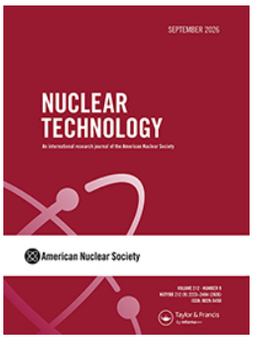

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Reducing Radioactivity in High-Level Waste from Spent Fuel Reprocessing and Core Debris at the Fukushima Daiichi NPP by Muon Cluster Fission Technology

Tadashi Narabayashi [a], Theodore Dickinson [b], Dominic Notter [b], Yoshihide Sakuragi [c], and Alvah C. Bittner [d]

[a] *Professor Emeritus, Hokkaido University, Founder & Director of GX ENERGY Ltd., INDEST, Institute of Science Tokyo, Tokyo, Japan;* [b] *Processing Department, RRS Solutions, Ferndale, WA;* [c] *Pacific Lotus Trading, Bellevue, WA;* [d] *Bittner and Associates, Kent, WA*

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Abstract — *This study utilizes the results of experiments on cluster fission and decay of fissile materials using cosmic ray muons to reduce the radiotoxicity of debris melted and solidified during the severe accident at the Fukushima Daiichi Nuclear Power Plant. Experiments confirmed that relatively stable radioactive thorium-232 undergoes nuclear transmutation into stable isotopes of lead and magnesium, halting the reaction. When radioactive powder is uniformly mixed with lead oxide and pure metal powder and heated in a thermite reaction, muon-induced cluster fission occurs instantaneously, followed by beta decay and transmutation into stable lead isotopes within a few hours. Radiation levels drop to background levels, and the radioactive material disappears. More than 1000 experiments conducted over 20 years have confirmed that in addition to thorium-232, mixed radioactive isotopes such as uranium dioxide and americium can be simultaneously transmuted and that a proven 100-pound (45 kg) reactor can process approximately 5 kg of radioactive material at a time. This research also includes feasibility studies on a radioactive debris reduction system that combines a robotic cart, a muon reactor, and an air purification system to collect and process debris that melted and solidified after the Fukushima Daiichi Nuclear Power Plant accident.*

Keywords — *high-level waste, spent fuel reprocessing, core debris, Fukushima Daiichi, americium, thorium, muon, neutrinos, cold fission, cluster decay, muonic atom reaction, muon nuclear fission, cosmic ray muons.*

I. INTRODUCTION

Muons originating from cosmic rays are generated when high-energy particles emitted from supernova explosions or the sun rain down on the earth and collide with the atmosphere. In the decommissioning research of the Fukushima Daiichi Nuclear Power Plant, muons originating from cosmic rays were used to successfully photograph uranium that had melted in the reactor and moved to another location on a photographic plate.

In the decommissioning study of Fukushima Daiichi Nuclear Power Plant, muons, a type of elementary particle, were used to take photographic plates of uranium that melted in the reactor and moved to another location by Nagoya University and Toshiba, as shown in Fig. 1. Fig. 2 compares muon radiography results between Units 2 and 5. No fuels melted downward through the melted piping of the control rod drive (CRD) mechanism and fell to the pedestal concrete floor [1,2].

"X-ray photography" using muons (muon particles) is gaining attention. Known as muography, this approach is

CONTACT Tadashi Narabayashi tadashi@gx-energy.co.jp

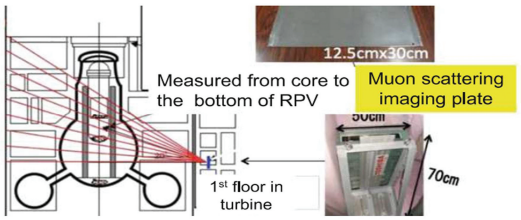

Fig. 1. Muon radiation radiography to find fuel debris [1,2].

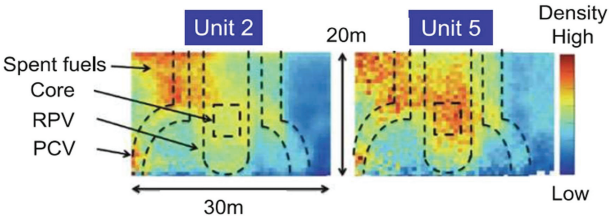

Fig. 2. Comparison of muon radiography results between Unit 2 and Unit 5 [1,2].

a radiation transmission testing method that uses muons instead of X-rays and can take images of large objects that are difficult to inspect with X-ray photography. Muons can penetrate almost all the materials, but they do not penetrate as easily as thicker, denser, or higher–atomic number of atoms (metals, etc.). Fig. 2 shows a comparison of muon radiography results between Units 2 and 5. Muography uses this property to represent what the muon has passed through, for example, as blue and what it has not passed through as red.

In 2016, an explanatory article titled "Application of Negative Muons to the Nuclear Field" was published by Dr. Joichiro Matsuzaki of the RIKEN Institute [3].

This study is based on the results of experiments on "cluster fission and nuclear decay of fissile materials using cosmic ray-derived muons," but it also builds on previous research using muons generated by an accelerator when a proton beam collided with graphite or beryllium targets. When muons are irradiated onto Am-243 or Pu-243 using an accelerator, nuclear transmutation occurs, resulting in the emission of neutrons and protons.

It has also been reported that the number of muons increases when the target is heated with a laser beam. The neutron emissions associated with muon transmutation are similar to delayed neutrons generated by spontaneous fission in nuclear reactors. If the number of muons increased due to heating in the core during the Fukushima Daiichi Nuclear Power Plant meltdown, the neutrons generated may have increased spontaneous fission.

These phenomena suggest the possibility reducing the radiation toxicity of debris that melted and solidified in the event of a severe accident at the Fukushima Daiichi Nuclear Power Plant. We believe that this paper will mark the starting point of research into the practical application of muon technology for industrial applications.

II. PREVIOUS RESEARCH ON NEGATIVE MUONS IN THE FIELD OF NUCLEAR PHYSICS

In previous research on negative muons in the field of nuclear physics, a reaction emitting five neutrons has been observed. Although the neutron separation energy required to emit one neutron is about 6 to 8 MeV, it is very interesting that there is a probability of five neutrons being emitted from a compound nucleus excited state of 10 to 20 MeV, as explained.

Muons are born from the decay of pions. In Japan, Dr. Hideki Yukawa [4] predicted the existence of mesons (pions) as the source of nuclear force in 1935, and Dr. Yoshio Nishina [5] discovered muons in cosmic rays using a cloud chamber in 1937. Currently, pions and muons can be artificially created using high-energy proton accelerators, making precise experiments and measurements possible.

The muon (μ+) is an elementary particle with a spin of one-half and a mass one-ninth that of a proton, and it is understood to be a second-generation lepton particle. A proton beam generated by a high-energy accelerator is collided with a target element such as carbon or beryllium. When the pion (π) produced in this collision decays, a muon is produced along with a neutrino (νμ) (Fig. 3). At this time, a "positive muon" (μ^+) and a "negative muon" (μ^-) can be obtained [3,7].

Negative muons pass through surrounding electrons and approach atomic nuclei, creating highly excited states of small muonic atoms around the nucleus.

Following the muon nuclear absorption reaction, particles such as neutrons and protons are emitted from the excited nuclear state, resulting in the creation of various nuclear isotopes. The negative muon adds one negative charge,

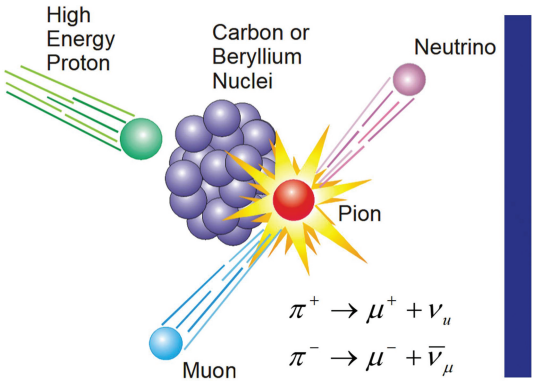

Fig. 3. Pion (π) produced a pair of muon μ+ and μ^- [6,7].

resulting in unique nuclear transmutation and element transmutation reactions. When negative muon nuclear capture occurs in a nucleus N (Z, A) with atomic number Z and mass number A, a muon (μ^-) binds with a proton (p) to form a neutron (n) and a neutrino (n) as an elementary process within the nucleus.

It is believed that most of the muon rest mass energy is carried away by the neutrino as kinetic energy, leaving about 10 to 20 MeV as nuclear excitation energy. Since protons are converted to neutrons, the mass number of the resulting nucleus remains unchanged, but an excited state (compound nucleus state) N'((Z-1), A)* of a nucleus with one smaller atomic number (Z-1) is formed.

As shown in Fig. 4, in the muon nuclear capture reaction of a Z nucleus, multiple neutrons are emitted from the compound nucleus excited state of the Z-1 nucleus and an isotope of the Z-1 nucleus is produced. The muon nuclear capture reaction is a reaction that transmutes a nucleus with atomic number Z into a nuclear isotope with atomic number Z-1. For nuclei with large Z, the probability of muon capture reaction is 100%.

High-energy muons also possess extremely strong penetrating power. As shown in Fig. 5, muons are one of

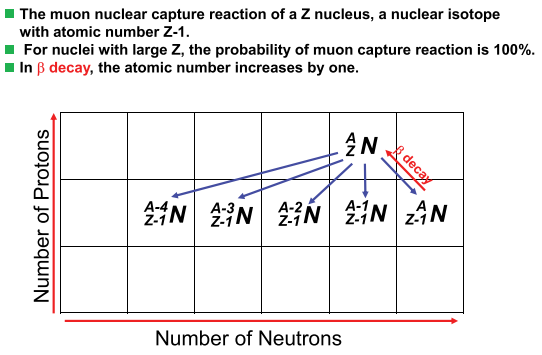

Fig. 4. Muon nuclear capture reaction [3].

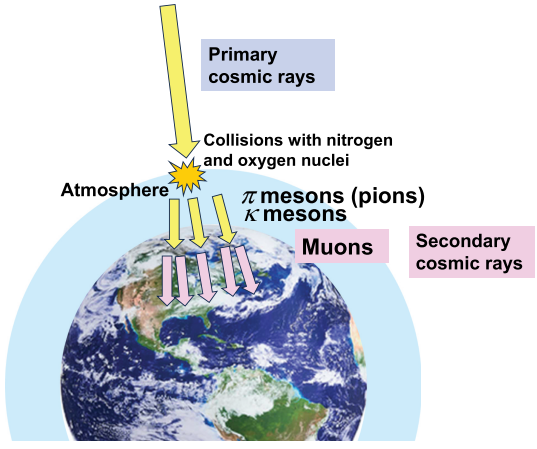

Fig. 5. Muons are a type of secondary cosmic ray.

the components of secondary cosmic rays. Cosmic rays, accidentally discovered in 1912 by the Austrian physicist Wilhelm Hess, are now the subject of cutting-edge research in astrophysics. Furthermore, the generation processes and behavior of various secondary cosmic rays after entering Earth's atmosphere are subjects of research on the interactions between ultra-high-energy particles and matter, which cannot be achieved with artificial accelerators. Protons, which constitute the majority of primary cosmic rays, collide with nitrogen and oxygen nuclei in the atmosphere as they pass through, transforming into various secondary cosmic rays before reaching Earth's surface.

In an important report of muon-induced fission by Hadermann [8], researchers explored a new technique that used neutrons generated via interactions with cosmic rays to detect the presence of fissile material. Cosmic ray muons can induce nuclear fission, particularly in fissile materials, and this process is relevant to muon-induced fission and potential applications such as detecting special nuclear material. When high-energy cosmic ray muons interact with nuclei, they can cause spallation, producing neutrons and radioactive isotopes.

It is said that one muon passes through the area of the palm of one hand every second, which was thought to be insufficient to generate the nuclear decay or fission of a huge number of nuclei, but a paper was found in the field of accelerators showing that the number of muons can be increased by at least eight times by heating the electrodes with a laser beam, which creates a matrix of holes [9]. The paper reports experimental findings that laser-ablating the surface of silica aerogel with holes and grooves significantly increases the emission rate of muonium atoms into a vacuum. The study also determined the

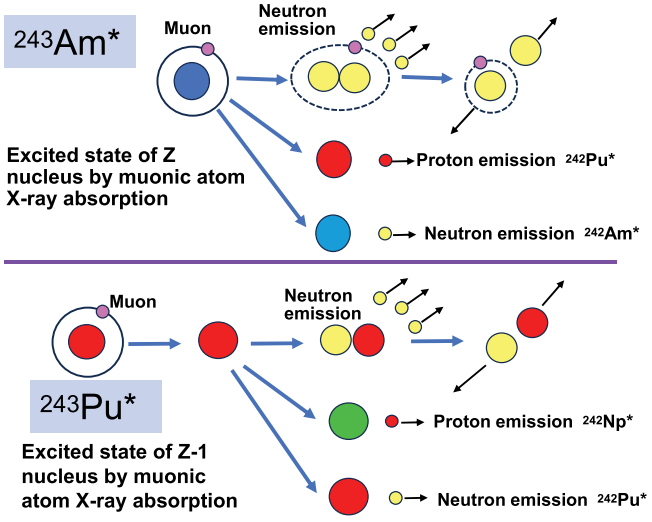

Fig. 6. Image of the two muon fission processes [3].

muonium formation fraction to be approximately 65.5%, and the emission rate remained stable for at least two days.

Professor Hidetsugu Ikegami discovered the Chemonuclear Reaction. He was the former Director of the Research Center for Nuclear Physics (RCNP) and Professor Emeritus, Osaka University, Japan, and later Honorary Doctor of Uppsala University, Sweden. His reaction predicted that it is possible to generate π mesons and subsequent muons without using a 540 MeV proton beam, and enabling cluster fission of thorium and Uranium, the annihilation of radioactive waste, etc.

Many papers can be found on cluster reactions of elements heavier than lead, including those on quantum mechanical spin, once nuclear fission or nuclear decay occurs due to muons, including Rose and Jones, with hundreds of citations [10], and those published by Oxford University as representative examples of nuclear physics research. The cluster fission reaction route in this study was also extracted based on the knowledge of these papers [11].

A huge amount of research has been conducted in recent years on muons using accelerators, and great results have been achieved. These findings are helping to elucidate the phenomenon of this research using cosmic muon showers. Importantly, American authors have already successfully conducted experiments, as will be explained in the next section.

Fig. 6 shows an image of the muon fission process. In transuranic elements and nuclei called minor actinides, the spontaneous fission isomer level drops to about 2 MeV, so if an excited state higher than this energy level can be formed by some means, spontaneous fission can be induced. One possible method is the muon capture reaction. As an example, let's consider the ^{243}Am nucleus. When a negative muon is captured in the muon orbital of a ^{243}Am nucleus to form a muon atom, nuclear fission occurs through two processes. In the first muon fission process, the ^{243}Am nucleus absorbs muon atomic X-rays generated in the muon atom cascade, exciting it to form a giant conjugate state of the ^{243}Am nucleus, and then undergoes fission via a spontaneous fission level (2.3 MeV) with lower energy than that level. In this fission case, the muon remains in the innermost ls orbital, as shown in Fig. 7, and the ^{243}Am nucleus inside it undergoes spontaneous fission, transmuting into two fission fragments. Along with spontaneous fission, 2-3 fission neutrons are emitted. The remaining muon is captured by the nucleus of the fission fragment with a larger atomic number, forming a muon atom of that nucleus and emitting muon atomic X-rays. In this process, a muon atom of ^{242}Pu is formed before fission, so muon X-rays of ^{242}Pu can be observed.

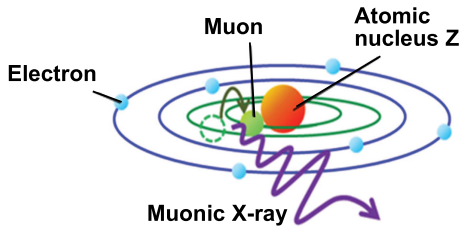

Fig. 7. Muonic atoms can cause various nuclear reactions.

Cosmic ray negative muons (μ-) are indeed detectable and are a product of cosmic ray interactions in Earth's atmosphere. Muons have the same charge as electrons and can form orbits around atomic nuclei instead of electrons. Atoms in this excited state are called "muonic atoms" and can cause various nuclear reactions. This muon excitation reaction generates an attractive force that draws the muonic atoms and can cause nuclei closer together (Fig. 7) and even various nuclear reactions. Endothermic or generates heat, the thermal energy is carried away by the neutrinos as high-speed kinetic energy, cooling the nuclei and maintaining a low temperature, and can easily pass through the walls of the reactor vessel, where the fission reaction is occurring, removing the thermal energy.

III. ABOUT OUR EXPERIMENTAL FACT

III.A. Background

More than 20 years ago, coauthors Dickinson and Notter [12] were working on a project involving a product containing a small amount of uranium yellowcake. They monitored the radiation levels before and after treatment and noticed a significant reduction in radiation. They began testing many different radioactive elements and created this method. At the time, no one, including major U.S. research institutes, understood the reason for this phenomenon.

Using their process, they experimented with various radioactive isotopes, including ^{60}Co, ^{238}U, ^{241}Am, and ^{232}Th, and were able to completely eliminate radioactivity. These results led them to become cofounders and co-owners of RRS Solutions. This groundbreaking phenomenon of complete radioactive material disappearance is highly complex, defying a universally accepted scientific explanation. Therefore, they turned to Professor Narabayashi of the Institute of Science Tokyo to unravel this phenomenon. Narabayashi was instrumental in investigating the cause of the accident and developing safety measures for the Fukushima Daiichi Nuclear Power Plant. He served as an external expert on the Fukushima Daiichi Nuclear Power Plant Accident Technical Review Committee of the Nuclear Safety and Security Commission. He also participated in the

Fukushima Daiichi Nuclear Power Plant Accident Analysis and Verification Team established by the Nuclear Regulation Authority in 2013, where he examined safety measures and debris removal. Based on muon images taken at Fukushima Daiichi Nuclear Power Plant Unit 2, Narabayashi hypothesized that this phenomenon may be a nuclear decay process caused by muons. Based on numerous papers and the latest muon research, he then began examining engineering applications for debris removal and radiation reduction at TEPCO's Fukushima Daiichi Nuclear Power Plant, as the cutting-edge muon engineering of muon transmutation.

The important thing is that, rather than using a gigantic beam accelerator with a radius of several hundred meters, it is possible to use negative muons, which are generated when high-energy cosmic rays that rain down on Earth from space react with the atmosphere, as a trigger. At the Fukushima Daiichi Nuclear Power Plant, this is a proposal for applications in science and technology.

III.B. Cluster Fission Routes

The following outlines three plausible ^{232}Th cluster fission pathways (p-1 to p-3)—with transitional half-lives—that are consistent with previous research [13]. These, it should be noted, are not exhaustive; indeed, there are other plausible cluster fission pathways, for example, $^{232}\text{Th} \rightarrow {}^{22}\text{O} + {}^{210}\text{Pb}$ (e.g., Ref. 14). As also reflected by Santhosh et al., two of these—(p-1) and p-3)—have been particular objects of study in the literature, but not the intermediate pathway to ^{25}Mg (p-2) [14]. This latter ^{25}Mg pathway—as that for ^{24}Mg (p-1)—will become especially relevant later with regard to our spectrographic results.

A-1) Route 1 of Cluster Fission of ^{232}Th

$$232_{90}\text{Th} \rightarrow 26_{10}\text{Ne} + 206_{80}\text{Hg}$$

$$26_{10}\text{Ne} \xrightarrow[197\text{ms}]{\beta} 26_{11}\text{Na} \xrightarrow[1.077\text{sec}]{\beta} 26_{12}\text{Mg (stable nucleus)}$$

$$206_{80}\text{Hg} \xrightarrow[8.15\text{min}]{\beta} 206_{81}\text{Tl} \xrightarrow[4.2\text{min}]{\beta} 206_{82}\text{Pb (stable nucleus)}$$

A-2) Route 2 of Cluster Fission of ^{232}Th

$$232_{90}\text{Th} \rightarrow 25_{10}\text{Ne} + 207_{80}\text{Hg}$$

$$25_{10}\text{Ne} \xrightarrow[602\text{ms}]{\beta} 25_{11}\text{Na} \xrightarrow[59.1\text{ms}]{\beta} 25_{11}\text{Mg (stable nucleus)}$$

$$207_{80}\text{Hg} \xrightarrow[2.9\text{min}]{B} 207_{80}\text{IT} \xrightarrow[4.77\text{min}]{\beta} 207_{82}\text{Pb (stable nucleus)}$$

A-3) Route 3 of Cluster Fission of ^{232}Th

$$232_{90}\text{Th} \rightarrow 24_{10}\text{Ne} + 20880\text{Hg}$$

$$24_{10}\text{Ne} \xrightarrow[3.38\text{min}]{\beta} 24_{11}\text{Na} \xrightarrow[14.959\text{h}]{\beta} 24_{12}\text{Mg (stable nucleus)}$$

$$208_{80}\text{Hg} \xrightarrow[42.5\text{min}]{\beta} 208_{81}\text{Tl} \xrightarrow[3.05\text{min}]{\beta} 208_{82}\text{Pb}$$
(essentially stable nucleus)

III.C. Testing Device and Testing Method for Cluster Fission

Cluster fission requires a fairly high temperature. To achieve this high temperature, an improved device similar to the well-known thermite reaction was used. The test apparatus and gamma-ray detector for measurement are shown in Figs. 8 and 9. In the commonly used thermite reaction, iron oxide and metallic aluminum powder are mixed together and ignited with a ribbon of metallic magnesium.

However, using a magnesium ribbon makes it impossible to confirm the magnesium product, so a plasma torch was used to generate the thermite reaction. In addition, lead oxide was used instead of iron oxide to improve shielding during the reaction.

The test crucible contained thorium dioxide (10 g) and the proprietary formulation of reducing reactants that would

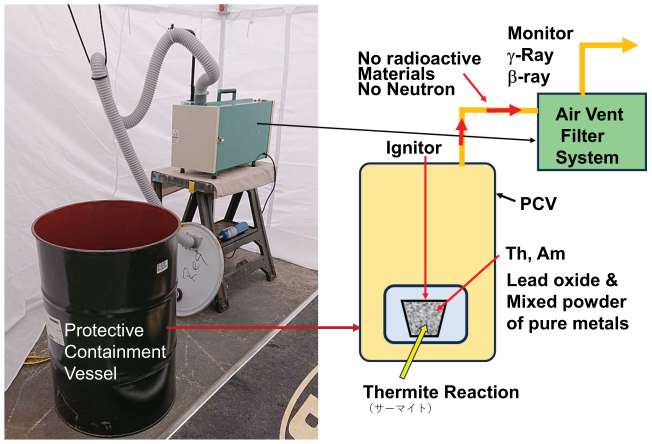

Fig. 8. Test device with air vent filter.

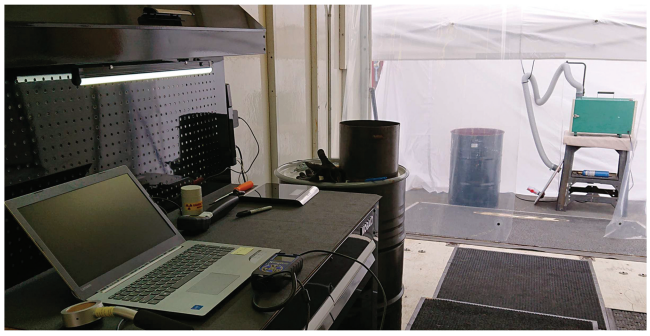

Fig. 9. Data logger in the measurement room.

cause the thermite reaction. The melting point of lead is 327.5°C, but its boiling point is relatively high, at about 1749°C (3180°F). A thorium dioxide test crucible and a uniquely formulated reducing agent induce the thermite reaction. The melting point of lead is 327.5°C, but its boiling point is relatively high, at about 1749°C (3180°F). Because thorium oxide deteriorates by cluster fission with muons, the use of the thorium oxide crucible was later discontinued.

A special thermite reaction is induced by mixing lead oxide powder with powders of several pure metals and reaction-promoting substances and heating them with a plasma torch. Because this reaches temperatures of over 2000K, a heat-resistant crucible made of thorium dioxide is used to contain the reactants.

As shown in Fig. 8, lead vapor is harmful to the human body, a reaction chamber was equipped with an air filtration system and igniting it. Fig. 9 shows a data logger in the measurement room. Beta and gamma radiation were both assessed prior to ignition and 30 minutes and 9 days after the reaction began (Ranger EXP Alpha-Beta-Gamma Meter, E.I. International, Inc. [15]), as shown in Fig. 10. Mass analysis was then performed at the University of Washington using their *Nu Instruments: Inductively Coupled*, which inductively coupled plasma mass spectrometry (ICP-MS) is a type of mass spectrometry that uses an inductively coupled plasma to ionize the sample.

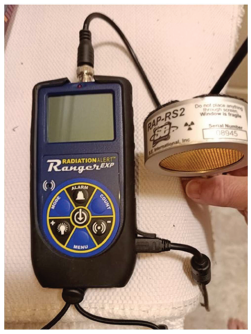

Fig. 10. Ranger α β γ detector.

III.D. Radiation Neutralization Test Results

III.D.1. Measurement Results

The cold fission cluster test starts after ignition. Astoundingly, the resulting thermo-metallurgical process temperature apparently did not exceed 3390°C (6134°F), the melting point of thorium dioxide, which is well above the known thermite reaction temperatures, and it did not melt the container. The bottle of thorium dioxide and the meeting for the test are shown in Figs. 11(a) and 11(b), respectively.

The demonstration test was conducted on May 7, 2018, by Theodore E. Dickinson, for Atom Frontier, Yoshihide Sakuragi, Matsujiro Hirooka, and Ian Portnoy of Dickinson Wright, PLLC. Measurements were taken using a calibrated, state-of-the-art Ranger EXP Alpha-Beta-Gamma Meter. Monitoring was conducted throughout the entire process.

Fig. 12 shows a measurement sample by using a Ranger EXP Alpha-Beta-Gamma Meter and plasma mass spectrometer [16]. A variety of other instrumentation not listed was also used, but the results revealed new phenomena that are essentially different from the simple interpretation of the radiological and spectroscopic findings. Fig. 13 shows the appearance of the powder solidified by reaction.

As shown in Fig. 12, this chart on a PC screen shows the process of the event repeatability. The beta ray recording chart on the PC screen was measured using one measuring device while switching the measurement location; therefore, the following measurement values are

(a) Thorium dioxide (b) Meeting for the test

Fig. 11. Testing device and measurement gamma ray detector. (a) Thorium dioxide. (b) Meeting for the test.

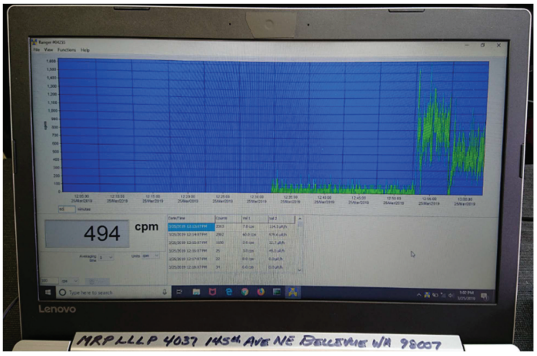

Fig. 12. Displaying data from the data logger on a PC.

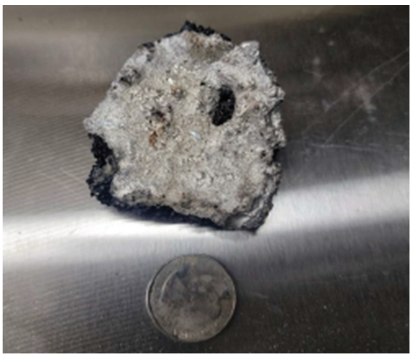

Fig. 13. The powder after the reaction.

recorded on the same screen. Measurements of the thorium immediately after the process showed that 85% of the thorium radioactivity had disappeared. After that, measurements of samples that had finished the process were continued, and the radioactivity level was at the background level after 72 hours. Radiation and spectrographic results are sequentially delineated and discussed in this section. Implications for future research are delineated in the concluding section.

III.D.1.a. Radiation

Table 1 summarizes the beta and gamma radiation levels over the course of the experiment. Examining this table, a broad—statistic significant pattern—is evident across the four assessments, $[F(3,3) = 52.26, p < .005]$.

As shown in Figs. 14 and 15, beta emissions decreased by 93% in 30 min (15 000 to 600 CPM) and 99.83% in 9 days and 19 days: lower than background radiation levels. As shown in Fig. 16, gamma emissions decreased by 93% in 30 min (4000 to 37.2 mR/h) and 99.83%: lower than background radiation levels.

III.D.1.b. Spectrographic Results

Tables 2 and 3 respectively outline salient spectrographic results and typical terrestrial proportions of Mg and ^{235}U and ^{238}U isotopes [16,17].[a]

Examining Table 2, one may first note that substantial portions of initial ^{232}Th (~half) are still present in the residual "White metallic disk" (D01) and a "Black powder" (S01) post-reaction products—with a ~51% (±2.5%) reduction weighted by relative sample masses. This result ordinarily would have suggested—in contrast to the above-reported observations—that beta and gamma radiation levels might have been near half those of the source material pre-treatment at Day 19. This result typically indicates that the levels of beta and gamma rays had decayed to virtually the same level as the pre-experiment background levels by the counting rate on day 9.

However, based on previously reported unique and similar cases involving lead, this is likely due to the reduction in radiation dose rates in tests using ^{232}Th, particularly because gamma rays and other radiation were shielded by lead shielding through surface pore sealing and internal shielding, introduced as an optional component of this uniquely developed flux material.

Further examining Table 2, it is noteworthy that substantial levels of Mg are in the residual "White metallic disk" (D01) and a "Black powder" (S01) post-reaction products. This is remarkably intriguing, as Mg was essentially not present prior to the pyro-treatment (i.e., not in the Th sample, pyro, or other materials). Equally intriguing, one also may note that in contrast with terrestrial isotope proportions (Table 2):

1. Somewhat more than equal relative proportions of ^{25}Mg to ^{24}Mg in both the "White metallic disk" (D01) and "Black powder" (S01) residual products (1.02:1 and 1.03:1).

2. No reported detection of ^{26}Mg in either D01 or S01. These latter results altogether profoundly contrast with the terrestrial range of 77% to 79% ^{24}Mg versus 10% to 11% ^{25}Mg $[t(1) = -3599.3, p < .0002]$; and 10% to 11% ^{25}Mg versus 11% ^{26}Mg $[t(1) = 6586.8, p < .0001]$.[b]

[a] We chose—though observed ^{235}U/^{235}U ratio is significantly different from ordinarily terrestrial—to not highlight this as anomalous ratios occasionally occur in trace samples (e.g., Ref. [13]).

[b] Analysis of variance (ANOVA) was here performed on Ln-transformed values using the mean score interaction as error. Q-QPlot—though limited in power—supported uses of Ln-transformation and use of the Bittner [18] recently overviewed the robustness of ANOVA and, relatedly, *t*-tests as $F(1, df) = t2(df)$.

TABLE 1

Radiation Assessments Across Experimental Periods

TYPE	Background	Source Material: ^{232}Th	30 Min. After	19 Days After
BETA *GAMMA*	~30 CPM ~9 μR/h	~15 000 CPM ~4000 μR/h	~600 CPM ~33 μR/h	~25 CPM ~7 μR/h

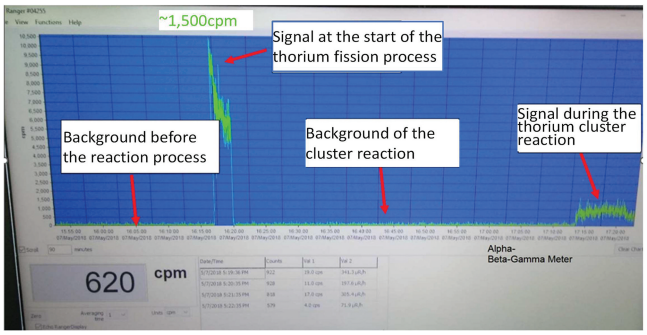

Fig. 14. Beta emissions reduced by 93% in 30 min (15 000 to 600 CPM).

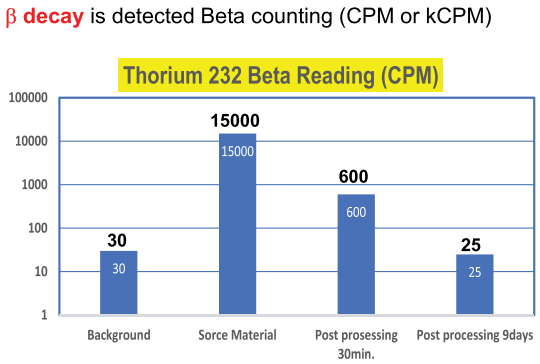

Fig. 15. Thorium fission and cluster reaction process: beta ray signal.

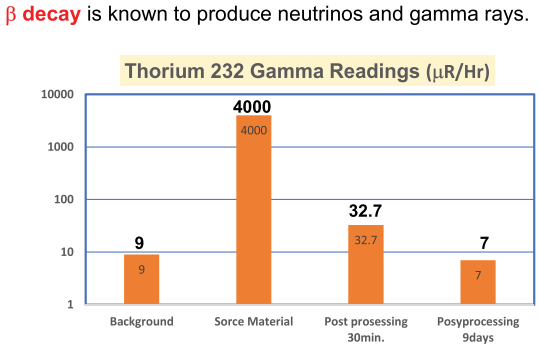

Fig. 16. Thorium fission and cluster reaction process: gamma ray signal.

III.E. Simultaneous Muon Neutralization Test for Radioactive Nuclides

On August 29, 2025, a neutralization test of mixed radioactive materials was conducted at RRS Solutions' laboratory, by using a small, proprietary device and proprietary formulations. The thorium dioxide, the uranium dioxide, and americium metal were mixed with thermite powder. Fig. 17 shows the simultaneous muon neutralization test.

Fig. 17 shows a snapshot of the simultaneous muon neutralization test. The surface of the steel reactor vessel, located inside the containment vessel, shows a glowing red reaction layer, indicating a temperature range of approximately 600°C to 800°C, as estimated from the color in Fig. 18. The reaction is stable and progresses slowly from top to bottom over several minutes. The area below the reaction layer is affected by the heat, but the muons are neutralized as they pass through the reaction layer. Due to the instantaneous nature of the reaction, a hissing sound, similar to boiling molten lead, can be heard. The thermite reaction products are heavy, and the beta radiation level decreases with a half-life of 15 h, resulting in a rock-like alloy of magnesium and lead.

In this test, 1100 g of a mixture of lead oxide and pure metal powder was mixed with 10 g of thorium dioxide, 5 g of uranium dioxide, and 1 g of americium. After the thermite reaction, all three radioactive substances—thorium dioxide, uranium dioxide, and americium—disappeared. The radioactivity counting rate suddenly drops by about three orders of magnitude. Only sodium-24, which has a half-life of 15 h, was counted, and after four days it had decreased to background levels.

By measurement of gamma rays associated with beta decay, as shown in Fig. 19, decay characteristics consistent with the approximately 15-h half-life of sodium-24 in cluster fission in the equations were confirmed in the route A-3. Since the half-lives of other radionuclides are short, the post-experimental count rate is determined by the half-life of sodium-24. Sodium-24 beta decays to magnesium-24, a stable element. The measured decay characteristics show good agreement with the straight

TABLE 2

Mass Spectrometric Results (ppm)

Sample	^{232}Th (ppm)	^{24}Mg (ppm)	^{25}Mg (ppm)	^{26}Mg (ppm)	^{235}U (ppm)	^{238}U (ppm)
D01 (Disk)	5829	1574	1619	ND	1.4	1.4
S01 (Sand)	6498	4718	4855	ND	1.8	1.7

TABLE 3

Terrestrial Isotope Relative Natural Abundances (%)

	^{232}Th (%)	^{24}Mg (%)	^{25}Mg (%)	^{26}Mg (%)	^{235}U (%)	^{238}U (%)
Natural abundance	100%	77%–79%	10%–11%	11%	0.72%	99.30%

(a) Radioactive Nuclides: ThO2, UO2, Am (b) Beta ray counting (121 kcpm)

(c) Neutralization test setup used for the neutralization test, showing the heated layer inside the container (the area that has turned red) and thermite reaction products.

Fig. 17. Simultaneous muon neutralization test (ThO2, UO2, Am).

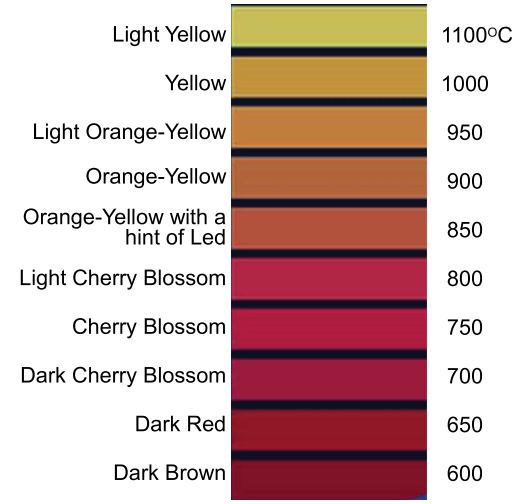

Fig. 18. The colors of the surface of heated iron/steel.

line representing the half-life of approximately 15 h of sodium-24, when the vertical axis is plotted on a logarithmic scale. These test results confirmed that a cluster reaction caused by muon is actually occurring.

IV. NUCLEAR WASTE DEACTIVATION

Tests have shown that the radioactive thorium introduced in the previous section can be rendered harmless by cluster fission. This may be hard to believe for people working in nuclear engineering, but cutting-edge elementary particle research has progressed to precise testing and research

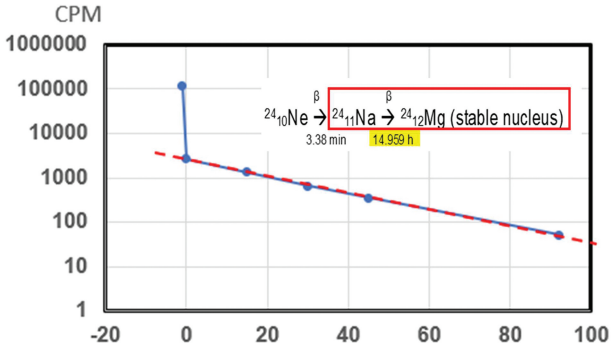

Fig. 19. The measured decay characteristics show good agreement with the half-life of approximately 15 h of sodium-24.

using high-energy beam accelerators, and catalytic nuclear fusion and cluster fission are already being studied as a matter of course with the intervention of muons and neutrinos, as reported in an explanatory article by the Atomic Energy Society of Japan. As cited in the references, many scientists are researching muon nuclear fission and neutrino emission. Although thorium-232 is a radioactive material, it is easy to obtain because of its low radiation dose. For example, when used in mountain climbing lanterns, it has the effect of making the light shine White, so it is mixed with mantle and sold at general mountain climbing equipment stores. In cloud chamber experiments by students, pieces of mantle are used as an easily available radiation source.

Muon fission and cluster decay of Am-241

$$^{241}_{95}\mathrm{AM} \rightarrow \ ^{34}_{14}\mathrm{Si} \ + \ ^{20}_{78}\mathrm{Tl}$$

$$^{34}_{14}\mathrm{Si} \xrightarrow[2.77\mathrm{sec}]{\beta-} {}^{34}_{15}\mathrm{P}_{\ \text{phosphorus}} \xrightarrow[12.43\mathrm{sec}]{\beta-} {}^{34}_{16}\mathrm{S}$$

$$^{207}_{81}\mathrm{Tl} \xrightarrow[4.77\mathrm{min}]{\beta-} {}^{207}_{82}\mathrm{Pb}$$

After ignition with a plasma torch and the beginning of a high-temperature reaction, the muon excitation reaction begins at the same time and, combined with the cooling effect of neutrinos, no radioactive material flows into the air purification system. It is thought that the inside of the reaction vessel instantly transitions starts to a cold fission state due to muon excitation fission and neutrino cooling.

This reaction may be able to start simultaneously with uranium oxide, plutonium oxide, and all minor actinides and cesium mixed with concrete powder.

As shown in Fig. 17, when spent fuel from a light water reactor is reprocessed, about 30 kg of high-level waste is generated per ton. The remaining oxides of uranium and plutonium can be recycled as fuel for light-water or fast reactors. In Japan and France, this high-level waste is melted into glass, filled into stainless steel canisters, solidified, and disposed of as vitrified waste in a geological repository. Japan's reprocessing and vitrification technologies are imported from France. High-level waste reprocessed in this geological repository can be reduced in volume to a fraction of that of direct disposal, and the period until any toxicity can be ignored can be shortened from 100 000 years to about 7000 years. Even so, 7000 years is considered too long in Japan, and obtaining a national consensus on geological disposal is an issue. Among this high-level waste, the most troublesome is americium, which generates high heat and has a high dose (toxicity). When cluster fission is used on americium, it undergoes beta decay and splits into silicon and thallium. Silicon undergoes further beta decay and is converted into sulfur via phosphorus. Thallium undergoes beta decay and is converted into stable lead. In other words, americium undergoes muon-excited fission into sulfur and lead.

There is another way to eliminate americium. It can be loaded into the blanket of a fast reactor in the form of a fuel assembly and then irradiated with fast neutrons during nuclear fission in the fast reactor to convert it into other substances with short half-lives and low toxicity. This is called the elimination of americium using a fast reactor, and the fast reactor acts as a burner to burn the americium. Since americium can be eliminated while generating electricity, it is expected to become widespread in the 21st century, when fast reactors become widespread.

As shown in Fig. 20, The total amount of fuel that has melted or is still inside the reactors at Units 1 through 3 of the Fukushima Daiichi Nuclear Power Plant is about 880 tons. As shown in Fig. 21, it is a molten mixture of concrete, iron, stainless steel, and zirconium cladding (or zirconia if

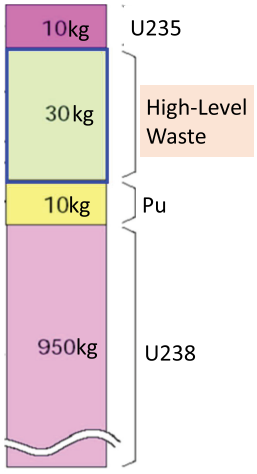

Fig. 20. High-level-waste in one ton of spent fuel.

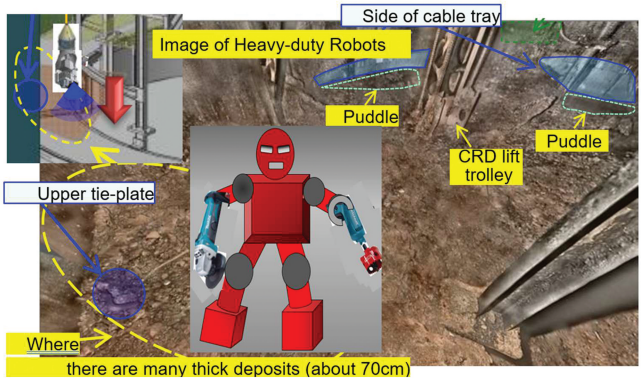

Fig. 21. Molten core debris that fell onto the pedestal in the floor below the reactor at the Fukushima Daiichi Nuclear Power Plant [19].

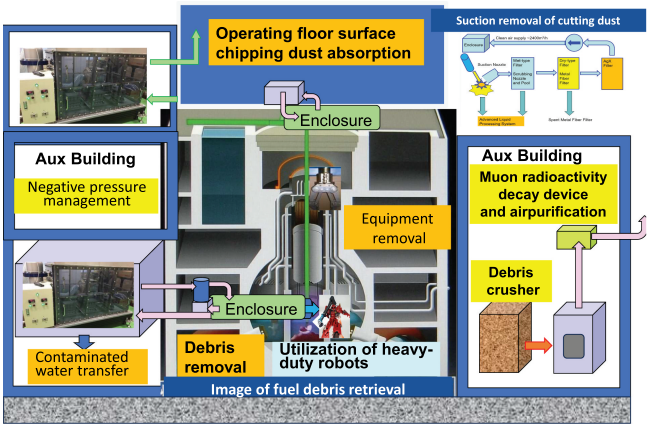

Fig. 22. Debris crusher and muon radioactivity decay device and air purification system [18].

oxidized). It is cut using water jet, hole saws, or laser beam and then removed with a robotic arm, as shown in Fig. 22.

As shown in Fig. 22, the rail track is also laid by a robotic arm. The rail-mounted cart is equipped with a water jet cutter, vacuum suction machine, and power shovel and will remove 5 kg of debris at a time. At the debris detoxification facility, the removed debris is crushed and mixed uniformly with lead powder for thermite reaction, reducing the debris' radioactivity.

As shown in Fig. 23, a rail-running cart enters the containment vessel through an airtight double hatch attached to the vessel and is precisely positioned on the track rails to cut up the debris. It is then transported to an auxiliary building by a power shovel, where it is crushed into powder in a crusher and uniformly mixed with lead oxide for the thermite reaction and pure metal powder. While we have already achieved success with up to 100 pounds (45 kg), using a proven 5-kg reactor and a robotic arm cart for criticality control will enable the processing of more than 1000 tons of highly radioactive debris within 15 years as follows:

The cart will operate each 5-kg transport twice an hour, eight hours a day, 300 days a year, and remove a total of 1080 tons of radioactive debris from each of the three nuclear power plants within a 15-year period. Fig. 24 shows a conceptual image of the debris collection and debris transport cart system to the muon reaction detoxification facility in the auxiliary building.

Fig. 25 shows the high-performance air purification system for removing radioactive dust and gases [20]. The air purification system is connected with the downstream of the muon neutralization and radiotoxicity system, as shown in Fig. 26. It can suction and neutralize radioactive dust and fumes, which are tiny particles of several tens of nanometers vaporized by laser heating during laser removal, machining, and laser cutting of radioactive materials inside the reactor containment vessel, as well as water-soluble particles and gases [21].

Metallic steels such as iron and stainless steel are mechanically separated using a sieve, and the remaining concrete fragments and oxide fuels of uranium and plutonium—which have a heavy specific gravity and can be crushed into fine particles—are separated using a spheroidization method that utilizes specific gravity and centrifugal force.

Cesium has a light specific gravity of 1.87 g/cm^3 and adheres to the crushed concrete powder. However, because its boiling point is between 678°C and 705°C, it melts and vaporizes during the thermite reaction and can be dissolved and separated in the scrubber water of the air purification system. Strontium has a low specific gravity of 2.64 and a boiling point of approximately

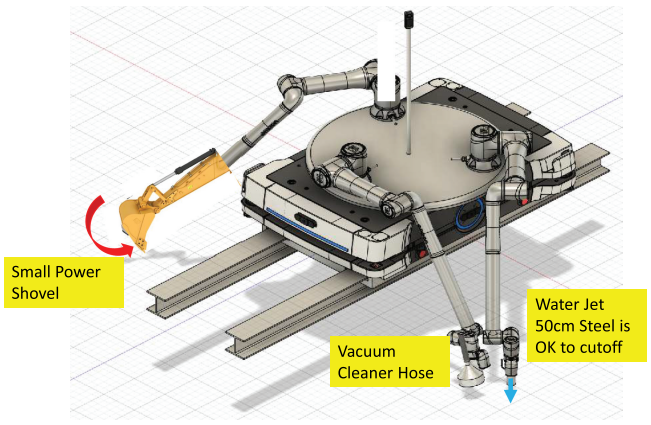

Fig. 23. Three robot arms mounted on a carriage that moves along a rail track.

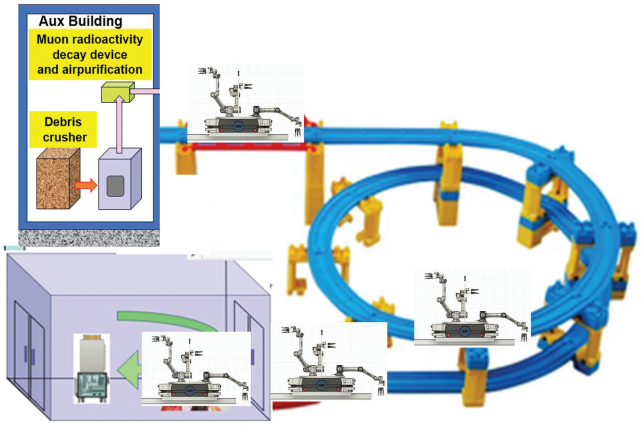

Fig. 24. Conceptual image of the debris collection and debris transport cart system to the muon reaction detoxification facility in the auxiliary building.

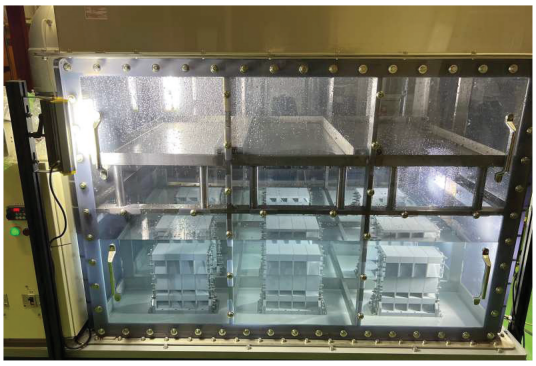

Fig. 25. The high-performance air purification system for removing radioactive dust and gases [19,20].

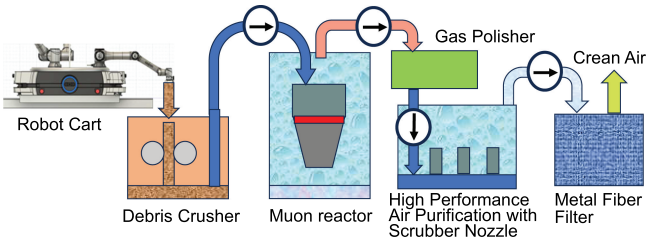

Fig. 26. Muon radioactivity neutralization device and air purification system for removing radioactive dust and gases.

1384°C, so it can be melted, vaporized, and recovered and separated using the scrubber water in the air purification system. The fuel components uranium oxide and thorium oxide solidify in the presence of the water flowing down from the core injection water, becoming brown and brittle enough to be broken with a hammer. Therefore, they are powdered and converted, along with the minor actinide americium, into harmless, stable lead and magnesium, which are non-radioactive, using a muon-neutralization reaction.

As described above, all radioactive materials thought to have high levels of radiation and heat in the debris at Fukushima Daiichi can be removed. According to nuclear engineering knowledge, cesium and strontium are thought not to undergo muon-neutralization reactions, but this will be confirmed through future tests. Both have half-lives of approximately 30 years, and their radioactivity will decay to one-ninth of their original level after 120 years of storage.

V. DISCUSSION

Atomic nuclei in this muon-excited state were achieved by heating them to high temperatures. How are the neutrinos generated removed the thermal energy? The "molten and solidified core-damaged waste that fell to the bottom of the reactor vessel or the support platform" is removed using a robotic cart, and a muon reactor, heated by thermite reaction, is used to generate muon cluster fission reactions. Muons are known to emit neutrinos when they expire and disappear. This causes gamma rays to be emitted during beta decay. For example, neutrinos are also emitted from the sun, where high-temperature nuclear fusion occurs. Neutrinos are also known to be emitted from operating boiling water reactors. Neutrinos carry away thermal energy at high speed as kinetic energy of high-speed particles, which has a cooling effect and keeps the temperature inside the reactor low. Muon-excited atomic nuclei are attracted to each other, creating an extremely stable flow state within the reactor for the neutrino-cooling effect. This creates a situation that could be called an implosion, rather than an explosion like a typical thermite reaction. Volatile gases in the unreacted layer below the muon reaction layer cannot escape to the top without passing through the muon reaction layer, so the radioactivity is lost through the muon reaction, or volatile gases that do not undergo a muon reaction are dissolved and collected in the scrubber water as they pass through the scrubber nozzle of the downstream air purification system. These mechanisms will need to be measured quantitatively in the future, but observing the actual phenomenon is truly impressive.

What is the state of the muon reaction layer? Previous research using accelerators has revealed that atoms of heavy nuclides are generated almost instantly with 100% probability. This was also the case in tests. The muon reaction ends when the high-temperature reaction surface of the thermite reaction slowly moves from top to bottom in a horizontal layer. After muon cluster fission, nuclides transition one after another with previously known and measured half-lives such as beta decay. The radioactivity counting rate during beta decay suddenly drops by about three orders of magnitude, so the initial radioactive nuclides such as americium and uranium will end instantly within the reaction layer.

VI. CONCLUSION

The significance of this research can be summarized as follows:

1. The muon-excited state was achieved by heating atomic nuclei to high temperatures.

2. This was achieved using an incredibly small device and simple process. By mixing radioactive thorium dioxide powder in a unique formulation and igniting it, a controllable thermite reaction was induced, experimentally confirming the muon-excited fission of thorium-232 and a series of decay phenomena.

3. The most troublesome of these high-level wastes is americium, which generates high heat and has a high dose (toxicity). When cluster fission is used on americium, it undergoes muon-excited fission and transforms into lead, an essentially stable atomic nucleus.

4. The half-life of thorium-232 is 14 billion years. We demonstrated that this time can be shortened to just a few days using this unique process and related formulation.

5. We successfully neutralized three radioactive substances simultaneously: thorium dioxide, uranium dioxide, and americium, with zero inflow of radioactive materials into the air purification system.

6. It is believed that the interior of the reactor vessel will instantly transition to a cluster fission state due to muon-excited fission and neutrino cooling.

7. We have demonstrated a solution to the management and storage of removed radioactive debris, one of the challenges in decommissioning the Fukushima Daiichi Nuclear Power Plant, by using cluster fission technology using muon-excited reactions. This provides a solution that allows decommissioning work to be carried out on a realistic scale and within a realistic time frame.

8. The muon reactor described in this paper is large enough to make this possible. It can process 5 kg of debris per batch. The RRS has already been demonstrated in reactors up to 100 pounds (45 kg). This 45-kg reactor can process 5 kg of debris. Three cart-type robots under criticality control will be able to process more than 1000 tons of highly radioactive debris from Fukushima Daiichi Nuclear Power Plant Units 1, 2, and 3 within 15 years.

9. In the future, it will be necessary to process powdered molten debris collected from the Fukushima Daiichi Nuclear Power Plant in a muon reactor and identify the nuclides and isotopes produced after the reaction, the presence or absence of neutrons, and the intensities and half-lives of alpha, beta, and gamma rays.

10. Given the proven success of detoxifying cobalt-60, we should also consider the possibility of nuclear decay for nuclides that are difficult to fission, such as cesium and strontium.

11. Identifying nuclides and isotopes using a quadrupole mass spectrometer. While simultaneous processing of multiple nuclides is known to be possible, we believe it is best to begin with basic research to confirm whether muon neutralization is possible using small amounts of each individual nuclide.

12. We also presented specifications for a rail-mounted robotic cart that can be realistically designed and manufactured. This will enable us to consider the technical progress of decommissioning work at the Fukushima Daiichi Nuclear Power Plant, including the schedule.

13. Muon cluster fission technology can also be applied to neutralizing high-level radioactive waste extracted at the Rokkasho-Mura Spent Fuel Reprocessing Plant. By significantly reducing radioactivity and heat generation, it is possible to shorten the geological disposal period from several thousand years to 120 years. If nuclides other than heavy nuclides such as cesium and strontium can be processed, this could be further shortened. Eliminating heat generation also allows for a significant reduction in the size of disposal sites, making it easier to gain understanding regarding site selection for geological repositories and public acceptance.

If neutralization and radiotoxicity reduction of high-level waste becomes practical, it will increase momentum for reprocessing in countries such as the United States, which currently stores spent fuel in concrete casks, and Nordic countries, which are considering direct disposal. This will promote the recycling of uranium and plutonium resources and the spread of fast reactors, thereby enabling the effective use of uranium resources. This is expected to contribute to solving humanity's energy resource problems, reducing CO_2 emissions, and preventing global warming.

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In summarizing this paper, we have named this Japan–United States collaborative research project, the "GX-Seattle Project," after the demonstration place of some of the research.

Author Contributions

CRediT: **Tadashi Narabayashi:** Conceptualization, Methodology, Supervision, Writing – original draft; **Theodore Dickinson:** Conceptualization, Methodology, Project administration, Resources, Supervision; **Dominic Notter:** Data curation, Investigation, Resources, Software, Validation; **Yoshihide Sakuragi:** Formal analysis, Methodology, Supervision, Validation, Writing – original draft; **Alvah C. Bittner:** Formal analysis, Software, Validation.

Disclosure Statement

No potential conflict of interest was reported by the author(s).

ORCID

Tadashi Narabayashi http://orcid.org/0009-0000-0039-1417

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