion

Extremely radiation hardened chips can be developed in mainstream CMOS technologies

Thank you!

More info: http://www.kuleuven.be/advise
paul.leroux@kuleuven.be
6.2 Development of a diamond radiation detector and a charge sensitive preamplifier based on diamond MESFET

Junichi H. KANEKO
Hokkaido University

Diamond radiation detectors and Diamond field emission transistors (FET) were developed aiming at usage under high-temperature and/or high-radiation environment. Especially, after the accident at the 1st Fukushima nuclear power plant, requested specifications for instruments used in reactor containment vessel became very severe. One of these instruments, there is a containment atmospheric monitoring system (CAMS). We assume to use diamond radiation detectors for gamma-rays and diamond FET for a charge sensitive preamplifier to CAMS. Required operation temperature was 300 °C and integrating dose was 5 M Gy, respectively. This development was carried out the collaboration between Hokkaido University, National Institute for Material Science (NIMS), AIST and Hitachi Ltd.

In this talk, development of diamond radiation detector and diamond metal-semiconductor field effect transistor (MESFET) will be talked. The developed diamond radiation detector and diamond MESFET worked under high-temperature of around 450 to 500 °C as show in Figure 1 and 2. In addition, they survived after heavy irradiation of several M Gy of gamma-rays.

![Figure 1 Example of high-temperature operation of diamond radiation detector developed by Hokkaido University.](image1)

![Figure 2 Example of high-temperature operation of a diamond MESFET developed by AIST.](image2)
6.3 Radiation Response of SiC-Based Semiconductor Devices

Takeshi Ohshima1),*, Sin-Ichiro Kuroki2) and Yasunori Tanaka3)
1) National Institutes for Quantum and Radiological Science and Technology (QST)
1233 Watanuki, Takasaki, Gunma 370-1292, Japan
2) Research Institute for Nanodevice and Bio Systems (RNBS), Hiroshima University
1-4-2 Kagamiyama, Higashi-Hiroshima, 739-8527, Japan
3) National Institute of Advanced Industrial Science and Technology (AIST)
1-1-1 Umezono, Tsukuba, Ibaraki 305-8568, Japan
*ohshima.takeshi@qst.go.jp

Electronic devices with extremely high radiation tolerance (rad-hard), such as MGy order, are required to develop remote-control systems for the decommissioning of TEPCO Fukushima Dai-ichi nuclear reactors. Silicon carbide (SiC) is regarded as a promising candidate for highly reliable electronic devices used in harsh environments such as high radiation and high temperature [1,2]. For the development of rad-hard electronic devices based on SiC, it is necessary to understand radiation response of SiC devices and to develop their radiation hardened technologies. We investigated effects of device structures on the radiation degradation of the electrical characteristics of SiC devices to develop ultra-radiation-hardened semiconductor devices using SiC [3,4]. As a result, it was found that junction type transistors which are known as static induction transistors (SITs) show the higher gamma-ray radiation tolerance than metal semiconductor field effect transistors (MESFETs) and meta-oxide-semiconductor FETs (MOSFETs) [3, 4]. Although MOSFETs have less radiation tolerance than other transistors, the degradation of their electrical characteristics can be suppressed by thinning gate oxide [5]. In addition to device structures, it is known that the radiation response of electronic devices depends on irradiation conditions, such as temperature, humidity and bias (applying electric voltage) conditions. For SiC MOSFETs, we revealed that gamma-ray irradiation at elevated temperature leads to less their degradation [6]. In addition, humidity enhances this degradation suppressive effect [7]. We will review the gamma-ray radiation response of SiC transistors in the presentation. We will also discuss radiation degradation mechanisms, and on the basis of these mechanism, we will propose radiation hardened technologies for SiC devices.

Part of this study was supported by The Center of World Intelligence Project for Nuclear S&T and Human Resource Development, Strategic Nuclear Power Joint Research Program, under the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan.

Radiation Response of SiC-Based Semiconductor Devices

Takeshi Ohshima
Sin-Ichiro Kuroki
Yasunori Tanaka
National Institutes for Quantum and Radiological Science and Technology

The part of results shown in this study were obtained under the collaborative research with A/Prof Y. Hijikata of Saitama University and T. Yoshie of Sanken Electric Co., Ltd. We thank them for their contribution. Part of this study was supported by the JAEA-Research Program and the R&D Program of the Nuclear Energy Research Institute, under the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan.

Acknowledgements

Expected Applications

Silicon Carbide (SiC) is a wide bandgap semiconductor with extremely low loss power electronics. Commercial devices are available.

Outline

1. Radiation Effects on semiconductor devices
2. Device Type
   - MOSFET
   - MESFET
   - SIT (Static Induction Transistor)
3. Degradation of the electrical characteristics of devices caused by charge trapped in insulator and interface traps
4. Degradation of the electrical characteristics of devices caused by displacement of atoms at the lattice
5. Degradation of the electrical characteristics of devices such as Metal Insulator (Oxide) Semiconductor (MOS) devices caused by charge trapped in insulator and interface traps

Radiation effects on electronic devices

Total Ionizing Dose Effects

Degradation of the electrical characteristics of electronic devices such as Metal Insulator (Oxide) Semiconductor (MIS MOS) devices caused by charge trapped in insulator and interface traps

Single Event Effects

Failure or/and destruction of electronic devices caused by induced charge (electron-hole pair)

Displacement Damage Effects

Degradation of the electrical characteristics of devices such as Solar Cells caused by crystal damage (displacement of atoms at the lattice)

Silicon Carbide (SiC) is a wide bandgap semiconductor with extremely low loss power electronics. Commercial devices are available.

Silicon Carbide (SiC) is a wide bandgap semiconductor with extremely low loss power electronics. Commercial devices are available.

Silicon Carbide (SiC) is a wide bandgap semiconductor with extremely low loss power electronics. Commercial devices are available.

Silicon Carbide (SiC) is a wide bandgap semiconductor with extremely low loss power electronics. Commercial devices are available.
Total ionizing dose (TID) effect

TID occurs when devices are exposed by gamma-rays

- Generation
- Recombination
- Trapped charge
- Interface traps

Schematic drawing of MOS band diagram in gamma-ray irradiation

- Metal
- Oxide
- Semiconductor

How device type affects TID

Graph showing change in $V_T$ for MOSFET, MISFET, SIT by irradiation

- SiC SIT > SiC MES > SiC MOS > Si MOS

Radiation resistance

SiC SIT > SiC MES > SiC MOS > Si MOS

Gamma-ray irradiation response of these devices were investigated

Threshold voltage shift values for SiC SITs, MESFETs, MOSFETs and Si MOSFETs as a function of absorbed dose.

Gamma-ray radiation was carried out at 8.8 kGy/h at RT in dry N2. No bias was applied to any electrodes during irradiation. Si MOSFET: McWhorter, Appl. Phys. Lett. 48, 133 (1986).
SiC SIT shows extremely high radiation resistance. However, MOSFET is also important devices from the point of view of low loss power electronics and, as a result, SiC MOSFETs are commercially available now. Actually, this is a very reasonable result because oxide does not have important role for SIT operation. Thus, in principle, devices with MOS structure are NOT strong against TID. According to Si MOSFETs, gate oxide thickness affect radiation hardness of MOSFETs. According to T. R. Oldham, and F. B. McLean, IEEE Trans. Nucl. Sci., 50, 483 (2003).

VT shift dramatically decreases when oxide < 20 nm. How to improve radiation hardness of SiC MOSFET

Change in threshold voltage for SiC MOSFETs with 10 and 20 nm thick gate oxide by gamma-ray irradiation. Gamma-ray irradiation was carried out at 8.8 kGy/h at RT. No bias was applied to any electrodes during irradiation. SiC MOSFETs with thin gate oxide show good radiation resistance.

SiC MOSFETs with thin gate oxides show good radiation resistance. Only ~ 0.1 V shift of VT after 1.13 MGy. 

Outline

- Radiation Effects on semiconductor devices
- Gamma-ray irradiation effects on SiC devices
- Device Type (MOSFET, MESFET, SIT (Static Induction Transistor))
- Design of SiC MOSFET (gate oxide thickness)

Summary

- Effects of environments on gamma-ray radiation response of SiC MOSFETs
- Bias applied to gate electrode
- Temperature and humidity
Bias applied into gate oxide during irradiation

Degradation is enhanced by positive bias.

Possible mechanism

Threshold voltage for SiC MOSFETs as a function of absorbed dose. Gamma-ray irradiation was done at room temperature in dry N₂. The values of bias applied during irradiation are described in the figure.

Possible mechanism

Degradation is enhanced by positive bias.

Radiation resistance: 150°C + Humid > 150°C + Dry > RT

Temperature, humidity during irradiation

Threshold voltage for SiC MOSFETs irradiated with gamma-rays as a function of gamma-ray dose.
Possible mechanism

High T and H

High T

Room T

Recombination

Trapped charge

Termination by H and OH

Increase

Increase

Recombination

Recombination
6.4 Radiation-hardened optically reconfigurable gate array

Minoru WATANABE *

Graduate School of Integrated Science and Technology, Shizuoka University, 3-5-1 Johoku, Hamamatsu, Shizuoka 432-8561, Japan
* watanabe.minoru@shizuoka.ac.jp

Currently, the total-ionizing-dose tolerances of radiation-hardened devices are limited to 1 Mrad. In order to increase the total-ionizing-dose tolerances, we have been developing a radiation-hardened optically reconfigurable gate array consisting of a holographic memory, a laser array, and an optically reconfigurable gate array VLSI [1,2]. By introducing parallel light configuration architecture, the total ionizing dose and soft-error tolerance of a programmable gate array can be increased. This paper presents an optically reconfigurable gate array and the evaluation results of the total ionizing dose and soft-error tolerances.

An optically reconfigurable gate array consisting of a holographic memory, a laser array, and an optically reconfigurable gate array VLSI has been developed. A photograph of an optically reconfigurable gate array is presented in Fig. 1. The optically reconfigurable gate array uses parallel light configuration architecture between a holographic memory and the photodiode-array of an optically reconfigurable gate array VLSI. Therefore, all programming elements are mutually independent. For that reason, even if a part of the programmable gate array and/or a part of the configuration circuit is damaged by radiation, the damaged part of the programmable gate array never affects the configuration procedure of the other non-damaged parts of the programmable gate array. A partly-damaged programmable gate array can be used continuously. Therefore, the total-ionizing-dose tolerance of the optically reconfigurable gate array VLSI using a non-radiation-hardened standard CMOS process technology can be increased drastically.

Up to now, we have confirmed that the optically reconfigurable gate array VLSI functions even after the optically reconfigurable gate array VLSI is exposed to a 1,027 Mrad total ionizing dose. The total ionizing dose tolerance of the optically reconfigurable gate array VLSI is 1,027 times higher than that of currently available radiation-hardened VLSIs. Moreover, we have demonstrated a 20 MHz high-speed scrubbing operation on the optically reconfigurable gate array. The soft-error interval of the configuration memory can be extended to over a year when the soft-error interval of an FPGA with a 100 ms scrubbing operation is 31.7 s. In optically reconfigurable gate arrays, the soft-error factor of the configuration memory can be out of consideration.
This research was partly supported by the Initiatives for Atomic Energy Basic and Generic Strategic Research No. 283101. The VLSI chip in this study was fabricated in the chip fabrication program of VLSI Design and Education Center (VDEC), the University of Tokyo in collaboration with Rohm Co. Ltd. and Toppan Printing Co. Ltd.

Radiation-hardened Optically Reconfigurable Gate Array

Minoru Watanabe

Department of Electrical and Electronic Engineering
Shizuoka University
E-mail: watanabe.minoru@shizuoka.ac.jp

Fukushima Research Conference
“Radiation Hardness and Smartness in Remote Technology for Nuclear Decommissioning”

Currently available radiation-hardened devices

<table>
<thead>
<tr>
<th>Total Ionizing-dose Tolerance</th>
<th>ASIC</th>
<th>Anti-Fuse FPGA</th>
<th>Flash FPGA</th>
<th>SRAM FPGA Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gate Array</td>
<td>100–1000 Krad</td>
<td>300 krad</td>
<td>300 krad</td>
<td>1 Mrad</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Soft Error Tolerance</th>
<th>Gate Array</th>
<th>100 MHz TMR</th>
<th>100 MHz TMR</th>
<th>100 MHz TMR</th>
</tr>
</thead>
<tbody>
<tr>
<td>External configuration memory</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>EPROM 200 Krad</td>
</tr>
<tr>
<td>Life time at 1000 Sv/hr</td>
<td>10 hr</td>
<td>3 hr</td>
<td>3 hr</td>
<td>3 hr</td>
</tr>
</tbody>
</table>

The total-ionizing-dose tolerances or life-time of current devices are insufficient. The life time must be at least over 100 days for the work.

Reparable VLSI concept

Reparable VLSI means a reprogrammable gate array just like FPGAs.

CLB (Configurable Logic Block)

IOB (Input/Output Block)

SM (Switching Matrix)

Block diagram of a reprogrammable gate array

Serial configuration of FPGA is too weak

However, current FPGAs cannot be used as a reparable VLSI because its serial configuration circuit is extremely weak for radiation.

If a part of a serial configuration circuit is damaged, configuration for almost all regions becomes impossible.
Alive probability of configuration circuit

According to our FPGA design, configuration circuit occupies 38% region of a chip.

Implementation area comparison

Alive probability of configuration circuit

Probability that pure gate array region is only damaged and configuration circuit is alive

- When one transistor is broken: 62.00%
- When two transistors are broken: 38.44%
- When three transistors are broken: 23.83%
- When four transistors are broken: 14.78%
- When 10 transistors are broken: 0.84%

Therefore, we cannot use current FPGAs as repairable VLSIs.

Radiation experiment for Cyclone II FPGA

Shizuoka University’s Co60 29.5 TBq gamma radiation source (Intensity is 3,800 Sv/h).

- We have done a gamma radiation experiment for four Altera FPGA boards with a Cyclone II FPGA (EP2C70F).
- The FPGA boards were exposed to radiation from 0 to 65 krad, in 5 krad increments by using a Cobalt 60 gamma radiation source.
- While JTAG configuration circuits on all Cyclone II FPGAs were firstly broken at 35 to 65 krad total on/offing dose, their programmable gate array could correctly work immediately before JTAGs were broken.

- Cyclone II FPGA

Our Approach

In order to realize a repairable VLSI,
We should use parallel configuration architecture.

- Even if a part of configuration circuit is damaged by radiation, the damaged part never affects the programming of non-damaged regions on the programmable gate array.
- We can reprogram even the last survived look-up table correctly.

In order to realize the parallel configuration, we have introduced optical technologies for VLSI technologies.
Cobalt 60 $\gamma$ radiation total ionizing dose experiment for a holographic memory

- Photopolymer holographic memory was used
- Radiation source is a Co60 gamma radiation source
- Even if 500 Mrad gamma radiation is applied, correct configuration pattern can be read
- Light intensity is 3.88 times lower than initial condition

Gate Array Structure

Optically reconfigurable gate array VLSI

An ORGA takes Island-Style gate array. The basic structure is same as that of current FPGAs. However, each programming element of the gate array is connected to a photodiode (independent). Thereby, all state of the gate array can be programmed in perfectly parallel.

Cobalt 60 $\gamma$ radiation total ionizing dose experiment for lasers

- Laser (DL-3247-165: Tottori SANYO Electric Co., Ltd.)
- Even after 400 Mrad radiation is applied, V-I characteristics was never varied and light power was not varied.
- Radiation tolerance of optical part is over 400 Mrad.
- This is 400 times higher radiation tolerance than Vertex 5-QV

Table 1: Specification of a fabricated ORGA-VLSI chip.

<table>
<thead>
<tr>
<th>Technology</th>
<th>0.18$\mu$m double poly 5-metal 0.35-micron CMOS process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Die size</td>
<td>$5.0 \times 5.0 \text{ mm}^2$</td>
</tr>
<tr>
<td>Supply voltage</td>
<td>3.3V</td>
</tr>
<tr>
<td>Photo diode</td>
<td></td>
</tr>
<tr>
<td>Rectifier area</td>
<td>$4.0 \times 4.0 \text{ mm}^2$</td>
</tr>
<tr>
<td>Switching energy</td>
<td>$2.5 \times 10^{-8} \text{ A}$</td>
</tr>
<tr>
<td>Vertical interval</td>
<td>$30.24 \text{ mm}$</td>
</tr>
<tr>
<td>Num. of photodiode</td>
<td>79,864</td>
</tr>
<tr>
<td>Wire array</td>
<td></td>
</tr>
<tr>
<td>Num. of logic blocks</td>
<td>500</td>
</tr>
<tr>
<td>Num. of 3 input</td>
<td></td>
</tr>
<tr>
<td>Num. of 2 input</td>
<td></td>
</tr>
<tr>
<td>Num. of 4 input</td>
<td></td>
</tr>
<tr>
<td>Core area</td>
<td>4.764</td>
</tr>
</tbody>
</table>

Fig. 1: Photograph of a fabricated ORGA-VLSI chip.
TID Tolerance experiment for the ORGA-VLSI

Delay measurement circuits.  
 Degradation measurement.  
✓ We have done a 1 Grad TID experiment for the ORGA-VLSI using a Co60 source  
✓ Two I/O blocks were only broken by radiation. The other components are alive  
✓ The response times of look-up tables became 1.86 times longer than that of the original look-up tables  
✓ The power consumption was increased to 1.95 times higher than original condition

FPGA scrubbing operation

Scrubbing operation?  
✓ EEPROM radiation tolerance is high compared with SRAM  
✓ Repair operation based on EEPROM is slow speed  
✓ Radiation tolerance depends on the repair speed

Soft Error Tolerance of Optically Reconfigurable Gate Array?

Experimental System for Scrubbing Experiment

Liquid Crystal Spatial Light Modulator  
Optically Reconfigurable Gate Array VLSI  
Lenses  
532 nm 1.5 W CW Laser  
120 mm
**Evaluation results**

<table>
<thead>
<tr>
<th>Scrubbing Period</th>
<th>100 ms</th>
<th>1 ms</th>
<th>10 μs</th>
<th>70 ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTBF</td>
<td>31.7 sec</td>
<td>50.0 min</td>
<td>3.47 days</td>
<td>496 days</td>
</tr>
</tbody>
</table>

* Condition: 1 particle per second

- We have confirmed that the ORGA system can achieve 70 ns high-speed scrubbing operations
- The error interval can be extended to 1.35 million times longer than that in the case of 100 ms scrubbing of current FPGA
- Soft-error on configuration memory can be out of consideration

---

**Soft-Error tolerance:**

**Evaluation results of scrubbing operation**

<table>
<thead>
<tr>
<th>Scrubbing Period</th>
<th>100 ms</th>
<th>1 ms</th>
<th>10 μs</th>
<th>10 ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTBF</td>
<td>31.7 sec</td>
<td>50.0 min</td>
<td>3.47 days</td>
<td>9.5 years</td>
</tr>
</tbody>
</table>

Condition: 1 particle per second, TMR

- To decrease the soft-errors, a scrubbing operation is useful for SRAM-based FPGA and ORGA
- Radiation tolerance depends on the period of scrubbing operation
- We have demonstrated that the ORGA system can achieve 50 ns high-speed optical scrubbing operations
- The error interval could be extended to 1.9 million times longer than that in the case of 100 ms scrubbing
- Anymore, soft-error on configuration memory can be out of consideration in ORGAs
## Comparison result

<table>
<thead>
<tr>
<th></th>
<th>ASIC</th>
<th>Anti-Pasti FPGA</th>
<th>Flash FPGA</th>
<th>SRAM-PGA Write-NDV</th>
<th>ORGA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Dose Tolerance</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gate Array</td>
<td>100–1000 Krad</td>
<td>300 krad</td>
<td>300 krad</td>
<td>1 Mrad</td>
<td>1 Grad</td>
</tr>
<tr>
<td>External configuration memory</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>EPROM 300 Krad</td>
<td>Holographic Memory 500 Mrad</td>
</tr>
<tr>
<td>Life Time at 1000 Sv/h</td>
<td>10 hr</td>
<td>3 hr</td>
<td>3 hr</td>
<td>3 hr</td>
<td>Over 1 Year</td>
</tr>
<tr>
<td><strong>Soft Error Tolerance</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gate Array</td>
<td>100 MHz TMR</td>
<td>100 MHz TMR</td>
<td>100 MHz TMR</td>
<td>100 MHz TMR</td>
<td>10 MHz TMR</td>
</tr>
<tr>
<td>Downstream configuration memory</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>Resistively Good</td>
<td>Scrubbing Period (100 ms) x</td>
</tr>
<tr>
<td>Configuration Memory Soft Error Interval</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>Very Long</td>
<td>MTBF 3.7 sec x</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Conclusion

- ORGA could achieve both TID and soft-error tolerances
- TID tolerance
  - VLSI: 1 Grad TID
  - Holographic Memory: 500 Mrad TID
  - Semiconductor Laser: 400 Mrad TID
  - ORGA system: 400 Mrad TID could be evaluated
- Soft-error tolerance
  - 10-ns high speed scrubbing is possible
  - Soft error on configuration memory can be out of consideration
  - ASIC (non-programmable device) level
7. Wrap-up Panel Discussion
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How to utilize measured data for debris retrieval?

Prof. Dr. Tamio ARAI
Vice-president
International Research Institute for Nuclear Decommissioning

Safety Function

1F specific requirements
- High fuel exposure and enrichment → high reactivity: background gamma ray
- MCCI → hydrogen generation caused by core concrete interaction
- Injecting sea water, melting cable → effects caused by salt and impurities

R/B

Collection, Transfer and Storage of Fuel Debris

1. Cooling down
2. Confinement (control of negative pressure and water level in torus room)
3. Deactivation (protection of fire and explosion)
4. Sub-criticality

Safety Function Requirements

- Nitrogen supply & exhaust gas treatment system
- Water treatment system
- Boric acid concentration system
- Circulation cooling & criticality control system
- Ventilation system for the building & cell

Purpose of data sensing

- to measure the amount of fuel debris to excavate
- to detect the leak out of radioactive materials

- to estimate and calibrate the pose of sensors
- to fuse the data measured by different sensors
- to remote-control sensing devices and excavating machines
- to record the process of fuel-debris retrieval
Characteristics of sensors and their use

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Proactive</th>
<th>Reactive</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel-debris retrieval</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Debris segmentation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inventory</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recriticality detection</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Detection of hydrogen</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Areas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inside of PCV &amp; RPV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transfer &amp; storage cells</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maintenance cells</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- properties: temporal(required time), spatial(size, weight), integral/differential
- Exchangeability, Reliability, Maintainability, Calibration easiness

Long-term retrieval with short life-time sensing devices

- Size and weight of sensors
  - transportable by robot's mobility
  - direction of sensing and light control
- Maintainability & Exchangeability
  - radiation tolerance
  - prolong life-time in severe radiation
  - frequent automatic X-changer
- Design of sensing environment
  - light sources
  - landmarks, corner-cubes
  - sweeper, water sprinkling hose
- 3D or 4D model of PCV

Computer Tomography using gamma ray

- Compton camera mounted on a mobile robots
  by Takahashi, Asama, Okamoto

- Radiation image on 3D model
  by Sato

How to utilize the accumulated data?

- **Voxel**: a unit volume with value(s) in 3D space
  - 2D image=Pixel, 3D image=Voxel
  - Popular application: volumetric imaging in medicine such as VSRAD(Voxel-based Specific Regional analysis system for Alzheimer's Disease) and in computer games.
  - **The simplest voxel is point-cloud**
  - to extract volumes, necessary to separate point-clouds

- Color and radioactive intensity at 3D Position
  - rendering of color image of just surface including radioactivity
  - radiation can be measured from one side (not 360 deg but 120.)
Sensor fusion

- Main data in fuel-debris retrieval
  - 3D shape and point cloud
    by light-section Method by time-of-flight method
    Color image
  - γ image at the surface of debris
  - Intensity map of neutron beam
  - Weight and intensity of γ beam of debris in unit-can.
  - Mapping/SLAM (Simultaneous Localization and Mapping)
  - Structure from Motion
  - Shaping / Mapping / Rendering
  - 2.5 D / 3D image
  - Point-cloud / VOXEL data

Inverse estimation of fuel distribution & Inventory

Strategies for Countermeasures against Radiation

- Shielding
  - Shield by lead/steel/tungsten (not realistic)
  - Lead glass
- Radiation-hardened devices/components
  - Radiation-hardened(resistant) Semiconductor
  - Camera tube(Hamamatsu Photonics) 200Sv dose
  - Radiation-hardened Camera(SONY) 1000Sv dose
- Robust design(Fault-tolerance/Maintainability)
  - Redundant and functionally degradable
  - Modular design and easy replace

Robust design & fault tolerant systems for function
- Maintainability & Exchangeability
- Combination of various sensors

Distributed sensors

- Robust design & fault tolerant systems for function
- Maintainability & Exchangeability
- Combination of various sensors

Image of fuel-debris retrieval

- Main purpose: prevent workers from radiation
  - 600 tons × 3 units
  - 30 years; 5 years/generation
  - Debris flow with high efficiency under distributed sensing systems

- Inventory utilizing VOXEL data by composed by 2.5 D vision, range, and CT
- Systematic approach in design of sensing system including maintainability
7.2 Robotics and Artificial Intelligence for Nuclear (RAIN) Robotics Hub

Barry Lennox  
*Director of RAIN, University of Manchester*

The RAIN Hub is a UK research programme, supported with more than £40M (1.7Bn Yen) from research councils, industry and academia, focused on the development and deployment of robotic systems in nuclear environments. It draws together experts in robotics, nuclear engineering and artificial intelligence from eight leading research institutes in the United Kingdom: Universities of Manchester, Oxford, Lancaster, Bristol, Sheffield, Liverpool, Nottingham and the UKAEA’s Remote Applications in Challenging Environments Centre (RACE).

Working with end-users, such as Sellafield Ltd, EDF Energy and Rolls Royce, small and large companies across the nuclear supply chain and centres of excellence, such as the Nuclear Advanced Manufacturing Research Centre and the National Nuclear Laboratory, the vision for RAIN is to make robotic systems become commonplace in the nuclear industry.

This short presentation will provide an overview of the main research programmes that are on-going within RAIN and provide examples of some of the technology that is being developed. This will include the CARMA, AVEXIS and aerial robotic platforms that have been designed to autonomously map radiation levels in dry and submerged environments and have been deployed into active facilities on the Sellafield site. The AVEXIS vehicle can be deployed through 150 mm access ports and with the support of the National Maritime Research Institute, Nagaoka University of Technology and the JAEA has been equipped with neutron, gamma and sonar detectors to enable it to help locate the melted fuel in the Fukushima-Daiichi reactors.

Recent results collected from aerial drone tests, undertaken to measure gamma dose rates around the Fukushima-Daiichi area will be presented and show how the slow dispersion of gamma materials can be tracked over relatively long periods of time.

Further details of the RAIN Hub are available at the following website:

http://rainhub.org.uk
Barry Lennox

UK Research and Innovation
University of Manchester

Vision

- ‘Where nuclear robotic deployment and development is the norm’
- Undertake world-leading research in the field of nuclear robotics
- Foster international collaboration
- Establish pathways to impact for creation of a responsible, collaborative and sustainable research and innovation infrastructure to lead the world in nuclear robotics
- Measurably improve and deploy RAI technology in Nuclear:
  - Decommissioning and Waste Management
  - Fusion Remote Operations and Maintenance
  - Plant Life Extension and Nuclear New Build

UK Nuclear Robotics

RAIN began in October 2017
Consortium of 8 research partners and many industry and academic organisations from around the world: Manchester, Oxford, Bristol, Nottingham, Lancaster, Sheffield, Liverpool and RACE (UKAEA).

£12.2M investment by UKRI with additional £30M from industry and academia.

Focused on decommissioning, new build, SMRs and fusion.

Work Programme and Demonstrators
Motion, Redundancy and Fault Tolerance

Underwater positioning remains a challenge. Integration of several techniques (vision, acoustic, etc.) provides redundancy and improved accuracy.

How can we ensure that robots continue to operate after faults develop?
- Fault tolerant control systems
- Redundancy in the design
- Radiation tolerance of electronic systems (Tom McHugh)
- Improved understanding of failure modes and life

Human Robot Interaction

- Develop augmented and virtual reality based HRI that allow variable autonomy and the simpler operation of robotic systems.

Haptic systems to enable improved operations in the presence of delays and other factors.

Use of haptic gloves for person-in-the-loop remote master / slave manipulation.

Demonstrators

- Demonstrators will be identified from the decommissioning, fusion, plant life extension, SMR and new build sectors.

AVEXIS deployed into M5S5 storage silo (Sellafield)
Led by Lennox and Watson (Manchester)

MIRAX generated image of reprocessing facility at Sellafield

Radiation surveys

- Numerous demonstrations completed.

CAIRMA deployed at Sellafield. Moe deployments at Sellafield being identified. Technology being commercialised by Nuvia.
Led by Lennox (Manchester)

Exploration techniques designed to understand location and radiation levels.
Led by Hawes and Havoutis (Oxford)
What can we learn from robots used for nuclear accidents in the past and now in Fukushima?

Yasuyoshi YOKOKOHI
Department of Mechanical Engineering
Graduate School of Engineering
Kobe University

Lessons Learned from the TMI Accident

- Successful robots (e.g. Remote Reconnaissance Vehicle (RRV) 1 & 2) were
  - compact with simple function,
  - easy-to-use and easy-to-maintain,
  - easy-to-modify according to the needs of the site
  - common mobile platform
- High-function, large-sized robot (Workhorse) was not eventually used
- Development of new robots should be planned carefully because the situations on the site may change.

Lessons Learned from the Chernobyl Accident

- Immediately after the accident, various devices (e.g. Unmanned lunar rover) were introduced in an emergency response.
- In the survey inside the sarcophagus, a high-function robot by foreign technology (Pioneer) was not used after all.
- Instead, simple robots by domestic technology were used.
MHI Super Giraffe

- For inspection and some other works (e.g., decontamination) at high and narrow space inside the reactor buildings of Fukushima (2012)
- 9-DOF manipulator + 3-DOF lifter
  - Difficult to maneuver for the operators
  - They cannot make efficient use of redundancy
- Obstacle avoidance by self-motion
  - Our method has been installed on the real robot (2014)
- Not deployed yet

Fuel Debris Removal Plan-A

- Side access using the access rail
- Needs to ensure a new boundary
  - Isolation cell
  - Welding the cell adapter to the PCV

Welding Robot

- 9-DOF system
  - 7-DOF manipulator
  - 2-DOF welding head
- Motion teaching is a painful work

Our Motion Planner [Tazaki]

- Nonlinear optimization problem
- Choosing several via-points to avoid local-minima

Initial Motion
(Staying each via-point for certain time)

Planned Motion
Robustness against Installation Errors

- 100[mm] in x direction
- 100[mm] in y direction
- 100[mm] in z direction
- 10[deg] around z-axis

Summary of Lessons Learned

- Considerations of site condition are needed
  - Simple function for easy-to-use
  - Simple design for easy-to-modify
  - Site condition and their needs may change
- Reasons why those robots were not used?
  - Workhorse (TMI)
  - Pioneer (Chernobyl)
  - Super Giraffe (Fukushima)
- Tighter collaboration between academia and industries
  - Self-motion for redundant manipulators
  - Path-planning of redundant manipulators
8. Parallel Session 2.2
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8.1 Prediction on radiation fields in PCV of Fukushima Dai-ichi NPS

Keisuke OKUMURA
Accident Progression Evaluation and Fuel Debris Characterization Division, Collaborative Laboratories for Advanced Decommissioning Science (CLADS), Japan Atomic Energy Agency (JAEA)
Tomioka-machi, Futaba-gun, Fukushima-ken, 979-1151, Japan

Grasping the distribution of fuel debris in the primary containment vessel (PCV) is indispensable for the decommissioning of the Fukushima Dai-ichi NPS (1F). However, the fuel debris have not been identified by radiation measurements in the past internal investigations of 1F. This is because the inside of the PCV is seriously contaminated by Cs emitted at the time of accident and gamma-rays emitted from fuel debris cannot be distinguished from those from Cs. In order to develop an effective detector to search for fuel debris, we have to understand the dose rate distribution inside PCV and the characteristics of radiations emitted from fuel debris.

We have developed a method to predict the dose rate distribution in a PCV by combining various numerical calculations with the measured results, and the method was applied to the Unit 1 and 2 of 1F. In this presentation, the obtained dose rate distributions and radiations for searching fuel debris will be discussed.

Fig. Calculation model and predicted dose rate distribution
Prediction on radiation fields in PCV of Fukushima Dai-ichi NPS (1F)

Keisuke OKUMURA

Dose Evaluation and Nuclear Material Accountancy Group, Accident Progression Evaluation and Fuel Debris Characterization Division, Collaborative Laboratories for Advanced Decommissioning Science (CLADS), Sector of Fukushima Research and Development, Japan Atomic Energy Agency (JAEA)

Calculation flow of fuel debris composition

1. Mixing of all nuclides
2. Release of volatile nuclides
3. Mixing of SS, concrete, boron, etc.
4. Cooling to evaluation time

FP release models

4 FP release models to estimate upper, lower, representative radiation sources of fuel debris

The "standard release model" is based on the FP release experiment for fuel debris (PHEBUS-FPT-4).

Outline and purpose

3-dimensional inventory calculation for radioactive isotopes in fuels
1/4 core model

Particle transport simulation in PCV (MC calculation)

Severe accident progression (SA) analysis and related experiments
- MAAP
- SAMPSON
- PHEBUS experiments
- Analysis of TMI-2 debris

Activation calculation for structural materials including impurities
- cladding, water rods, channel boxes, grid spacers, top & bottom nozzles, core shroud, upper and lower tie plates

Measured results from PCV/BPV investigations
- cosmic-ray muon radiography
- local dose rate measurements with robots

Contribute to the future investigations and procedures of 1F decommissioning

Dose rate calculation by Monte Carlo code
Predicted dose rate distribution in Unit-1 at the end of 2021

3 investigations (1st, B1, B2) were considered to modify source distribution.

Dose rate calculation and internal investigations for Unit-2

The dose rate near the fuel debris is not so high as predicted first due to Cs release (84%) and self-shielding (smaller or comparable to dose rate from Cs contribution).
Simulation of fuel debris retrieval

- Upper access
- Side access

Understanding of changing dose rate distribution in decommissioning

- Optimization of decommissioning procedures
- Proposal of future PCV/RPV investigations
8.2 Radiation Monitoring of a Nuclear Reactor Using a Robotic Platform

Simon Watson

*The University of Manchester*

The Universities of Lancaster and Manchester, in collaboration with the Japan Atomic Energy Agency, the National Maritime, Port and Aviation Technologies and Nagaoka National University of Technology, have been developing technologies to explore fuel debris at the bottom of the Primary Containment Vessel in the Fukushima Daiichi Nuclear Power Plant. A Remotely Operated Vehicle (ROV) was designed to explore fuel debris and to investigate the distribution and surface profile of fuel debris at the bottom of the primary containment vessel using a sonar and a compact radiation detector. This presentation will provide an update on the radiation detectors which have been used and their integration into a small ROV and results from active tests which have been conducted at the TRIGA reactor in Slovenia and non-active tests at the Naraha test facility in Japan.
Motivation

- To assess the viability of conducting radiological characterisation using a small Remotely Operated Vehicle

Use Cases
- PCV at Fukushima Daiichi 1F
- Sellafield Legacy Ponds
- TRIGA research reactor – Ljubljana

AVEXIS ROV

- Developed for radiological inspections at Sellafield and Fukushima Daiichi

CeBr₃ Detector

- Inorganic scintillator sensitive to gamma radiation
- Good performance characteristics
  - High light yield
  - Fast response
- Small form factor
  - 10mm diameter crystal
Submersible requirements

- On-board power supply
  - Integrated HV supply within the unit.
  - Unit runs from 5 V supply
- Leak protection
  - Aluminium casing added
  - Waterproof BNC connectors
- Longer, lighter cabling
  - 50m RG178 signal cable (< 2mm ø)

MCA combined spectra

Based on work from [3]

Radiation Hardness Testing

- Dalton Cumbrian Facility.
  - $^{60}$Co irradiator
  - Capable of supplying dose rates up to 450 Gy/min
- Detector remained operational up to a dose rate of 15 Gy/hr
  - Past this point efficiency dropped

Stilbene detector

- Stilbene detector as neutron sensitive element
  - Look into radiation tolerance and limitations
  - Good mixed field separation
  - Integrate a low voltage supply

[3] Based on work from [3]
TRIGA reactor - Slovenia

- TRIGA research reactor – Ljubljana
- The CeBr was also tested to dose rates up to 15Gy/hr and was seeing a throughput of counts.
- Stilbene detector inserted
  - Seized operation
  - Became activated

Submerged Tests

- Submerged location tests with Cs-137
- Spectra shifted ~20 channels
  - Caused by temperature
- Na & Co sources were too small

Underwater distance estimation

- Distance from source increased
- Counts drop more than theoretical calculations for a point source

<table>
<thead>
<tr>
<th>Distance (cm)</th>
<th>Average Counts (cps)</th>
<th>Theoretical percentage drop</th>
<th>Experimental percentage drop</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>33.4</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>20</td>
<td>6.8</td>
<td>0.25</td>
<td>0.20</td>
</tr>
<tr>
<td>30</td>
<td>1.3</td>
<td>0.11</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Naraha Testing

- AVEXIS has been tested with a sonar system for object identification at the Naraha Test Facility
  - No radioactive sources used
Next Steps

- The next stage of development is the integration of the radiation sensors with a localisation system.
- Overlay radiological data onto geometric models.

References


8.3 Detection of Alpha Particle Emitters Originating From a Nuclear Fuel at the Fukushima Daiichi Nuclear Power Plant

Yuki Morishita
Collaborative Laboratories for Advanced Decommissioning Science (CLADS), Japan Atomic Energy Agency, 790-1 Motooka Ohtsuka, Tomioka Town, Futaba-gun, Fukushima, 979-1151, Japan

Abstract
Several papers have reported the presence of alpha particle emitters originating from Nuclear Fuels at the Fukushima Daiichi Nuclear Power Plant (FDNPP) (Shozugawa et al., 2012; Schneider et al., 2013). However, no measurement results at the actual FDNPP site have been published. A commercial ZnS(Ag) scintillator-based alpha counter cannot show where the alpha emitters are originating from: nuclear fuels or naturally occurring radionuclide such as Radon (Rn) and progeny. Therefore, we developed an alpha particle imaging detector which is capable of measuring an alpha particle spectrum and 2-dimensional distribution. Actual measurements for smear samples were performed at the FDNPP site. The detector was composed of a very thin (0.05-mm-thick) cerium-doped Gd₃(Ga,Al)₅O₁₂ (Ce:GAGG) scintillator and silicon photomultiplier (SiPM) arrays (Morishita et al., 2018). The floor of the reactor building in FDNPP was wiped off by using smear papers, and the radioactivity of these papers was measured by the alpha particle imaging detector. In addition, we measured a Plutonium (Pu) sample (mainly 5.5MeV alpha particles from ²³⁸Pu) obtained from a nuclear fuel facility by using the same detector for comparison with the smear papers. The alpha spectrum was in the energy range of 5–6 MeV, which corresponds to the alpha particle energy of ²³⁸Pu (Fig.1). Moreover, the 60 keV gamma-ray peak from ²⁴¹Am was identified by gamma spectrum measurements (Fig.2). Based on these results, we report actual findings of alpha emitters in the FDNPP reactor buildings originating from nuclear fuels.

Fig.1 Comparisons of alpha spectra between the smear paper and the Pu sample.

Fig.2 Gamma-ray spectra of smear papers measured using CZT-based gamma spectrometer. The arrows indicate the ²⁴¹Am peak.
References


Detection of Alpha Particle Emitters Originating From Nuclear Fuel at the Fukushima Daiichi Nuclear Power Station

Prepared by Yuki Morishita, Ph.D.
(JAEA/CLADS, University of Michigan)

Fukushima Research Conference
November 26 to 27, 2018

Outline

1. Alpha particle imaging detector development
2. Measurement at the Fukushima Daiichi Nuclear Power Station (FDNPS) site

Introduction

Various papers have reported alpha particle emitter radiation originating from Nuclear Fuels at the FDNPS (Shozugawa, 2012; Schneider, 2013; Zheng, 2012).

- Significant risk of internal exposure.
- No measurement results have been published.

Gamma-ray measurement results of collected samples using a Ge(Li) semiconductor detector

Shozugawa et al.
Environmental Pollution 163 (2012) 243 - 247

Gamma Ray Detector

\[ ^{239}\text{Np} \rightarrow ^{239}\text{Pu} \]
• Develop alpha particle imaging detector and demonstrate the measurement results at the actual FDNPS site.

- Good energy resolution for alpha particles, ability to discriminate between artificial alpha emitters and $^{222}$Rn.
- Less sensitivity to beta and gamma ray background.

• 3.7-kBq alpha source ($^{241}$Am)
• 74-kBq beta source ($^{90}$Sr/$^{90}$Y)
• $^{241}$Am gamma-ray source
• Dose rate: 1 mSv/h at the center of the detector
The count above the LLD was zero. Gamma ray influence was negligible.

The beta count was 100 times smaller when using the 0.05-mm-thick GAGG.

1. Alpha particle imaging detector development
2. Measurement at the Fukushima Daiichi Nuclear Power Station (FDNPS) site

The 0.05-mm-thick GAGG showed the best alpha energy resolution and was less sensitive to beta and gamma ray backgrounds.
The floors in reactor buildings units 2 and 3 were swiped with smear papers.

Afterwards, the smear papers were covered with a thin polyethylene film.

The smear paper was 5 cm in diameter.

(a) The detector used at the FDNPS site.

(b) Smear papers were placed over the alpha particle imaging detector.

(c) A piece of regular paper was used between the detector and the smear paper to help discriminate alpha from beta particle radiation.

Lower range values ➔ Beta particles

Higher range values ➔ Alpha particles

With a piece of paper between the detector and the smear paper

Higher range values (Alpha particles) were erased.
The alpha spectra were present in the 4 to 6 MeV ranges resultant from 5.5 MeV alpha particle emitted from 238Pu. Beta spectra were subtracted.

The spectra were similar in shape and value.

MOX Pu sample → Major isotope is $^{238}$Pu.

The spectra were similar in shape and value.

Beta particle spots were present on the smear paper.

Beta particle spots were present in uniform distribution.

Alpha particle spots were present in uniform distribution.
There are spots only in the MOX Pu sample.

Many spots in uniform distribution as found in the Smear paper.

It is highly likely that the particle diameters are different.

60 keV gamma-ray peaks were detected in smears nos. 2 and 4.

\[ ^{241} \text{Am}, \text{a} \, ^{241} \text{Pu decay product} \]

SC levels have exceeded 4 Bq/cm².

\[ \text{SC(Bq/cm}^2\text{)} = \frac{\text{Measured count(cps)}}{S \times F \times \varepsilon_s \times \varepsilon_i} \times \text{area ratio} \]

\begin{align*}
S: & \text{Wiped area (}=100 \text{ cm}^2) \\
F: & \text{Removal factor (}=0.1) \\
\varepsilon_s: & \text{Source efficiency (}=0.25) \\
\varepsilon_i: & \text{Instrument efficiency (}=0.99) 
\end{align*}

The alpha spectrum was in the energy range of 5–6 MeV, which corresponds to the alpha particle energy of \(^{238}\text{Pu}\) (5.5 MeV).

The alpha emitters in FDNPS must have different diameters from the Pu particle in the MOX fuel fabrication facility.

The surface contamination level of alpha emitters exceeded 4 Bq/cm².


This work was done in collaboration with Shiro Takahira, Hiroyuki Kikuchi, and Wataru Utsugi from Tokyo Electric Power Company Holdings, Inc.
8.4 Gamma-ray imaging based on compressed sensing

D. Boardman

Australian Nuclear Science and Technology Organisation

Abstract

We present the imaging results from two novel single pixel gamma-ray imaging systems, developed at ANSTO, in order to support the characterisation phase of decommissioning activities. The ability to remotely locate, identify, and quantify gamma emitting radionuclides can provide crucial information for the development of an efficient decommissioning plan. The imaging systems have been designed around the theory of compressed sensing and make use of a single spectroscopic detector and a set of dual, rotating, nested tungsten masks. The imaging system designs provide a large field of view and cover an energy range of 40 keV to 3 MeV. The first system has been specifically developed to image the High Flux Australian Reactor (HIFAR) reactor vessel with a hemispherical $2\pi$ field of view and provided quantitative information on the location of the gamma-ray emitting radionuclides present, whilst operating in a $\sim$10 Sv/h dose rate environment. The second system is a portable, high sensitivity imager with a cylindrical $360^\circ \times 90^\circ$ field of view used for localising and identifying low to medium dose rate sources in the remaining facility infrastructure. Gamma ray images were then accurately overlaid on optical images to allow for easy visualisation of the location of gamma emitting radionuclides. The spectroscopic gamma-ray imaging of point sources has been demonstrated with only 1/10$^{th}$ of the measurements normally required by traditional aperture based imaging techniques. The compressive gamma-ray imaging technique provides a novel and highly configurable spectroscopic imaging capability for applications in the nuclear industry.
ANSTO overview

- Formed in 1953
- HIPE critical 1958
- Annual turnover > $350 million
- ORNL Reactor Critical 2006
- Circa 1200 employees; 300 Ph.D.s
- $1 billion assets under management

ANSTO locations

- Darlington
- Lucas Heights
- Sydney
- Melbourne
- Adelaide
- Brisbane
- Perth
- Tasmania
- Northern Territory
- South Australia

Gamma-Ray Imaging via Compressed Sensing

David Boardman
Compressed Sensing

Measurement process

\[ y = M \mathbf{x} \]

\[ M \times 1 \]

measurements

\[ \begin{bmatrix} y_1 \\ \vdots \\ y_M \end{bmatrix} = \begin{bmatrix} \varphi_{1,1} & \cdots & \varphi_{1,N} \\ \vdots & \ddots & \vdots \\ \varphi_{M,1} & \cdots & \varphi_{M,N} \end{bmatrix} \mathbf{x} \]

\[ N \times 1 \]

signal

\[ M \ll N \]

Sensing matrix

\[ \min_{\mathbf{x}} \frac{1}{2} \| y - M \mathbf{x} \|_2^2 + \rho \| \mathbf{x} \|_1 \]

Compressive Gamma Imaging

- Platform technology
  - Detector optimisation
    - Low cost non-position sensitive detectors
    - Use any detector material (CZT, SrI2, CLLBC, CLYC, LaBr, CeBr)
    - Different detector geometries (0.5 mm³ – 44 cm³) for different dose environments
  - Mask optimisation
    - Mask thickness
    - Angular resolution
- Developed two system models

Part I – HIFAR imaging system

High Flux Australian Reactor at ANSTO

10 MW DIDO class reactor
Primary use: Neutron scattering and radioisotope production
Operated 1958 – 2007
Superseded by OPAL

HIFAR circa 1960
Calibrated Dose Rate and Activity

- 5 TBq $^{60}$Co source
- Electrometer Farmer 2570 ionisation chamber
- Dose rate accurate to ~1%
- Vary source to detectors distance to obtain relationship between ROI cps and dose rate

**Imaging from alternate locations**

**Summary**

- Dedicated system developed for imaging within the HIFAR reactor chamber
- First spectroscopic gamma-ray images of the reactor chamber (~10 Sv/h)
- Identified, located and quantified hotspots. Locations correlate with steel sleeves detailed in the historical records
- Key input into the decommissioning plan
Part II – Portable imaging system

- Portable system overview
  - 360° x 90° gamma & optical Field of View (FOV)
  - 40 keV - 3 MeV energy range (flashing up to 8 MeV)
  - 0.5 cm² CT - 44 cm CL BE
  - 20° angular resolution

Point source measurement

Signal to noise ratio

\[ \text{SNR} = \frac{\bar{x} - \mu_{B}}{\sigma_{B}} \]

- \( \bar{x} \) is the signal of the i-th pixel
- \( \mu_{B} \) = mean of the background
- \( \sigma_{B} \) = standard deviation of the background

1.7 MBq Am point source. 1 m

Compressed Sensing

M = 16
SNR = 10

M = 256
SNR = 35

Reconstructed image

Raster Scan
Extended source

- 2 x 10$^{5}$ Ge rods (0.8 m long)
- 2.6 m from detector
- 30 µSv/h dose rate at detector
- Background dose rate 0.5 - 0.7 µSv/h

Spectra

64 Measurements

D$_{2}$O plant room

source locations

source at 1 m

source at 2.3 m

source at 3.7 m

source at 5 m

Multiple point sources

- 1.7 MBq $^{241}$Am at 11 m
- 1.88 MBq $^{137}$Cs at 0.25 m
- 0.25 MBq $^{60}$Co at 0.5 m

Source locations

Site testing

- 241Am, M=25
- 137Cs, M=25
- 60Co, M=25
Thoronium bunker

Molybdenum production

Dingo - Radiography / Tomography

Centre for Accelerator Science

Identification of Cadmium prompt gamma-rays

Misaligned quadrupole focusing optics

Accelerator under normal operating conditions
Summary
- Platform imaging technology – reconfigure to desired application
- First demonstration of remotely deployed and operated gamma imaging system in 10 Gy/h environment
- Fast – compared to existing gamma spectrometers
- Low-cost – single non-position-sensitive detector
- Broad energy range (40 keV – 3 MeV) over large field of view (400 x 300)
- Excellent SNR
Gamma-ray imagers capable to operate in intense radiation fields are required for decommissioning of Fukushima Daiichi nuclear power plant. We propose a new gamma camera, named virtual pinhole camera (VPC) using directional gamma-ray detectors. Figure 1 show a schematic drawing of VPC. The VPC is constructed with arrays of directional gamma-ray detectors. The VPC requires no collimator and has wide view angle. In order to realize VPC, directional detectors were constructed with a compound semiconductor, thallium bromide (TlBr) in this study. Because TlBr has very high photoelectric absorption efficiency, small-volume gamma-ray spectrometer can be fabricated with TlBr. In this study, two types of directional detectors were fabricated. One detector consists of a Si scattering detector and a TlBr absorption detector. Only the incident gamma-ray scattered with small angle at the Si detector was detected with the TlBr detector. The direction and energy of the incident gamma-rays are determined with the detector system. The other type of directional detector consists of a led absorber and a TlBr detector. Because the incident angle of gamma-rays is limited by the led absorber, the detector system exhibits directivity. The results of detector fabrication and evaluation will be shown at the presentation.

Figure 1. Schematic drawing of VPC
9. Student Poster Session

**Award**

**Radiation measurement and sensing area**
- Mitsuhiro NOGAMI (Tohoku University)

**Radiation hardness device area**
- Kosuke MURAOKA (Hiroshima University)

**Robotic area**
- Naruki SHOJI (Tokyo Institute of Technology)

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Short-Channel 4H-SiC Trench MOSFETs for Harsh Environment Electronics

T. Ishii1, a), S.-I. Kuroki1, b), H. Sezaki2), S. Ishikawa2), T. Maeda2), T. Makino3), T. Ohshima3), M. Östling4), and C.-M. Zetterling4)

1) Research Institute for Nanodevice and Bio Systems (RNBS), Hiroshima University
1-4-2 Kagamiyama, Higashi-Hiroshima, 739-8527, Japan
2) Phenitec Semiconductor Co., Ltd, Ibara, 715-8602, Japan
3) National Institutes for Quantum and Radiological Science and Technology (QST)
1233 Watanuki, Takasaki, 370-1292, Japan
4) KTH Royal Institute of Technology, Kista SE-16440, Sweden
E-mail: a)tomoyasu-ishii@hiroshima-u.ac.jp, b)skuroki@hiroshima-u.ac.jp

Semiconductor devices operable in high radiation and/or high temperature environment have been required. Silicon carbide (SiC) device is attracted a lot of attention because high temperature and high radiation resistance of SiC is higher than silicon. We demonstrated 4H-SiC planar MOSFETs at high temperature of 450°C and high gamma-ray radiation of over 1 MGy [1]. In addition, we demonstrated pseudo self-aligned-gate 4H-SiC trench MOSFETs to reduce parasitic capacitance [2]. For high frequency operation, it is better to introduce short-channel MOSFETs, but we need to consider the negative phenomenon called short-channel effects (SCE) such as decrease of threshold voltage and punch-through behavior. In this work, we investigated a suppression of SCE in the pseudo self-aligned-gate 4H-SiC trench MOSFETs.

Planar and trench MOSFETs were fabricated on a same p-type 4H-SiC epitaxial wafer. The source/drain region were formed by ion implantation. After that, high temperature annealing was performed. SiO2 hard mask was deposited. The SiO2 layer and SiC layer were etched to form the trench structures. Gate oxide was formed by dry oxidation. Niobium/Nickel ohmic contacts and Aluminum electrodes were formed. Fig. 1 shows a cross-sectional schematic of fabricated MOSFETs.

Fig. 2 shows threshold voltage roll-off characteristics of the planar and the trench nMOSFETs. This graph was derived from $I_D-V_G$ characteristics. Threshold voltage of the planar-nMOSFETs abruptly decreased as the channel length became smaller than 2 μm. On the other hand, at the trench-nMOSFETs with channel length of below 2 μm, the threshold voltage kept its value around the original value of the 5 μm-device. Therefore, the short channel effect was suppressed by the trench structure. Since the electric field in the channel from the S/D regions was suppressed by the structure. As a result, the pseudo self-aligned-gate 4H-SiC trench MOSFETs have a great potential for the short channel devices.

Part of this work was partially supported by JSPS KAKENHI (Grants-in-Aid for Scientific Research) for international joint research, Grant Numbers JP15KK0240, and JSPS KAKENHI (B), Grant Numbers JP17H03253.

Due to recent advances in growth technology, applications of diamond radiation detectors are progressing. Particularly, in medical irradiation, space, accelerator, there is a strong demand for enlarging the sensitive area. In previous study, high-performance 5mm square diamond radiation detectors by use of lift-off method and HP/HT type-IIa substrates were reported. In addition, Fano factor of diamond detector was evaluated for first time. In this study, to make further large sensitive volume, influence of substrates on charge carrier transport properties was evaluated. Furthermore, 8mm square diamond energy spectrometer was developed and uniformity of charge carrier transport properties was evaluated.

Single-crystal CVD diamond layers were grown homoepitaxially on (100) surfaces of three different-type diamond substrates with off-angle of 3degrees in the <110> direction. These substrates were as follows: “general grade” CVD-type (8 × 8mm) provided by Element Six Ltd, HP/HT Ib-type (3 × 3mm) and HP/HT Ila-type (5 × 5mm) provided by Sumitomo Electric Industries Ltd.. The growth condition was as follows: CH₄:H₂ ratio 0.2%, gas pressure 110Torr and substrate temperature 850°C. This condition gave excellent charge carrier transport characteristics on HP/HT Ila-type substrate. Then grown layers were lifted off using electrochemical etching. Electrodes with 3mm diameters were fabricated on both sides of growth layers. They were studied using CL measurement and alpha-particle-induced charge distribution measurement.

An 8mm square sample grown on a CVD-type substrate, charge collection efficiencies (CCE) were 99.9% for holes and electrons, energy resolutions were 0.39% for holes, 0.50% for electrons. μτ products were (5.0±0.3)×10⁻⁵cm²/V for holes and (1.8±0.2)×10⁻⁵cm²/V for electron. These μτ products were intermediate between growth layers grown on a HP/HT Ib-type substrate and a HP/HT Ila-type substrate. These results were probably influenced by crystallinities of substrates. Fig. 1 shows the position dependence of μτ products in an 8mm square diamond detector. ‘A’ region was grown at the peripheral part of the plasma. μτ products probably deteriorated because etching of growth defects was insufficient.

References
P3 Robot development of creative robot contest for decommissioning
Yuuta ENDO¹
Shigekazu SUZUKI¹

¹) National Institute of Technology, Fukushima College; 14103@fsnct.com

1. Introduction
The decommissioning reactor has been regarded as important since the accident at Fukushima Daiichi Nuclear Power Station due to the earthquake disaster. Initiatives such as human resource development for decommissioning measures of Units 1 to 4 of Fukushima Daiichi Nuclear Power Plant are under way. National Institute of Technology, Fukushima College has also participated in the Robot Contest for Decommissioning for the past two years to develop human resources. Two years ago the robot created by referring to the rescue robot. Last year, we designed and built a debugging robot from inside the reactor building with improvements based on previous reflections. The problem of the Robot Contest for Decommissioning is to move up and down without sliding the mock-up stairs. Foster a new way of thinking to solve the problem of Fukushima Daiichi Nuclear Power Plant by the Robot Contest for Decommissioning. Consider the problem of actually making a robot and realistically making a robot, aiming to develop problem discovery and resolution ability.

2. Event summary
a) To select the playing field in each team from the two fields of the following assumes the reactor building. (a) Mock-up stairs and (b) Standard step field
b) As a field environment, there is no lighting and it is dark.
c) It is necessary to remotely control the robot. Radio waves do not reach.

3. Explanation of robot
The name of the robot is Hairon. It is used for 2 years. Competition challenge is to carry 5 kg baggage up and down the stairs. The operation of the robot is performed by a wired controller. I made a shielding material to protect the robot from the influence of radiation. For the shielding material, FRP with copper powder added was used.

4. Event result
Robot could not climb the stairs two years ago. One of the reasons is that the robot body is smaller than the size of the stairs. This is because the friction of the crawler used for the robot is small. Last year, in order to improve the problem of rubbing, robot added a slip stopper to the crawler. However, robot loaded 5 kg of baggage, but it slid through the mockup stairs.
P4 Development of an Underwater Swimming Robot for Sensing in the Nuclear Reactor with a Landing Mechanism

Satoru OCHI1, Hideharu TAKAHASHI2, Gen ENDO3 and Hiroshige KIKURA2
1 Department of Mechanical Engineering, Tokyo Institute of Technology/ N1-7, 2-12-1, Ookayama, Meguro-ku, Tokyo 152-8550, Japan
2 Laboratory for Advanced Nuclear Energy, Institute of Innovation Research, Tokyo Institute of Technology/ N1-7, 2-12-1, Ookayama, Meguro-ku, Tokyo 152-8550, Japan
3 School of Engineering, Tokyo Institute of Technology/I1-68, 2-12-1, Ookayama, Meguro-ku, Tokyo 152-8550, Japan

In the Fukushima Daiichi Nuclear Power Plant (NPP), the investigation of NPP condition is conducted so that fuel debris can be removed. Because of radiation, the sensor for measurement and visualization must be transported and manipulated by a robot. Some research has applied ultrasound technique for visualizing of the internal condition of containment vessels. Measuring fuel debris shape and detecting a leakage location by cooling water flow measurement has been researched. Ultrasound can be applied to opaque liquids, and has high radiation resistance. However, the vibration of the robot during moving and swimming causes a disturbance to the measurement, thus it is difficult to measure while swimming.

In this research, we aim to develop an underwater swimming robot that can land on the floor inside the containment vessel and keep its posture during measurement. By keeping still during the measurement, it can be avoided the vibration of the robot. The developed robot (Figure.1) consists of the lower landing mechanism and the upper swimming propulsion mechanism. The landing mechanism was designed to passively pull out the legs by the differential mechanism as the robot lands vertically. This differential mechanism makes it possible to compensate for a rugged floor surface. The propulsion mechanism consists of four vertical thrusters which give the robot vertical controllability and propulsion power. And the robot is controlled by this propulsion mechanism moving to the position to be measured. In addition, we installed an ultrasound sensor on the robot and conducted an experiment to detect a leakage by water flow measurement.

In this poster, we report in detail on the landing mechanism, the control mechanism of the developed robot and experiment that detect a leakage and discuss the applicability of this system to PCV internal survey.

Figure.1 Underwater Swimming Robot for Sensing in the Nuclear Reactor with a Landing Mechanism
P5 Radioactive Distribution Mapping of Multiple Radiation Sources Using a Mobile Robot Equipped with a Radiation Detector

Takuya Kishimoto, Hanwool Woo, Yusuke Tamura, Yusuke Oshima, Kenji Shimazoe, Hiroyuki Takahashi, Atsushi Yamashita, and Hajime Asama
The University of Tokyo
kishimoto@robot.t.u-tokyo.ac.jp

We propose the system of radioactive distribution mapping using a mobile robot. The robot localizes its position when it observes radiation. The observing positions and detector’s data are combined to reconstruct a radioactive distribution map.

We use Rao-Blackwelized Particle filter for Simultaneous Localization and Mapping (SLAM). On the other hand, Maximum Likelihood Expectation Maximization (MLEM) is used for reconstruction of the radioactive distribution map.

Experiment in which multiple radiation sources are used is conducted. The robot observes radiation at 8 positions using a compton camera as a radiation detector. Radioactive distribution map partially overwraps the position of radiation sources. However, measuring error occurs discrepancy. As future works, we create more accurate radioactive distribution map.
P6 Posture stability evaluation of disaster plant investigation robot by robot simulator

Ginga SATO1)  
Shigekazu SUZUKI1)  
1) National Institute of Technology, Fukushima College; 14122@fsnet.com

Due to the accident of Fukushima Daiichi Nuclear Power Plant, 1F is decommissioning now. In the vicinity of the nuclear reactor building, radiation dose is decreasing. People started to enter the vicinity of the building and work is ongoing. However, inside the nuclear reactor building, the place where people can enter is restricted because it is still high radiation dose.

Robot work is required in places where such people do not enter. In order to surely advance the work, it is necessary to have skilled operators and robots with performance for task execution. Even now, task execution is expected reliably and safely when remote work is done with a robot etc. In some case trouble has been reported. For this reason, efforts to improve the robot operation proficiency of the operator as well as advancing robot development according to the task are important. It is also important to build a framework to evaluate the operation proficiency.

Therefore, in this research, we will research and develop a method to evaluate during maneuvering training using “choreonoid” from features that can be tried repeatedly in the same environment and ease of data acquisition for evaluation. Specifically, an evaluation method introducing stability margin is constructed. It is an index based on supporting polygon and center of gravity position obtained from robot and ground contact point information on the ground.
Precise control of threshold voltage of 4H-SiC JFET for radiation hardened image sensors

K. Shimizu¹,², Y. Tanaka¹, S. Kuroki³, T. Makino⁴, A. Takeyama⁴, and T. Ohshima⁴
¹) National Institute of Advanced Industrial Science and Technology, 1-1-1 Umezono, Tsukuba, Ibaraki 305-8568, Japan
²) Interdisciplinary Graduate School of Medicine and Engineering, Yamanashi University, 4-3-11 Takeda, Kofu, Yamanashi 400-8511, Japan
³) Research Institute for Nanodevice and Bio Systems, Hiroshima University, 1-4-2 Kagamiyama, Higashihiroshima, Hiroshima 739-8527, Japan
⁴) National Institutes for Quantum and Radiological Science and Technology, 1233 Watanuki, Takasaki, Gunma 370-1292, Japan
*E-mail: shimizu-keigo@aist.go.jp

Introduction  In the Fukushima Daiichi nuclear power plants, radiation hardened image sensors have been required for decommissioning. Silicon Carbide (SiC) is expected as semiconductor material enabling the stable operation in high temperature and high radiation environments. By using JFET structure without the gate insulating oxide layer like as MOSFET, we could obtain high reliability as the radiation-hardened devices. In this work, we successfully fabricated SiC-JFETs with normally-on and normally-off characteristics to develop the radiation hardened image sensors.

Results and discussion  Fig. 1 shows a schematic cross-section of the SiC-JFET structure fabricated in this work. The JFET was fabricated using the n-type epitaxial layer with the doping concentration of $2 \times 10^{17} \text{cm}^{-3}$ and the thickness of 3.0μm on the 4H-SiC(0001) substrate. The p-type and n-type regions were formed by Al and P ion implantations at 600°C, respectively. After ion implantation, activation anneal was carried out at 1650°C for 10 min in Ar atmosphere. Source, gate, and drain contacts were formed by evaporating Al and Ni of 15nm and 50nm, respectively followed by the sintering annealing at 950°C for 2min in Ar atmosphere. Finally, Al was deposited for pad electrodes.

Fig. 2 shows $I_d-V_g$ characteristics for normally-on and normally-off SiC-JFET fabricated in this work. $V_{th}$ can be controlled by changing the channel depth ($W_{ch}$). Fig. 3 shows the temperature dependence of $I_d-V_g$ characteristics for normally-off SiC-JFET. The high On/Off ratio and high subthreshold slope are achieved at wide range of temperature from 25°C to 300°C. Especially, a leakage current is remarkably suppressed below detection limit even at 300°C. Additionally, we must point out that $V_{th}$ keeps the positive value (normally-off operation) even at 300°C. In our presentation, we will talk about the radiation resistance of the SiC-JFETs.

Fig. 1. Schematic cross section of SiC-JFET fabricated in this work
Fig. 2. $I_d-V_g$ characteristics of the normally-on and normally-off SiC-JFET at 25°C
Fig. 3. Temperature dependence of $I_d-V_g$ characteristics in the temperature range of 25°C to 300°C

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Research Expansion of the Internally-Balanced Magnetic Unit

– Principle of Balancing Method using Magnetic Spring and Application Mechanisms –

Tori Shimizu, Tohoku University

To detach permanent magnets with a control force much smaller than their attraction force, “Internally-Balanced Magnetic Unit (IB Magnet, Fig. 1 a)”[1] has been developed and incorporated into magnetic devices such as those used in wheels of wall-climbing robots, anchor mechanism for multirotors and magnetic joints of modular robots[2]-[4]. In contrast to its drastic reduction rate on the control force, the IB Magnet has two major problems on its nonlinear spring for balancing force to cancel the internal force: complication of its design procedure and trade-off relationship between balancing precision and mechanism volume. The researchers have proposed a principle of an IB Magnet using a like-pole pair of magnets as a magnetic spring, whose repulsion force exactly equals the attraction force of an unlike-pole pair (Fig. 1 d). To verify the principle, the researchers realized its prototype model and found through experiments its reduction rate comparable to those of conventional IB Magnets.

Magnetic spring method is also a potential solution to the demagnetizing problem of the IB Magnet used in the nuclear power plant decommissioning. Demagnetization of a magnet due to the high nuclear radiation and high temperature has been a matter of great concern when applying the IB Magnet to robots and other machines used in nuclear power plants, especially in those in accidents, because the nonlinear spring is designed to fit the adhesion characteristic of a fully magnetized magnet. As the magnet decays, the repulsion force of the spring exceeds the adhesion force of the magnet, resulting in a forced release of the IB Magnet (Fig. 2 a). By using a pair of magnets identical to the magnet for adhesion, the IB Magnet using magnetic spring is expected to sustain the force balance because the demagnetization of the magnets occurs at likely rates so that the repulsion force of the spring fits to the decreasing adhesion force by itself (Fig. 2 b).

Moreover, regarding the IB Magnet as a highly efficient force-displacement converter, the researchers discussed application examples containing IB Magnets as their internal mechanisms. So far, a magnetic crawler, a magnetic gripper, a parallel finger gripper, a brake, and a jumping mechanism, each requiring no powerful actuators, have been realized and proved their effectiveness.

P9 Study on Leakage Location Estimation System with Ultrasonic Flow Vector Map

Naruki Shoji1, Hideharu Takahashi2 and Hiroshige Kikura2

Graduate Major in Nuclear Engineering, Tokyo Institute of Technology
2-12-1 Ookayama, Meguro-Ku, Tokyo 152-8550, Japan

Laboratory for Advanced Nuclear Energy, Tokyo Institute of Technology
2-12-1 Ookayama, Meguro-Ku, Tokyo 152-8550, Japan

Recently, robot investigations have been conducted to obtain information (e.g. fuel debris distribution, dose ratio distribution and leakage points etc.) in the primary containment vessels (PCVs) of Fukushima-daiichi nuclear power plant (NPP). The optical images have been captured and analyzed in the investigations. However, these investigations have not yet unveiled completely the location of leaks (the repair of which is vital for fuel debris removal) and accurate distribution of fuel debris (an important factor in deciding the future fuel removal procedure). These inspections are hindered by a high-dose radioactive environment and an opaque liquid which becomes from the suspended particulates in the coolant water. Therefore, methods other than optical methods are required to inspect within the PCVs. Then we focused on ultrasonic measurement techniques. Ultrasonic sensors have a high-dose radioactive tolerance and can apply to an opaque liquid. Therefore, ultrasonic techniques are expected as investigation methods. Classical ultrasonic techniques, however, just capture images from echo signals, then it is difficult to identify locations of leaks from only images because these images have no flow information of coolant water. Therefore, we have decided to combine an ultrasonic imaging and a flow measurement technique. As a flow measurement technique, we have developed an ultrasonic velocity profiler (UVP) system. And also, we have combined the UVP and phased array technique and may be measured flow vector map. Leakage locations may be identified by observing flow behavior of coolant water. Then, our aim is development of leakage location estimation system. Especially, the UVP system with phased array sensor is used to obtain a flow vector field. In the actual environment within the PCVs, the leaking speed and leakage locations are unknown. Therefore, flow measurement required wide measurable distance range and wide detectable velocity range. However, the conventional UVP method have a restraint condition between the measurable distance range and the velocity range; These cannot be increased simultaneous. Then, we developed an algorithm for wide distance and velocity range measurement in the UVP. In addition, the estimation of simulated leakage was conducted using this method and the applicability of this system was verified.
**1. Introduction**

For decommissioning operations of the Fukushima Daiichi nuclear power plant, radiation-hardened robots are required. However, currently available semiconductor devices are vulnerable to radiation and cannot correctly keep robot operations under a heavy radiation environment.

Therefore, we have been developing Optically Reconfigurable Gate Arrays (ORGA) which will be applied for radiation-hardened robots [1]. To use ORGA for robots, we need to design and implement a full-hardware robot controller. In the previous study, the inverse kinematics module of a leg was implemented onto a Cyclone V FPGA [2].

This paper presents a new control unit for six legs implemented on an Arria10 FPGA.

**2. Control algorithm of six-legged robot**

In this research, a robot with six legs was used as a prototype. The robot has 18 servo motors for six legs. The servo motors were controlled by Arria10 FPGA through servo motor drivers. The control algorithm implemented onto the Arria10 FPGA consists of coordinate transformation modules from the global coordinate system to the local coordinate systems of each legs (CdTs), inverse kinematics calculation modules which calculate the angle of each joints from orbit (Ivks), conversion modules from the angles of joints to PWM pulse widths (Ang2Pwms), and PWM signal generation modules (PWMs) [2]. In this implementation, we have used the Cyber Work Bench (CWB) as a high-level synthesis compiler which is provided from NEC Corporation.

The CWB converted from C language to Verilog-HDL code and the compilation result was implemented onto the Arria10 FPGA as.

We’ve evaluated the circular motion of the legs on the robot. Although the entire orbit at the tip of each legs was calculated by software, almost all of the control functions were performed with each hardware module on the Arria10 FPGA.

**Table 1: Resource consumption**

<table>
<thead>
<tr>
<th>Module</th>
<th>ALMs</th>
<th>Register</th>
<th>BRAM kbs</th>
<th>DSP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arria 10 Soc</td>
<td>251,688</td>
<td>107,958</td>
<td>43,643</td>
<td>1,667</td>
</tr>
<tr>
<td>PW M</td>
<td>134</td>
<td>214</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ang2Pwm</td>
<td>707</td>
<td>957</td>
<td>34</td>
<td>5</td>
</tr>
<tr>
<td>Ang2Pwm (no DSP)</td>
<td>1,741</td>
<td>1,600</td>
<td>34</td>
<td>0</td>
</tr>
<tr>
<td>Ang2Pwm</td>
<td>3,887</td>
<td>5,102</td>
<td>196</td>
<td>37</td>
</tr>
<tr>
<td>(no DSP)</td>
<td>10,831</td>
<td>9,497</td>
<td>195</td>
<td>0</td>
</tr>
<tr>
<td>CdT</td>
<td>299</td>
<td>973</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>CdT (no DSP)</td>
<td>2,087</td>
<td>2,167</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6 legs</td>
<td>40,254</td>
<td>57,528</td>
<td>1,788</td>
<td>348</td>
</tr>
<tr>
<td>(no DSP)</td>
<td>110,058</td>
<td>102,636</td>
<td>1,782</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 1 shows the resource usage. The resource usage in the case of using DSP was lower than that in the case of not using DSP. In the future, we will replace the Arria10 FPGA with a radiation-hardened optically reconfigurable gate array.

**Acknowledgment**

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**References**


P11 Application of Double-sided Silicon Strip Detector for Compton Camera
Zhong Zhihong, K Shimazoe, H Takahashi, M Uenomachi
The University of Tokyo, Graduate School of Engineering, Department of Nuclear Engineering and Management

Abstract

In the decommissioning procedure of Fukushima Daiichi nuclear reactor, one key issue is to locate the fuel debris in reactor building. One solution is to use Compton camera, since it has high detection efficiency to gamma-rays with MeV energy that is concerned. It also has high resolution and the ability to detect a wide range of area. We proposed the use of Double-sided Silicon Strip Detector as the scatterer in Compton camera. Its unique structure allows a significant save on readout electronics. We used an Application Specified Integrated Circuit (ASIC) to read and process the signal from the detector, which implements the slew-rate time-over-threshold (ToT) technique. We evaluated the performance of the detector and ASIC. For the \(20 \times 20\, \text{mm}^2\) detector we tested, the leak current is less than 0.5 \(\mu\text{A}\) under depletion voltage. The corresponding capacitance is \(~30\, \text{pF}\). For the ASIC, the equivalent noise charge (ENC) when connected to a 30-pF detector is \(~1500\, \text{electrons (RMS)}\). When measured by a test pulse, the ToT signal from the ASIC shows good linearity. The spectrum of the DSSD detector shows a good potential to be used as the scatterer in Compton camera system.
An operator for teleoperation robot generally controls the robot by seeing the image from the camera which is attached to the robot to obtain the state of the robot. However, it is very difficult for the operator to obtain information for the robot because its camera can obtain only information within the angle of view. However, this method requires algorithms and hardware that realize communication band securing and highly efficient compression with low delay. On the other hand, multiple robot arms with camera enable to be efficient work and observation from various viewpoints. However, this method has a problem that interference between arms.

Therefore, in this study, we propose an assistance system for operator of teleoperation robot through cooperation between real space and virtual space. Moreover, we apply this system to E2 Spider which challenged in the Standard Disaster Robotics Challenge in WRS2018 (World Robot Summit 2018). E2 Spider is a disaster response robot and has two main crawlers and four sub crawlers, and two JACO 2 arms. This robot has six intel RealSense Depth Camera D435; Two in front, one in each arm, one in the right side and one in the back.

Our proposed assistant system consists of three laptop computers; one is attached to E2 spider, two is used for the operator. Two laptop computers for the operator is used for display of images from the camera and for display of the robot state. These laptop computers communicate each other via a router. The laptop computer on the spider controls crawlers and the arms based on the operation information of the controller sent from the operator via OpenRTM-aist. As a feedback, the value of the rotary encoder installed in each crawler and arm is transmitted to one laptop computer for the operator. The position and angle of the robot is expressed as a virtual 3D robot model with Choreonoid. They are calculated with the odometry and the angles of two sub-crawlers and each joint. The odometry is calculated based on the rotation amount of the crawler. Each angle is calculated by the values of the rotary encoder. The position and angle of the robot is expressed as a virtual 3D robot model with Choreonoid. They are calculated with the odometry and the angles of two sub-crawlers and each joint. The odometry is calculated based on the rotation amount of the crawler. Each angle is calculated by the values of the rotary encoder. The operator can check the state of the arm and whether it does not interfere the other arm by seeing the 3D model. Moreover, it can be confirmed from various angles due to 3D model in the virtual space. Similarly, it is possible to confirm the angle of the sub-crawler and to assist traveling in the case of off-road running.

Additionally, the camera image is transmitted to the other computer for the operator.

In WRS 2018, it is required to set up the robot in a state it can operate within five minutes. In this system, system startup is scripted. It is possible to be in the state it can operate remotely in about three minutes by executing the script once in each laptop computer. When the script ends, our proposed system returns automatically to the state before starting. This enable to recover in a short time by only operators even if the trouble occurs. In WRS competition, it was confirmed that our system ran with no trouble in the all of eight missions as a result.
The accident in Fukushima Daiichi Nuclear Power Plants (FDNPP) on March 11, 2011 released large amounts of radionuclides into the atmosphere. The main fission products from the FDNPP accident are $^{129m}$Te-$^{129}$Te, $^{131}$I, $^{132}$Te $^{132}$I, $^{134}$Cs, $^{136}$Cs and $^{137}$Cs. [1] There are still contaminated areas with considerable amounts of radioactive substances in Fukushima prefecture.[2]

Some of the most contaminated areas are the reactor buildings, and very large amounts of radionuclides (mainly $^{137}$Cs and $^{134}$Cs) have been detected from measurements inside the reactor buildings. Therefore, to execute decommissioning tasks in the reactor buildings, radiation distribution measurements inside the buildings are necessary.[3]

For the decommissioning and decontamination processes, it is necessary to know the radiation levels inside the reactor and other buildings. To measure and monitor gamma-ray radiation is therefore important. There have been several attempts to measure the radiation distributions inside the reactor buildings by using gamma-ray detectors with a wide Field of View (FoV), which can quantitatively visualize the Cs contamination. These active detectors can measure the radiation distribution rapidly to identify the locations of the radiation sources.[4]

However, with the large amounts of radionuclides still inside the reactor buildings, it is difficult to obtain information about local dose distributions. Gamma spectrometers or radiation area monitors are not always working. They are also easily broken, and not resilient to high dose radiation fields.[5]

In this research, an integral type gamma-ray imager based on Optically Stimulated Luminescence (OSL) technology are proposed.[6] OSL has been used extensively for personal radiation dosimetry for many years. By combining it with a pinhole camera principle, this passive detector is capable to visualize the position of radioactive substances. Therefore, to optimize the structural design and detection measurement system we are using the simulation code PHITS (Particle and Heavy Ion Transport code System) and then compare the calculated result with the experiments.
Decommissioning of Fukushima Daichi nuclear reactor has a lot of challenge. A direction sensitive gamma-ray detector is required to localize the position of debris in nuclear reactor building. One of the solution is using Compton camera since it has high detection efficiency to gamma-rays with MeV energy. Compton camera is one of the good choice cause it has high-resolution, relatively high-efficient, and have wide range of gamma-ray source. We developed a detector using $8 \times 8$ Ce: Gd$_3$Al$_2$Ga$_3$O$_{12}$ (Ce: GAGG) scintillator array coupling with photodiode array. For the scatter side, the one GAGG size is $10 \times 10 \times 5$ mm and for absorber side is $10 \times 10 \times 10$ mm. This detector connected to 64 channel slew-rate time-over threshold Application Specific Integrated Circuit (ASIC) for parallel readout of deposited charge. Equivalent noise charge (ENC) on this TOT ASIC with a detector capacitance of 30 pF was $\sim$1500 electron (RMS). The ASIC chip has a good linearity and good equivalent noise charge. By combining Ce: GAGG scintillator coupling with photodiode and slew-rate time over threshold ASIC we are building a fast high sensitivity Compton camera.
In the Fukushima Daiichi Nuclear Power Plant (NPP), there is a place where the background of \( \gamma \) rays (mainly \(^{137}\text{Cs}\)) is high, which hinders the promotion of the decommissioning work. In order to promote the decommissioning work, information on the spatial distribution of \(^{137}\text{Cs}\) is necessary. Therefore, we aim to fabricate \( \gamma \)-ray imagers using directional detectors that can operate in intense radiation fields (around several mSv/h) such as Fukushima Daiichi NPP building environment or its surroundings. Pinhole cameras and compton cameras are widely used for \( \gamma \)-ray imaging. But these \( \gamma \)-ray imaging technique is not suitable for using in intense radiation fields. So, a new \( \gamma \)-ray imaging method is required. We proposed a new \( \gamma \)-ray imaging system, that is virtual pinhole camera (VPC). In order to realize VPC, there is a need to develop innovative directional \( \gamma \)-ray detectors. Detectors of constituting VPC are required good energy resolutions and operation in intense radiation fields. TlBr semiconductor detectors have good potential to apply to constitute of VPC. Because TlBr has a high density and high absorption efficiency for 662 keV \( \gamma \)-ray from \(^{137}\text{Cs}\). We fabricated several TlBr detectors (Fig. 1) to evaluate the characteristics of TlBr detector in intense radiation fields. The \(^{137}\text{Cs}\) spectrum obtained from the TlBr detector is shown in Fig. 2. Detailed results will be posted on the poster.
Abstract
Concrete is widely used in our lives such as buildings, bridges, dams, etc. The strength formation reaction process is defined by

$$2C_3S + 6H_2O \rightarrow C_3S_2H_3 + 3Ca(OH)_2$$

Therefore, it is possible to estimate the degree of progress of the strength formation process by measuring the water content coefficient in concrete, and it is possible to more safely avoid the risk of lowering the strength. Each conventional inspection method has advantages and disadvantages, so there is no standard test method yet. In this study, as a new method, we measure the moisture content inside a concrete sample by using subterahertz waves that penetrate concrete and have strong absorption in water [1]. As a light source, a GUNN diode with an oscillation frequency of 60 GHz was used. Since this frequency is a frequency sensitive to water, it is suitable for water content measurement of concrete. Fig.1 shows the results of measurement of transmission and reflection intensity in concrete moisture content change. As a result, as the water content increased, the transmission intensity decreased and the reflection intensity increased. This is because water content of concrete absorbs terahertz waves, so it is considered that the absorption increases as the moisture content increases. From this result it can be said that the moisture content of the concrete can be measured by transmission and reflection intensity measurement by terahertz wave.

Reference
Hybrid Pixel Devices By Bonding SOI-Si and 4H-SiC for Radiation-Hardened Image Sensors

Fumiaki Hasebe1), Tatsuya Meguro1), Takahiro Makino2), Akinori Takeyama2), Takeshi Ohshima2), Yasunori Tanaka3), and Shin-Ichiro Kuroki1)

1) Research Institute for Nanodevice and Bio Systems, Hiroshima University
1-4-2 Kagamiyama, Higashihiroshima, Hiroshima, 739-8527, Japan
2) National Institutes for Quantum and Radiological Science and Technology (QST), 1233 Watanuki, Takasaki, 370-1292, Japan
3) National Institute of Advanced Industrial Science and Technology (AIST), 1-1-1 Umezono, Tsukuba, Ibaraki, 305-8568, Japan
E-mail: {fumi-hasebe, skuroki}@hiroshima-u.ac.jp

Responding to the accident at Fukushima Daiichi Nuclear Power Station, research and development for safety decommissioning processes are progressing both in Japan and overseas. So far for such decommissioning operations, many robots have been installed, however the available time for operation is limited by electronics, in particular, image sensors. 4H-SiC has excellent properties for the radiation-hardened electronics[1,2], however for the image sensors, 4H-SiC do not have sufficient absorbance at visible light. At a pixel device in a conventional Si CMOS image sensor, Si MOSFETs are sensitive and vulnerable to radiation. In this work, SOI (Silicon-On-Insulator)-Si PD and 4H-SiC MOSFETs were integrated in a same substrate for the radiation hardened image sensors, and were demonstrated.

The 4H-SiC pMOSFETs were fabricated on 4H-SiC (0001) 4° N-type epitaxial substrate. The source and drain (S/D) regions were formed by thermal ion implantation of Al and high temperature annealing using a carbon-cap layer. After this process, 20 nm gate thermal oxide was formed. Silicon PDs were fabricated with SOI substrate with 1.5 μm Si(100) active layer. The SOI substrate was thermally oxidized, and SiO2 of 10 nm thickness was formed. After boron ion implantation on the SOI, the SOI substrate and the 4H-SiC epitaxial substrate were bonded with diluted HF solution and pressed by two plates for 24 hours. The Si handle substrate and BOX-SiO2 were chemically removed. As the result, SOI-Si(100) layer of 1.5 μm thickness was formed on the 4H-SiC substrate. On the SOI-Si/4H-SiC substrate, phosphorus ions were implanted for forming N⁺ region of the SOI-Si PDs. The SOI-Si layer was patterned to form Si PDs and silicon gate of 4H-SiC pMOSFETs by dry etching. Finally, an interlayer insulating film was formed, and an Al electrode was formed after etching the contact bias.

The microphotograph of the fabricated hybrid pixel device with the SOI-Si PD and 4H-SiC pMOSFETs were shown in Fig.1. The typical feature size of the SOI-Si PD was 500 μm² and that of 4H-SiC pMOSFET was channel length/width = 10 μm/50 μm. Output characteristics under dark condition and visible light were shown in Fig.2. In this measurement, VDD and VRS were fixed to -5.5 V, and at the RST a rectangular voltage with VHi=0 V and VLow=-5 V and with a frequency of 100 Hz was applied. Under a dark condition, the output voltage shift from the reset state was 0.62 V. On the other hand, under a visible light of 7 klux, the output voltage shift became 0.74 V. As the results, the hybrid pixel devices with SOI-Si PD and 4H-SiC pMOSFETs were successfully demonstrated.

A part of this work was supported by The Center of World Intelligence Project for Nuclear S&T and Human Resource Development, Strategic Nuclear Power Joint Research Program, under the MEXT, Japan.

![Fig. 1. SOI-Si PD/4H-SiC pMOS pixel device.](image1)

![Fig. 2. Output characteristics with RST operation of 100 Hz under dark condition and under visible light.](image2)
P18 Radiation-hardened motor controller
Takumi Hatamochi and Minoru Watanabe
Graduate School of Science and Technology, Shizuoka University
3-5-1 Johoku, Hamamatsu, Shizuoka 432-8561, Japan
Email: watanabe.minoru@shizuoka.ac.jp

1. Introduction
In recent years, radiation-hardened robots are needed for the Fukushima Daiichi nuclear power plant. However, transistors are vulnerable to radiation. The transistors are deteriorated by radiation so that permanent failures occur on them [1].
In this paper, we report radiation-hardened motor controller and its radiation tolerance.

2. Motor controller
A circuit diagram of a motor controller using a bipolar transistor is shown in Fig.1. The base of the transistor is controlled by a field programmable gate array (FPGA). The pulse width modulation (PWM) signal is generated by the FPGA.
The rotational speed of the motor is measured by a photo interrupter as shown in Fig.2. The PWM speed control was performed based on the information from the photo interrupter.

3. Radiation experiment
Radiation experiments were conducted on the motor controller. While performing a PWM operation on the motor controller, the radiation is exposed to the controller using a cobalt 60 radiation source. The total-ionizing-dose is 12 Mrad.

4. Experimental results
The rotation speed of the motor could be kept as a constant until 12 Mrad. Fig. 3 shows the relationship between the duty ratio of the PWM control signal to the motor controller and the radiation dose.

5. Conclusion
We confirmed that the total-ionizing-dose of the motor controller using a bipolar transistor is at least 12 Mrad. We are continuously doing the radiation experiment to clarify the limitation of the total-ionizing-dose tolerance.

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Reference
P19 Modal planning in Non-Prehensile Manipulation with Multiple Mobile Robots
Changxiang Fan, Shouhei Shirafuji, Jun Ota
The University of Tokyo

In disaster sites where the narrow space restrains the application of large-scaled industrial robots, small-sized mobile robots can work as a coordinated system to transport big-scaled objects, for which a fine manipulation planning is required. In manipulation planning, defining a mode as a set of certain configurations that hold the same constraint, configuration space comprises varying dimensional sub-spaces corresponding to each mode. A planner should be capable not only to probe the configuration space of each mode, but also to reason about the transition-ship between modes. However, when multiple mobile robots manipulate an object with non-prehensile method, the object contacts with robots and the environment it lies in. Such multi-contact states complicate the transition-ship between modes, and thus make it difficult to probe the mode space while creating their respective configuration spaces simultaneously. On the other hand, the engaged number of robots should be well determined, through which the multi-contact on the object can guarantee the stability of object during the manipulation. Consequently, modal planning is desirable to build up the roadmap of modes before probing the configuration space, with modes proper created.

With a mode defined as an object’s contact state with robots and environment, we created modes by combining environmental contact and robot contact, which were created respectively beforehand, to generate contact states provided such multi-contact set, together with gravity, achieved force closure on the object. We specially considered environmental contacts where relative sliding might either happen or not, since more robots were needed to keep the object stable when sliding happened than that when sliding did not happen between the object and environment.

To investigate the transition-ship between modes, based on the geometrical relationship between different contact states, we proposed the rule to decide the transition between modes according to whether contact states changed under robots' motion or the object's motion. Furtherly, mobile robots were divided into active robots and passive robots, considering the possibility that a robot contact changes either actively under its own motions, or passively under the object’s motions.

With all the possible modes generated and their transition-ship acquired by our method, mode transition graph could be generated to sequence manipulation actions, treating each mode as a manipulation state.

Finally, two simulations were implemented to show the application of our method on specific manipulation tasks.
I. INTRODUCTION
We are currently developing a radiation-hardened power supply unit which can be applied for robots working under high-radiation environments just like the Fukushima Daiichi nuclear power plant that has faced a disaster. This paper presents the evaluation result of the radiation-hardened power supply unit.

II. POWER SUPPLY UNIT
Fig. 1 shows the circuit diagram of a proposed stabilized power supply unit. The stabilized power supply unit mainly consists of a comparator, a transistor, a zener diode. First, a zener diode is used to generate a reference voltage. The output voltage is compared with the reference voltage using the operational amplifier. When the output voltage is lower than the reference voltage, the transistor turns on to increase the output voltage. When the output voltage is higher than the reference voltage, the transistor turns off to decrease the output voltage. As the result, the power supply unit can keep the output voltage constant.

III. RADIATION EVALUATION RESULT
The developed power supply unit was exposed to a 30 TBq Cobalt 60 gamma radiation source. The power supply circuit was irradiated up to 80.5 Mrad by gamma rays. Although deterioration was confirmed in some semiconductor elements constituting the power supply circuit, the radiation-hardened power supply unit can still work correctly.

IV. CONCLUSION
This paper has presented a proposal of a radiation-hardened power supply unit. We have confirmed that the total-ionizing-dose tolerance of the radiation-hardened power supply unit is at least an 80.5 Mrad. The radiation tolerance of the radiation-hardened power supply unit is sufficient to be used for robots working for decommissioning operations.

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REFERENCES
P21 Terahertz waveguide for non-destructive inspection

Tohoku Univ. Oyama lab

Jun Miyaura, Ryo Hasegawa, Tadao Tanabe, Yutaka Oyama

Abstract

Frequency range of terahertz wave is located between 0.1~10 THz. Terahertz wave has some characteristics. This wave is high permeability for insulators as radio wave property and high reflectivity on metal surface condition as light wave property, and has low energy. So it is safe and non-invasive for human tissue. Furthermore, it corresponds to phonon modes, intermolecular vibrations and local vibrations. Based on these characteristics, terahertz wave is expected to be applied for some applications like as non-destructive inspection, medical treatment and security.

However, in the atmosphere, terahertz wave is largely absorbed due to water vapor and the propagation length is limited. This is because the energy of terahertz wave corresponds to the rotation of water molecules. Therefore, terahertz waveguide is effective for terahertz applications.

In this study we have fabricated terahertz waveguide by using polypropylene (PP). Polymer has attracted attention as a material of terahertz waveguide because it absorbs little in the terahertz frequency. Especially PP is suitable for waveguide because it is bendable. Ni paste was applied as core part of higher effective refractive index in waveguide.

For the fabricated waveguide, transmittance properties were measured using terahertz source based on difference frequency generation of infrared beams in GaP. Furthermore, the transmission characteristics were calculated by the FDTD method. The results are shown in Fig.1, which are discussed in a poster presentation with some non-destructive terahertz testing for infrastructure.

Acknowledgments

This research is partly supported by “Program for Fundamental Research and Human Resource Development toward Nuclear Decommissioning”.

![Fig.1 Terahertz transmission of waveguide](image-url)
Radiation Hardened Silicon Carbide Electronics

K. Muraoka1,a), S. Ishikawa1,2), H. Sezaki1,2), T. Maeda1,2), T. Makino3),
T. Ohshima3), and S.-I. Kuroki1, b)

1) Research Institute for Nanodevice and Bio Systems, Hiroshima University,
1-4-2 Kagamiyama, Higashi-Hiroshima, Hiroshima, 739-8527, Japan
2) Phenitec Semiconductor Corporation, 150, Kinoko-cho, Ibara,
Okayama, 715-8602, Japan
3) National Institutes for Quantum and Radiological Science and Technology,
1233 Watanuki, Takasaki, Gunma, 370-1292, Japan
E-mail: {ak-muraoka, bskuroki}@hiroshima-u.ac.jp

1. Introduction
Silicon Carbide (SiC) is an attractive material for harsh environment electronics owing to the wide bandgap of 3.26 eV. High-temperature and radiation-hard electronics have been required for nuclear accidents, e.g. the Fukushima-1 plant accident. 4H-SiC Metal-oxide-semiconductor field effect transistors (MOSFETs) can operate under gamma-ray radiation [1]. For the high frequency operation of the 4H-SiC MOSFETs circuits, enhancement of carrier mobility is strongly required. A Ba interface medication technique enhanced the channel mobility [2]. In this study, we fabricated two types of SiC-MOSFETs with the conventional oxide and Ba-introduced oxide. The electrical characteristics after high gamma-ray radiation were investigated.

2. Experimental

Lateral nMOSFETs were fabricated on 4° off-axis 4H-SiC (0001) p-type epitaxial substrates. The channel impurity density was 6×10¹⁷ cm⁻³. Chemical cleaning of SiC substrate was performed as follows: (1) Sulfuric acid hydrogen peroxide mixture with H₂SO₄ and H₂O₂ mixture, (2) SC-1 with NH₄OH, H₂O₂, and deionized water, (3) diluted HF solution. Each gate oxide was formed after the chemical cleaning. The dry thermal SiO₂ was grown at 1150°C in a dry oxygen ambient. The dry SiO₂ thickness was 10 nm. A Ba-introduced oxide was formed with the following processes. Firstly, a barium peroxide (BaO₂) layer of 2.8 nm was deposited by the RF sputtering method. Subsequently, a silicon dioxide (SiO₂) layer of 40 nm was deposited by the RF sputtering method. Both depositions were performed in the same vacuum chamber at room temperature. The deposited sample was oxidized in O₂ ambient at 950°C, and the total thickness of the stacked oxide increased to 92 nm. After formation of gate-oxide, ohmic electrodes were formed on source/drain regions with a Ni/Nb bilayer of 100 nm. Aluminum was deposited by the RF sputtering method as gate-metal and pad-electrode. Gamma-ray radiation on the MOSFETs was carried out at cobalt-60 irradiation facility, Takasaki Advanced Radiation Research Institute in Japan. After gamma-ray irradiation up to 1130 kGy(SiO₂), electrical characteristics were measured at room temperature.

3. Results and Discussions

Figure 1 shows the total dose ionization effect on the field effect mobility of the 4H-SiC MOSFETs with the dry SiO₂ and the Ba-introduced oxide. Before irradiation, the dry SiO₂ produced the mobility of 0.03 cm²/Vs, and the Ba-introduced oxide had 12 cm²/Vs. The introduced Ba increased the mobility 400 times higher than that of dry SiO₂. Even though the nMOSFETs with the dry SiO₂ had the almost constant value up to a total dose of 1130 kGy(SiO₂), the mobility of Ba-introduced MOSFETs tended to increase for absorbed doses above 40 kGy(SiO₂). The subthreshold swing of Ba-introduced MOSFETs increased after gamma-ray irradiation. It is considered that Ba, ionized by irradiation, causes the increasing trend of the mobility.


Fig. 1 Total dose ionization effect on field effect mobility at the SiC-MOSFETs.
1. Introduction

Recently, although Field Programmable Gate Arrays (FPGAs) are used for space systems, the radiation tolerances of FPGAs are still insufficient. Therefore, we have been developing radiation-hardened optically reconfigurable gate arrays (ORGAs) [1]. Optically reconfigurable gate array can achieve a high total-ionizing-dose tolerance. This paper presents a new ORGA to support Triple Modular Redundancy (TMR) implementation.

2. Triple Modular Redundancy

A TMR consists of three identical circuits and taking a majority voting circuits. TMR can obtain a correct value by voting the results of three modules. By using TMR, soft error tolerance can be enhanced.

3. Optically reconfigurable gate array

ORGAs consist of a holographic memory, a laser array, and a gate array VLSI. Holographic memory store configuration contexts. The circuit information is read from the holographic memory by addressing a laser array and programmed onto the gate array in perfect parallel. Therefore, reconfiguration time is very short or nanosecond order so that high speed scrubbing operation can be realized.

A gate array shown in Figure 1 consists of Configuration Logic Brock (CLB), Switching Matrix (SM), and Input /Output Brock (IOB).

4. Evaluation

In this study, we have developed a new ORGA with TMR. We have implemented a 4-bit multiplier circuit onto the ORGA. The soft error tolerance has been analyzed by simulation. In this simulation, we have confirmed that even if it is under a strong radiation condition, the TMR operation can executed correctly.

Acknowledgment

This research was partly supported by the Initiatives for Atomic Energy Basic and Generic Strategic Research No. 283101.

References

I. Introduction

Under a high radiation condition, soft-error tolerant device is necessary [1]. This paper shows a triple modular redundancy (TMR) and a quintuple modular redundancy (QMR) implementations of an 8-bit adder circuit which were implemented onto CPLD and were evaluated by Am241.

II. TMR

We have constructed a TMR of an 8-bit adder circuit on CPLD. In the TMR circuit, even if a particle is incident to the CPLD, correct operation can be expected. Externally, an error check circuit was constructed on an FPGA. An Am241 radiation source was placed directly above the CPLD and soft-errors were measured by the FPGA for 8 hours. As a result, 14 soft errors were observed. However, no soft error occurred on the TMR circuit of the 8-bit adder. It was confirmed that radiation tolerance is sufficient.

III. QMR

A similar test was also carried out in a QMR circuit of the 8-bit adder. The QMR has 5 identical modules and majority voting circuits. As well, the same radiation test was performed on the QMR as TMR. As the result, no soft error was confirmed as well as TMR implementation. The QMR is useful for more higher radiation condition than TMR.

Acknowledgment

This research was partly supported by the Initiatives for Atomic Energy Basic and Generic Strategic Research No. 283101.

Reference

### 10. Company Exhibitions: Posters, Videos, and Robot Demonstrations

展示：ポスター・映像・機器デモンストレーション

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11. Summary

Application of expected robot technology expanded

Towards the decommissioning of the Fukushima Daiichi Nuclear Power Station (1F), Tokyo Electric Power Company Holdings, Inc., the expectations are increasing for the advancement of remote-control technology and robot technology that reduce the radiation exposure to engineers working in the high radiation environment.

From now, towards the expansion in the application of the robot technology to the 1F decommissioning, it will be required to upgrade the radiation resistance of the electronic equipment which enables robots to work in high radiation environment. Also it will be required for robots to adapt to the works under severe conditions in 1F such as narrow pass and underwater. Furthermore, towards the retrieval of the fuel debris, it is becoming necessary to develop a technology on radiation measurement, position recognition and the measurement of the surrounding environment, which will contribute to the radiation imaging and detection of nuclear fuel debris in high radiation environment of 1F.

The fifth Fukushima Research Conference (FRC) held

In order to develop the above-mentioned technologies, the Collaborative Laboratories for Advanced Decommissioning Science (CLADS), Japan Atomic Energy Agency (JAEA), held the FY2018 Fifth Fukushima Research Conference (FRC) at the “Tomioka Town Art & Media Center Manabi-no-Mori” in Tomioka Town, Futaba County, Fukushima Prefecture from November 26 to 27, 2018. The title of the conference was “Radiation Hardness, Smartness and Measurement in Remote Technology for the Decommissioning of the Fukushima Dai-ichi Nuclear Power Station”, which will be necessary from now for promoting the decommissioning. The experts in the related wide fields such as remote-control instruments, semiconductor devices, materials, and radiation measurement gathered in the conference and discussed about the future perspective towards the advancement of the remote-control technology for decommissioning. In addition, from the necessity to develop young human resources that will bear the future, the student poster session was held as a part of the International Education Program (OECD/NEA NEST Project**). The participation of domestic and oversea young researchers was strongly welcomed to this poster session. In total, 330 researchers including those from the other countries such as US, Europa and Australia participated in the two-day FRC.

Enthusiastic lectures presented

At the opening on the first day, two preliminary lectures were presented. First, Mr. Daniel Iracane, Deputy Director of the OECD/Nuclear Energy Agency (NEA) presented a lecture on the NEST Project* that is a framework related to education, technique and
science/technology in nuclear energy field.

Then, Professor Koji Okamoto, Director General of the CLADS, JAEA explained the outline of the research and development promoted in the CLADS and the objectives of holding the conference.

Further, the preliminary lecture was followed aiming to transmit the basic knowledge necessary to understand the present topic, “Radiation Hardness, Smartness and Measurement in Remote Technology for the Decommissioning” to general public and experts. In the lecture entitled “Radiation Environment in 1F and Development of Robot Technology”, it was presented that how to operate the remote-control instruments in the severe radiation environment at 1F and what is the concept of radiation “dose” that had been often discussed since the accident of 1F. After the lecture, the hot discussion was exchanged. For example, one of the audiences asked, “What kind of radiation would affect the radiation dose in 1F?”. The lecturer answered, “Compared with the direct radiation from radioactive materials, the contribution of the scattered radiation is rather large.”.

Next, three researchers presented the lectures entitled “Towards the Robot Operation in High Radiation Environment.”. The lecturers presented the practical results such as, 1) the development of robot arm and radiation-resistant camera, 2) the activities aiming at the practical application of radiation-resistant semiconductor devices, and 3) the technological development to visualize radiation. After the lectures, the audiences asked many practical questions as to the time of the application of the developed devices and the time of the practical usage in 1F.

Exchange of advanced information among the experts

On the second day, the expert workshop was held aiming to exchange the advanced information among the experts.

In the morning session, lectures were presented under the title “Operation Experiences in High Radiation Environment”. The contents of the lectures were, 1) about the International Thermonuclear Experimental Reactor (ITER) where the radiation resistance is required like decommissioning, 2) the operation experiences and future plan of remote-control equipment and measurement technology inside the reactor containment vessel of 1F, and 3) the development of three-dimensional radiation imaging technology.

In the afternoon, the student poster session was held. Twenty-four students including oversea students learning in Japan participated in this session. The students presented their research related to the 1F decommissioning, and actively exchanged the discussion with the experts. Three students presenting the excellent posters were awarded the Excellent Poster Prize.

In order to discuss highly specialized topics, the final session was divided into two parts; the session for radiation-resistant devices, and the session for radiation measurement. In
addition to the oral presentations, the panel discussion was also held in the radiation-resistant devices session. In each session, the active discussion was exchanged as to “What kinds of radiation we should measure in order to retrieve fuel debris?” and “Are there any plan to apply the research results to 1F? When the research results will be applied to 1F?”.

Exhibition of decommissioning technology held

In the conference, the exhibition of decommissioning technology was held for the first time at the FRC. In addition to the universities and the research organizations, many private enterprises participated in the exhibition. Various presentations in wide fields were displayed in the exhibition, such as manufacturing, marketing and operation of remote-control technology (drone, crawler, robot arm, etc.), electronic components and materials (semiconductor device, shielding material, 3D printer), and measurement instruments (Compton camera, radiation-resistant camera, etc.). In particular, the operation demonstration of crawler by the presenter who had experiences in operating the remote-control instruments at 1F attracted much attention of the participants.

The CLADS will continue to hold international conferences, and thereby we will contribute to the technological development of remote-control and radiation measurement, which are global subjects towards the 1F decommissioning. In addition, we will also contribute to the development of young human resources that will bear the next generation.

*: NEST (NEST : Nuclear Education Skills and Technology)

A project that was proposed by the Organisation for Economic Co-operation and Development/The Nuclear Energy Agency (OECD/NEA) to enhance the young generation’s interest in nuclear science and technology. The objective of the project is to construct an international network among universities, research organizations, and industries in the world through the specific international education project in which young researchers and engineers participate. The present conference is regarded as a part of the international education programs on the advanced remote-control technology towards the decommissioning, conducted by the CLADS and the University of Tokyo.
総論

◇待望されるロボット技術の応用拡大
　東京電力ホールディングス福島第一原子力発電所(1F)の廃炉に向け、過酷な放射線環境下で現場作業者の被ばく線量を低減、遠隔技術やロボティクス高度化への期待が集まっている。
　今後、1F廃炉でのロボット技術の運用拡大に向けて、高放射線場でも作業できるための電子機器の耐放射線性の向上や、1F建屋内の狭部や水中という過酷な条件でも作業できる適応力が求められている。さらに、燃料デブリの取出しに向けて、1Fの高放射線環境での放射線イメージングや核燃料デブリの検知に資する、放射線計測および位置認識・周辺環境の把握のための技術開発に取組むことが必要となっており。

◇第5回FRCを開催
　このため、廃炉国際共同研究センター(CLADS: Collaborative Laboratories for Advanced Decommissioning Science)では、平成30年11月26日、27日の二日間に亘り、福島県双葉郡富岡町にある「福岡町文化交流センター 学びの森」において、今後、廃炉を推し進めていく上で必要となる「廃炉遠隔技術のための耐放射線化、運用技術及び計測技術の高度化」と題した平成30年度第5回福島リサーチカンファレンス(FRC: Fukushima Research Conference)を開催した。遠隔機器、半導体デバイス、材料、放射線計測に関連する幅広い専門家を交えて、廃炉遠隔技術の高度化に向けた将来展望を議論することに加え、特に、将来を担う人材育成の必要性から、国際教育プログラム(OECD/NEA NESTプロジェクト*)の一環として、学生スターセッションを設けることで、国内外の若手研究者の参加を積極的に募りました。今回FRCでは、米国や欧州、豪州などの海外からの研究者も含め二日間で延べ330名が参加した。

◇熱気の籠る講演が展開
　初日の開会にあたっては、2件のオープニング講演が行われた。先ず、OECD/NEA次長のダニエル・イラカン氏から、OECD/NEAの原子力の教育、技能、科学技術に関する枠組みであるNESTプロジェクトについての講演があった。
　続いて、CLADSの岡本孝司センター長から、CLADSで取り組んでいる研究開発の総論と本会議の開催趣旨について説明があった。
　さらに、本FRCのテーマである「廃炉遠隔技術のための耐放射線化、運用技術及び計測技術の高度化」の理解に必要な基本知識を市民ならびに専門家に向けて発信することを目的に基調講演が行われた。
　ここでは、「福島第一原子力発電所の放射線環境とロボット技術の展開」と題し、1Fの過酷な放射線環境下における遠隔機器の運用の在り方や、1F事故以来、頻繁
に議論されてきた放射線の「線量」という概念についての説明が行われた。講演後には会場から「1Fの放射線量に寄与しているのは、どのような放射線であるのか？」との質問に対して「放射性物質からの直接線よりも散乱線からの寄与が大きい。」との回答があるなど活発な議論が交わされた。

次に、3名の研究者が「高放射線場でのロボットの運用に向けて」と題し、ロボットアームと耐放射線カメラ開発、耐放射線半導体デバイス実用化を目指した取組み、そして放射線可視化技術開発といった実践的な成果発表について講演した。ここでは、会場から、開発したデバイス機器の実用化や1F投入の時期という実践に向けた質問が多く寄せられた。

◇専門家による先端情報の交流

二日目は、専門家間の最先端の情報の交流を目的とした専門ワークショップを開催した。

午前のセッションでは、廃炉と同様に耐放射線性が求められている国際熱核融合炉、1F原子炉の格納容器内における遠隔機器や計測技術の運用経験と将来計画、そして、3次元放射線イメージング技術の展開という「高放射線場での運用経験」に関わる講演が行われた。

午後のセッションでは、留学生を含む24件の参加があり、学生が取り組んでいる1F廃炉に関わる研究について発表が行われ、専門家との間で活発な意見交換が行われた。また、優れたポスター発表3件に対して優秀ポスター賞を表彰した。

最終セッションでは、より高度な専門的な議論を行うために、耐放射線性デバイスのセッションと放射線計測セッションとに分かれ、口頭発表を行うとともに、「耐放射線デバイス」セッションではパネルディスカッションも行った。それぞれのセッションでは、「燃料デブリを検出するためには、どのような放射線を測ればいいのか」や「今後、研究成果の1F投入の方針はあるのか？また、時期は？」など積極的な討議が行われた。

◇廃炉技術の展示会を開催

FRCでは初となる廃炉技術に係る展示会を実施し、大学、研究機関に加えて、多くの民間企業が参加した。出展には、ドローン、クローラー、ロボットアームなどの製造、販売、運用の遠隔機器関連や、半導体デバイス、遮蔽材、3Dプリンタの電子部品・材料関連、さらに、コンポットカメラ、耐放射カメラなどの計測機器関連と、幅広い分野からの出展があった。特に、1Fにおける遠隔機器の運用経験のある出展者によるクローラーの動作デモに参加者から注目を集めた。

廃炉国際共同研究センターは、引き続き国際的な会議を開催し、グローバルな課題である1F廃炉に向けた遠隔技術や放射線計測の技術開発、そして次世代を担う若い研究者達の人材育成に貢献していく。
経済開発協力機構/原子力機関（OECD/NEA: The Organisation for Economic Co-operation and Development/The Nuclear Energy Agency）が、若い世代の原子力科学技術への関心を高めるために打ち出した構想で、若手の研究者・技術者等が参加する特定の国際教育プロジェクト等の実施を通じて、各国の大学、研究機関、産業界の間で国際的なネットワークを構築することを目的とするものである。今回は、CLADS と東京大学が実施する廃炉に向けた先進的な遠隔操作技術に関する国際教育プログラムの一環として捉えられている。
Appendix A

Photographs

No.1
Appendix B

NEST CLADS Project of OECD/NEA
Education and Training on Advanced Remote Technology for Decommissioning

Program on November 26th in 2018, Monday

Place: Tomioka Town Art and Media Center

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Program on November 27th in 2018, Tuesday

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<td>Participation in Fukushima Research Conference on “Radiation Hardness, Smartness and Measurement in Remote Technology for the Decommissioning of Fukushima Dai-ichi Nuclear Power Station” (Closed Oral and Poster Sessions, and Panel Discussion)</td>
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</tbody>
</table>

Program on November 28th in 2018, Wednesday

Place: Fukushima Dai-ichi Nuclear Power Station

<table>
<thead>
<tr>
<th>Start</th>
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<th>Contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>13:00</td>
<td>16:30</td>
<td>Participation in the Site Tour of Fukushima Dai-ichi Nuclear Power Station</td>
</tr>
</tbody>
</table>
Program on November 29th in 2018, Thursday*  
Place: Naraha center for remote control technology development of JAEA  
Instructor: Dr. Kuniaki KAWABATA of JAEA

<table>
<thead>
<tr>
<th>Start</th>
<th>Finish</th>
<th>Contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>10:00</td>
<td>11:00</td>
<td>Lecture on remote wireless operation system applied to emergency response and decommissioning of Fukushima Daiichi Nuclear Power Plant (Mr. Ryoki of KAJIMA CORPORATION)</td>
</tr>
<tr>
<td>11:00</td>
<td>12:00</td>
<td>Facility tour in Naraha center for remote control technology development</td>
</tr>
<tr>
<td>12:00</td>
<td>13:00</td>
<td>Lunch</td>
</tr>
<tr>
<td>13:00</td>
<td>14:00</td>
<td>Orientation for whole program and experiments</td>
</tr>
<tr>
<td>14:00</td>
<td>16:30</td>
<td>Step-up, robot operation experiments &amp; remote measurement experiments by using the robots</td>
</tr>
</tbody>
</table>

Program on November 30th in 2018, Friday*  
Place: Naraha center for remote control technology development of JAEA  
Instructor: Dr. Kuniaki KAWABATA of JAEA

<table>
<thead>
<tr>
<th>Start</th>
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<th>Contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>10:00</td>
<td>12:00</td>
<td>Remote measurement experiments by using the robots</td>
</tr>
<tr>
<td>12:00</td>
<td>13:00</td>
<td>Lunch</td>
</tr>
<tr>
<td>13:00</td>
<td>13:30</td>
<td>Technical orientation for data processing and visualization</td>
</tr>
<tr>
<td>13:30</td>
<td>15:30</td>
<td>Data processing of measured sensory data and visualization experiments</td>
</tr>
<tr>
<td>15:30</td>
<td>16:30</td>
<td>Discussion</td>
</tr>
</tbody>
</table>

※ subject to change depending on circumstances and progress status.
Program on December 3rd in 2018, Monday

Place: Hongo Campus, The University of Tokyo

Instructor: Dr. Yusuke TAMURA of the University of Tokyo

<table>
<thead>
<tr>
<th>Start</th>
<th>Finish</th>
<th>Contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>10:00</td>
<td>11:00</td>
<td>Lecture on radiation measurement (Dr. Shimazoe of the University of Tokyo)</td>
</tr>
<tr>
<td>11:00</td>
<td>12:00</td>
<td>Lecture on SLAM (Dr. Ji of Chuo University)</td>
</tr>
<tr>
<td>12:00</td>
<td>13:00</td>
<td>Lunch</td>
</tr>
<tr>
<td>13:00</td>
<td>17:00</td>
<td>Orientation&lt;br&gt;Radiation measurement experiment using a Compton camera mounted on a mobile robot</td>
</tr>
</tbody>
</table>

Program on December 4th in 2018, Tuesday

Place: Hongo Campus, The University of Tokyo

Instructor: Dr. Yusuke TAMURA of the University of Tokyo

<table>
<thead>
<tr>
<th>Start</th>
<th>Finish</th>
<th>Contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>10:00</td>
<td>12:00</td>
<td>Radiation measurement experiment using a Compton camera mounted on a mobile robot (simulation)</td>
</tr>
<tr>
<td>12:00</td>
<td>13:00</td>
<td>Lunch</td>
</tr>
<tr>
<td>13:00</td>
<td>17:00</td>
<td>Robot tele-operation experience with the bird’s-eye view system&lt;br&gt;Data processing, visualization</td>
</tr>
</tbody>
</table>

Program on December 5th in 2018, Wednesday

Place: Hongo Campus, The University of Tokyo

Instructor: Dr. Yusuke TAMURA of the University of Tokyo

<table>
<thead>
<tr>
<th>Start</th>
<th>Finish</th>
<th>Contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>10:00</td>
<td>12:00</td>
<td>Preparation for presentation</td>
</tr>
<tr>
<td>12:00</td>
<td>13:00</td>
<td>Lunch</td>
</tr>
<tr>
<td>13:00</td>
<td>14:30</td>
<td>Presentation</td>
</tr>
</tbody>
</table>
The NEST CLADS Project of JAEA/CLADS
- On Advanced Remote Technology –
(Summary of its Execution in 2018)

Collaborative Laboratories for Advanced Decommissioning Science (CLADS)
Sector of Fukushima Research and Development,
Japan Atomic Energy Agency (JAEA)

1. Background of the NEST Project

OECD/NEA has launched the Nuclear Education, Skills and Technology (NEST) Framework in 2016.
to energize the succeeding generations to pursue careers in the nuclear field and to provide them with the ability to obtain, share and advance the knowledge and technology in the nuclear by:
- exposing them to international challenging project of real-world issue;
- transferring the knowledge and expertise accumulated in the current generation to them through hands-on training;
in international links between universities, research institutes and industry.

2. Project description and challenges

To contribute to the NEST activities, JAEA/CLADS and the University of Tokyo have proposed the NEST CLADS Project in research area of Advanced Remote Technology which has the wide effect not only on nuclear technology for the decommissioning and so on but also on other technologies and industries.

Decommissioning under intense gamma-ray irradiation environments is one of real-world challenging issues, especially decommissioning of the 1F* as a remarkable example.

* The Fukushima Daiichi Nuclear Power Plant of Tokyo Electric Power Company Holdings, Inc.

3. Schedule

The NEST CLADS Project in 2018 consists of theoretical seminars, practical exercises and site tours of Naraha Center* and the 1F**, and is scheduled as follows:

<table>
<thead>
<tr>
<th>Date</th>
<th>November</th>
<th>December</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>26</td>
<td>27</td>
</tr>
</tbody>
</table>

The Program
- Theoretical Seminars
- Site Tours
- Practical Exercise III in JAEA
- Practical Event in the University of Tokyo

* Naraha Center for Remote Control Technology Development of JAEA
** the Fukushima Daiichi Nuclear Power Station of Tokyo Electric Power Company Holdings, Inc.
4. Practical Exercises (1)

Practical exercises (1)

in Naraha Center for Remote Technology Development of JAEA

- Immersive experience by virtual reality for understanding of circumstances inside the reactor buildings and virtual operations by simulated remotely operated robot
- Operation experiences of obtaining information of experimental environment by laser range finders and a camera sensor mounted on a mobile robot in the mock-up
- 3D projection of obtained sensory data

Virtual Reality and simulation system

Cardboard pedestal mock-up

4. Practical Exercises (2)

Practical exercises (2)

in The University of Tokyo

- Detection of radioactive sources by using a gamma-ray detector mounted on a mobile robot
- Mapping of radiation distribution and combining the map with the experimental environment of practical exercises (1)
- Operation experiences of remote control robot using bird’s-eye view system

Detection of radioactive sources (Left: Mobile robot with a Compton camera, Right: An example of radioactivity distribution mapping)

Bird’s-eye view system (Left: Mobile robot with four fisheye cameras, Right: Generated bird’s-eye view)
This is a blank page.
国際単位系（SI）

### 表1. SI基本単位

<table>
<thead>
<tr>
<th>基本量</th>
<th>名称</th>
<th>記号</th>
<th>記号</th>
</tr>
</thead>
<tbody>
<tr>
<td>長さ</td>
<td>メートル</td>
<td>m</td>
<td>m</td>
</tr>
<tr>
<td>図形</td>
<td>面積</td>
<td>m²</td>
<td>m²</td>
</tr>
<tr>
<td>質量</td>
<td>キログラム</td>
<td>kg</td>
<td>kg</td>
</tr>
<tr>
<td>時間</td>
<td>秒</td>
<td>s</td>
<td>s</td>
</tr>
<tr>
<td>電流</td>
<td>アマノル</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>熱力学温度</td>
<td>ケルビン</td>
<td>K</td>
<td>K</td>
</tr>
<tr>
<td>物質のモル</td>
<td>モル</td>
<td>mol</td>
<td>mol</td>
</tr>
<tr>
<td>光度</td>
<td>サンダル</td>
<td>cd</td>
<td>cd</td>
</tr>
<tr>
<td>電場強さ</td>
<td>ボルト healthcare</td>
<td>V</td>
<td>V</td>
</tr>
<tr>
<td>電流密度</td>
<td>アンペア每平方メートル</td>
<td>A/m²</td>
<td>A/m²</td>
</tr>
<tr>
<td>電磁気波の強さ</td>
<td>ワット每メートル平方</td>
<td>W/m²</td>
<td>W/m²</td>
</tr>
<tr>
<td>電磁誘導</td>
<td>フラクダメータ</td>
<td>V/m</td>
<td>V/m</td>
</tr>
<tr>
<td>負荷密度</td>
<td>ニュートン每メートル平方</td>
<td>N/m²</td>
<td>N/m²</td>
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</table>

### 表2. 基本単位を用いて表示されるSI組立単位

<table>
<thead>
<tr>
<th>組立単位</th>
<th>名称</th>
<th>記号</th>
</tr>
</thead>
<tbody>
<tr>
<td>電圧</td>
<td>1サイエンス</td>
<td>V</td>
</tr>
<tr>
<td>1サイエンス</td>
<td>1サイエンス</td>
<td>V</td>
</tr>
</tbody>
</table>

### 表3. 固有の名詞と記号で表示される組立単位

<table>
<thead>
<tr>
<th>組立単位</th>
<th>名称</th>
<th>記号</th>
</tr>
</thead>
<tbody>
<tr>
<td>電圧差（電圧）</td>
<td>平面角ラジアン</td>
<td>rad</td>
</tr>
<tr>
<td>電位差（電圧）</td>
<td>立体角ステラジアン</td>
<td>sr</td>
</tr>
<tr>
<td>交流電圧</td>
<td>三角波</td>
<td>V</td>
</tr>
<tr>
<td>電流</td>
<td>三角波</td>
<td>A</td>
</tr>
<tr>
<td>交流電流</td>
<td>三角波</td>
<td>A</td>
</tr>
<tr>
<td>交流電流密度</td>
<td>三角波</td>
<td>A/m²</td>
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</table>

### 表4. 単位の中に固有の名称と記号を含む組立単位

<table>
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<tr>
<th>組立単位</th>
<th>名称</th>
<th>記号</th>
</tr>
</thead>
<tbody>
<tr>
<td>原子線量</td>
<td>クールッ</td>
<td>Gy</td>
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<tr>
<td>周辺線量当量</td>
<td>シルバト</td>
<td>Sv</td>
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### 表5. SI単位の構成

<table>
<thead>
<tr>
<th>単位</th>
<th>記号</th>
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<tbody>
<tr>
<td>1サイエンス</td>
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### 表6. 固有の名称をもつ単位の例

<table>
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<th>標準名</th>
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### 表7. SI単位の変換

<table>
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<th>単位</th>
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### 表8. SI単位の変換

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<tbody>
<tr>
<td>1サイエンス</td>
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</table>

### 表9. 国際単位系（SI）の接頭語

<table>
<thead>
<tr>
<th>接頭語</th>
<th>名称</th>
<th>記号</th>
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### 表10. SI単位の変換

<table>
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<th>記号</th>
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<tbody>
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<td>1サイエンス</td>
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</table>

補足：SI単位系は、科学技術の発展と情報社会の進展に伴い、世界的に広く採用されてきている。
<table>
<thead>
<tr>
<th>名称</th>
<th>記号</th>
<th>基本単位</th>
</tr>
</thead>
<tbody>
<tr>
<td>ヘルツ</td>
<td>Hz</td>
<td>s^{-1}</td>
</tr>
<tr>
<td>ベクレル</td>
<td>Bq</td>
<td>s^{-1}</td>
</tr>
<tr>
<td>ジュール</td>
<td>J</td>
<td>m^2 kg s^{-2}</td>
</tr>
<tr>
<td>ワット</td>
<td>W</td>
<td>m^2 kg s^{-3}</td>
</tr>
<tr>
<td>ケルビン</td>
<td>K</td>
<td></td>
</tr>
<tr>
<td>アンペア</td>
<td>A</td>
<td>s^{-1}</td>
</tr>
<tr>
<td>キログラム</td>
<td>kg</td>
<td></td>
</tr>
<tr>
<td>メートル</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>サン</td>
<td>cd</td>
<td></td>
</tr>
<tr>
<td>水銀柱ミリメートル</td>
<td>mmHg</td>
<td></td>
</tr>
<tr>
<td>デシベル</td>
<td>dB</td>
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<tr>
<td>文献単位</td>
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