Report on the Visual Study and Groundwater Analysis of the Cactus Crater Containment Structure on Runit Island, Republic of the Marshall Islands

Report to Congress
October 2022

United States Department of Energy
Washington, DC 20585

Message from the Secretary of Energy

As directed by Section 2, Public Law 112-149, Insular Areas Act of 2011, this report provides information regarding the activities and results of the visual survey and groundwater radiochemical analysis of the Cactus Crater Containment Structure on Runit Island in the Republic of the Marshall Islands and a determination on whether the surveys and analyses indicate any significant change in the health risks to the people of Enewetak from the contaminants within the Cactus Crater Containment Structure.

This report is being provided to the following Members of Congress:

- **The Honorable Joseph Manchin**
  Chairman, Senate Committee on Energy and Natural Resources

- **The Honorable John Barrasso**
  Ranking Member, Senate Committee on Energy and Natural Resources

- **The Honorable Raúl M. Grijalva**
  Chairman, House Committee on Natural Resources

- **The Honorable Bruce Westerman**
  Ranking Member, House Committee on Natural Resources

- **The Honorable Patrick Leahy**
  Chairman, Senate Committee on Appropriations

- **The Honorable Richard Shelby**
  Vice Chairman, Senate Committee on Appropriations

- **The Honorable Rosa L. DeLauro**
  Chair, House Committee on Appropriations

- **The Honorable Kay Granger**
  Ranking Member, House Committee on Appropriations

If you have any questions or need additional information, please contact Ms. Katie Donley, Deputy Director for External Coordination, Office of the Chief Financial Officer, at (202) 586-0176 or Ms. Becca Ward, Deputy Assistant for Senate Affairs or Mr. Michael Harris, Legislative Affairs Advisor, Office of Congressional and Intergovernmental Affairs, at (202) 586-5450.

Sincerely,

Jennifer M. Granholm

Executive Summary

The purpose of this report is to provide information to Congress regarding the activities and results of the U.S. Department of Energy's (DOE) visual survey and groundwater radiochemical analysis of the Cactus Crater Containment Structure on Runit Island in the Republic of the Marshall Islands, and a determination on whether the surveys and analyses indicate any significant change in the health risks to the people of Enewetak from the contaminants within the Cactus Crater Containment Structure, as directed by Section 2 of Public Law 112-149, Insular Areas Act of 2011.

DOE completed two visual studies of the Cactus Crater Containment Structure on Runit Island, in 2013 and 2018. These studies assessed the condition of individual concrete panel cap segments that protect the mound of encapsulated contaminated soil and radioactive debris below from erosion. Although the studies revealed that some concrete panels contained visual defects consisting mostly of cracks and spalled concrete panel seams and corners, DOE determined they were not structural in nature nor likely to present any additional hazard associated with the spread of radioactive contamination into the environment. Additionally, nondestructive and core sample testing results showed that the exterior concrete cap was not compromised and was serving its intended purpose of providing an effective barrier to reduce natural erosion of underlying waste pile materials.

The Runit Island groundwater monitoring program indicates that under existing conditions, there appears to be no clear evidence that dispersion of Cactus Crater-derived radioactivity is having a measurable impact on the radiation environment in offshore lagoon or surrounding ocean waters. Elevated levels of $^{239+240}Pu$ contamination observed in the lagoon water appear to be dominated by plutonium from the lagoon sediments and not from the flow of Cactus Crater-derived contamination into the lagoon.

Based on the visual studies and the data observed from the Runit groundwater monitoring program, DOE has determined that there has been no significant change in the health risks to the people of Enewetak from the contaminants within the Cactus Crater Containment Structure.

In 2022, DOE initiated a collaboration with the U.S. Army Corps of Engineers (USACE) to assist with design and installation of additional groundwater monitoring resources to improve future data and provide a more detailed picture of groundwater flow and characteristics in and around the Cactus Crater Containment Structure.

REPORT ON THE VISUAL STUDY AND GROUNDWATER ANALYSIS OF THE CACTUS CRATER CONTAINMENT STRUCTURE ON RUNIT ISLAND, REPUBLIC OF THE MARSHALL ISLANDS

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I. Legislative Language

DOE is providing this report as directed by Section 2, Public Law 112-149, Insular Areas Act of 2011, which provides in part:

> "(ii) REPORT.—The Secretary shall submit to the Committee on Energy and Natural Resources of the Senate, and the Committee on Natural Resources of the House of Representatives, a report that contains—
>
> (I) a description of—
>
> (aa) the results of each visual survey conducted under clause (i)(I) *[visual study of the concrete exterior of the Cactus Crater containment structure on Runit Island]*; and
>
> (bb) the results of the radiochemical analysis conducted under clause (i)(II) *[radiochemical analysis of the groundwater surrounding and in the Cactus Crater containment structure on Runit Island]*; and
>
> (II) a determination on whether the surveys and analyses indicate any significant change in the health risks to the people of Enewetak from the contaminants within the Cactus Crater containment structure."

II. Introduction

The purpose of this report is to provide information regarding the activities and results of DOE's visual survey and groundwater radiochemical analysis of the Cactus Crater Containment Structure on Runit Island in the Republic of the Marshall Islands (RMI), and a determination on whether the surveys and analyses indicate any significant change in the health risks to the people of Enewetak from the contaminants within the Cactus Crater, as directed by Section 2, Public Law 112-149, Insular Areas Act of 2011 [codified at Title 48 U.S. Code (U.S.C.) Section 1921b(f)(1)(B)].

<u>Background</u>

The Enewetak Atoll is a former U.S. atmospheric nuclear weapons test site in the RMI, which is located in the central Pacific Ocean between the Hawaiian and Philippines Islands. Between 1946 and 1958, the U.S. conducted 67 atmospheric nuclear weapons tests in the Marshall Islands, 43 of which were conducted at Enewetak Atoll. Radioactive fallout from these tests resulted in contamination of the atoll and the local marine environment. The Enewetak Atoll continued to be used for various U.S. Department of Defense programs until the mid-1970s. In 1972, Enewetak Atoll was returned to the Trust Territory of the Pacific Islands and the U.S. Government initiated an extensive radiological cleanup and rehabilitation program through 1980. While the people of Enewetak returned to their ancestral homeland in 1980, Runit Island remains uninhabited.

During the radiological cleanup of Enewetak Atoll, radioactively contaminated soil was identified, removed, and transported to Runit Island, which is located on Enewetak Atoll (Hamilton, 2013; DNA, 1981). Approximately 100,000 cubic yards of contaminated soil, encapsulated in cement, and an estimated 6,000 cubic yards of radioactively contaminated debris composed largely of oversize soil, structural steel, and concrete was placed inside an unlined crater (Cactus Crater) on the northern side of Runit Island to form a dome shaped structure approximately 374 feet in diameter and 24 feet tall. The waste-pile was then covered by a concrete cap to protect the waste from erosion. The concrete cap is composed of 357 individually formed, trapezoidal shaped, concrete panel segments and a top section all with a design thickness of 18 inches (Hamilton, 2013; DNA, 1981; Ristvet, 1980). The structure is referred to as the "Cactus Crater Containment Structure" or "Cactus Crater" and locally as the "Runit Dome."

The purpose of the radiological cleanup of Enewetak Atoll was to reduce the concentration of transuranium elements (TRU) plutonium ($^{238,239,240}Pu$) and americium (^{241}Am) contained in surface soils of the areas affected by the nuclear tests. Approximately half the total inventory of TRU radioactivity in Cactus Crater came from contaminated soil excised from five northern islands. Only a very small quantity (approximately 0.1 percent by volume) of contaminated material was from the southern islands. The remaining radioactive soil originated from cleanup of Runit Island and its surrounding reef areas. The total TRU activity of excised soil encapsulated in the Cactus Crater was estimated to be 545 giga-becquerel (GBq) (NAS, 1981). Of this total activity, approximately 24 percent (131 GBq) was encapsulated in a slurry mixture of contaminated soil and cement placed in the crater below water level via a tremie, a tool used to pour concrete underwater. In comparison, it is estimated that the marine sediments in the Enewetak Atoll lagoon contain more than 67,000 GBq of TRU activity (Noshkin, 1980; Noshkin et al., 1987; Noshkin and Robison, 1997).

III. Visual Study

DOE conducted two visual studies of the Cactus Crater Containment Structure in 2013 and 2018 to assess the physical condition of the structure. DOE also conducted structural evaluations of the Cactus Crater Containment Structure concrete cap in 2013 and 2016 in support of groundwater monitoring activities.

DOE performed the 2013 visual study using a handheld camera with individual photos taken of each panel segment (Hamilton, 2013). The study revealed that the cap was being encroached upon by the surrounding vegetation and some concrete panels showed visual defects consisting mostly of cracks and spalled (flaked and/or peeled) seams and corners. DOE conducted the 2018 visual study using an unmanned aerial system (UAS) to better acquire consistent visuals and documentation of the condition of the concrete panels (https://marshallislands.llnl.gov/runit_visual_survey.php; Hamilton and Nyholm, 2021; Hamilton et al., 2019a; Hamilton et al., 2018a; Hamilton et al., 2018b). More than 500 UAS photo images were taken and used to produce a viewable montage or photomosaic record of the structure (see Figure 2, Section VIII). High resolution UAS video was also taken to provide footage of the overall integrity of the containment structure cap and highlight the general condition of the key wall extending around the perimeter of the structure and of the riprap material placed along the ocean shoreline (Hamilton et al., 2019; Hamilton et al., 2018a; Hamilton et al., 2018b). The results of the two visual studies indicated that the cracks and spalling of concrete were not considered structural in nature or likely to present any additional hazard associated with the spread of radioactive contamination into the environment.

The 2013 nondestructive evaluation (NDE) study utilized ground penetrating radar for sub-grade evaluation, impact echo (IE) for concrete thickness and condition, and spectral analysis of surface waves (SASW) for concrete condition (Hamilton, 2020a; Hamilton, 2013). Conclusions drawn from the NDE study indicated that the concrete cap was structurally sound and in contact with the waste material below with very few (less than 0.6 percent) voided or poorly supported regions. The SASW data supported findings from the IE test results and indicated that most of the concrete was of sound condition.

The 2016 study consisted of compressive strength testing, petrographic examination, and chemical analysis of concrete cap core specimens collected by a licensed engineer (Hamilton, 2020b). Analyses of concrete core specimens indicated that the exterior concrete remained well-cemented, appeared to be properly consolidated and cured, and had satisfactory strength and binding properties. The compressive strength of the concrete core specimens averaged 46,200 ± 7600 kilopascals (6704 ± 1100 pounds per square inch) with a measured load capacity varying between 22,200 and 50,440 kilograms (49,000 - 111,000 pounds) (Hamilton, 2020b). Microcracks and small macrocracks observed along the exterior portion of concrete did not appear to be adversely affecting the strength properties or overall integrity of the concrete.

The results of the two integrity studies further supported the visual studies results indicating that the Cactus Crater Containment Structure concrete cap was still serving its intended purpose of providing an effective barrier to reduce natural erosion of underlying waste material.

<u>Concrete Repair</u>

Based on the 2013 visual study, cosmetic repair of the concrete and the development of a program to eradicate rooting vines was incorporated into the scope of the 2018 visual study to allow for more accurate assessment of future changes in the condition of the concrete cap (Hamilton, 2013). Vegetation was removed and 46 cracked panels and 34 spalls were repaired under the supervision of a licensed engineer using a combination of pre-packaged cement-based mortar and two component, high strength structural epoxy formulations specifically designed to repair cracks in concrete (Hamilton, 2019c).

Since 2018, DOE has regularly conducted general maintenance activities on the Cactus Crater Containment Structure and has employed and trained local workers to remove vegetation growing on the structure, take photographs, and report any significant changes in the overall integrity of the structure every 3 to 6 months (see Figure 9, Section VIII).

IV. Groundwater Radiochemical Analysis

The goal of the groundwater monitoring program on Runit Island is to determine if and to what extent groundwater and Cactus Crater-derived radionuclides are moving from the containment structure into the surrounding environment in order to quantify potential health or ecological risks posed by leakage of radioactive contamination into the environment.

Pump tests of reconstituted monitoring wells conducted from 2013 to 2018 indicate that groundwater within the Cactus Crater Containment Structure is in communication with lagoon and/or ocean water. Therefore, groundwater quality, fluid hydrodynamics, and the transport of radionuclides will be variously affected by tidal fluctuations, heavy rainfall, sea surface conditions driven by wind speed and direction, and storm surge. A significant challenge in quantifying the movement of radionuclides is that any leakage of Cactus Crater-derived radioactivity through the groundwater aquifer into the surrounding marine environment must be identified and evaluated in the presence of the very large burden of radioactivity that already exists in the adjacent lagoon water and sediments seawater, and surrounding soil.

The radioactivity that already exists in the adjacent lagoons is from fallout due to the nuclear weapons testing that was done in that location, as well as migration of unencapsulated radioactive contamination contained in buried subsurface soils and surface contamination on Runit Islandvia leaching into the groundwater aquifer. . This radioactive debris deposited in local surface sediments forms an open source for continuous remobilization of radionuclides into bottom water of the lagoon. This source of radioactive contamination is also available for uptake by nearshore marine organisms.

At the onset of the Runit Island groundwater monitoring program, DOE identified three groundwater boreholes from previous scientific studies and reestablished the boreholes as groundwater sampling wells. These existing boreholes have been used to provide initial groundwater testing and analysis and to help assess the requirements and logistics needed to drill and install any additional groundwater sampling wells needed to improve sampling and monitoring capabilities.

This report contains results of analyses of groundwater collected from two reconstituted boreholes from a 1980 study conducted by the NAS, identified as CD-16 and CD-17, and a third borehole, identified as ARU-2, from Project EXPOE (see Figure 1, Section VIII). CD-16 is located approximately 45 feet away from the base of the structure on the lagoon side (Ristvet, 1980). CD-17 is a shallow water borehole located on the third ring from the base of the Cactus Crater Containment Structure cap (Hamilton, 2013). ARU-2 is located approximately 330 feet south-southeast of Cactus Crater Containment Structure.

Groundwater samples were collected from CD-16 and CD-17 in 2013, 2015, 2016, and 2018, and analyzed for a range of targeted fallout radionuclides and metal contaminants;

groundwater from ARU-2 was sampled in 2013, 2016, and 2018 (see Table 1, Section VIII). CD-17 groundwater samples collected in 2016 included a 4-hourly daily cycle to study the influence of tidal fluctuations on water quality. Lagoon water samples were collected for comparative purposes directly off Runit Island and at other locations across the lagoon and in the open ocean. Some additional seawater samples were collected in shallow water on the ocean reef and in the lagoon close to the Cactus Crater Containment Structure.

Radiochemical analyses were performed on groundwater and marine samples for chlorine-36 (^{36}Cl), cesium-137 (^{137}Cs), iodine-129 (^{129}I), uranium-236 (^{236}U), plutonium isotopes (^{239}Pu, ^{240}Pu), ^{240}Pu/^{239}Pu atom ratios, tritium (^{3}H), gross-alpha, gross-beta, and strontium-90 (^{90}Sr) (see Table 2, Section VIII). Groundwater samples collected from CD-17 in 2015 were also tested for standard water quality measures plus a variety of metal ions (see Table 4, Section VIII).

CD-17 is a shallow well, depending on the influence of tidal fluctuations, the standing groundwater in CD-17 rarely exceeded a few feet. Therefore, contaminant levels observed in CD-17 may not be representative of the full range of contaminants that could be found in deeper layers or from other locations on or around the Cactus Crater Containment Structure. However, these data, together with analyses of lagoon and open ocean seawater samples, provided a scientific basis for identifying key radionuclides and/or isotopic signatures that might be used as tracers to study the release of Cactus Crater-derived contamination through the groundwater aquifer into the local marine environment.

The annual mean activity concentration of soluble $^{239+240}$Pu measured in groundwater collected from CD-17 was 1.9 milliBq per liter (mBq/L), approximately ten times (approximately 0.17 mBq/L) that measured in offshore lagoon waters over the same period (see Figure 3, Section VIII). By comparison, the mean activity concentration of soluble ^{137}Cs measured in CD-17 was 2.4 Bq/L, more than 2000 times higher than the mean activity concentration of approximately 0.001 Bq/L measured in lagoon water (see Figure 4, Section VIII).This indicates that ^{137}Cs is likely to a better candidate for source tracing of Cactus Crater-derived radionuclides into the marine environment. Moreover, ^{137}Cs is a soluble radionuclide that is more readily mobilized and transferred in solution compared with TRU contaminants.

It also appeared that the concentration of fallout radionuclides in groundwater from Cactus Crater had not changed significantly over time. For example, the average reported activity concentration of soluble $^{239+240}$Pu and ^{137}Cs in groundwater from two levels in a separate NAS borehole (CD-1) in 1980 was 1.8 mBq/L and 4.0 Bq/L, respectively, or little changed from the annual mean activity concentration found in CD-17 for these monitoring years.

The mean activity concentrations of $^{239+240}$Pu and ^{137}Cs measured in groundwater samples from CD-16 and ARU-2 were about a third of that observed in groundwater from CD-17. The activity concentration of ^{137}Cs observed in surface waters of the lagoon was comparable with levels found in open ocean surface (see Figure 4, Section VIII). This observed level of ^{137}Cs activity concentration indicated that any release of ^{137}Cs from the Cactus Crater Containment Structure through the groundwater aquifer is having a negligible impact on radiological conditions in the wider marine environment on Enewetak Atoll.

In contrast to ^{137}Cs, the range of activity concentration of $^{239+240}Pu$ observed in lagoon water was significantly elevated in comparison with levels observed in the open ocean. This observation applied equally to locations around the lagoon as well as for surface seawater samples collected off Runit Island (see Figure 3, Section VIII). This observation is in line with results from previous studies which have established that Enewetak Atoll lagoon seawater contains elevated and persistent levels of $^{239+240}Pu$ contamination compared with the open ocean which is attributed to the solubilization of residual TRU contamination contained in bottom sediment of the lagoon (Buesseler et. al., 2018; Hamilton, 2021b; Nelson et al.,1973; Noshkin, 1980; Noshkin and Robison, 1997; Noshkin et. al, 1974;Noshkin and Robison, 1997; Noshkin, 1980).

TRU contamination entered the marine environment by direct deposition of close-in fallout debris from the nuclear weapons testing program and is a continuous source-term for remobilization and redistribution of $^{239+240}Pu$ and ^{241}Am into the water column. The analyses of samples confirm that persistently higher levels of $^{239+240}Pu$ (about 100 to 150-fold) remain in surface waters of Enewetak Atoll lagoon relative to that contained in regional open ocean surface waters. At the same time, retrospective analyses, dating back to the early 1960s, of a sectioned coral core collected off Runit Island show a decreasing trend in activity concentrations of $^{239+240}Pu$ and, by association in surrounding sea water, (see Figure 5, Section VIII). This trend continues through the post-cleanup era after construction of the Cactus Crater Containment Structure.

In general, $^{240}Pu/^{239}Pu$ isotopic ratios (i.e., atom ratios) can be used to differentiate between different sources of plutonium contamination in the environment (Hamilton et al., 2008; Hamilton, 2019). The annualized $^{240}Pu/^{239}Pu$ atom ratio measured in groundwater samples collected from CD-17 averaged approximately 0.11. While the $^{240}Pu/^{239}Pu$ atom ratio observed in lagoon waters collected in the surf zone closest to the Cactus Crater Containment Structure is 0.063 ± 0.002 and measured in a seawater sample collected on the ocean reef adjacent to the riprap material surrounding the structure is 0.059 ± 0.005. Based on the fact that the $^{240}Pu/^{239}Pu$ atom ratio results for the groundwater from CD-17 were different than the Pu atom ratios measured in nearshore seawater samples collected from the surf zone in the lagoon and on the ocean reef adjacent to the containment structure, the local marine radiation environment within a few hundred meters from the shoreline of Runit Island appears to be dominated by Pu mobilization from sedimentary sources to solution and not from leakage of radioactive contaminants from the Cactus Crater Containment Structure. At this time, any ^{137}Cs and $^{239+240}Pu$ that enters the lagoon through the groundwater aquifer surrounding Cactus Crater Containment Structure is not distinguishable from the other sources of fallout contamination in the lagoon.

Measurement of Standardized Water Quality Parameters and Heavy Metals

Groundwater samples collected from CD-17 in 2015 were analyzed for a wide range of fallout radionuclides and compared with the U.S Environmental Protection Agency (EPA) Maximum Contaminant Levels (MCLs) for drinking water (see Table 3, Section VIII). The results indicated that the activity concentration of most fallout radionuclides contained in the groundwater beneath the Cactus Crater Containment Structure were less than the corresponding MCLs for drinking water. ^{90}Sr and gross beta were the exception as they were approximately 20 times and almost 10 times higher than the recommended MCL (respectively). The results indicated that any outflows of groundwater from the Cactus Crater Containment Structure into the lagoon are unlikely to present a significant human health or ecological risk.

The activity concentration of ^{3}H and ^{129}I in groundwater from CD-17 was found to be higher than the concentration measured in lagoon water and the open ocean (see Figures 6 and 7, Section VIII). There was no statistically significant difference in the activity concentration of ^{3}H in lagoon water versus levels observed in the open ocean and ^{129}I was only marginally elevated in lagoon water relative to that measured in the open ocean. These data are consistent with previously measured levels for ^{137}Cs and indicate that any outflow of radioactive contaminants into the lagoon from the Cactus Crater Containment Structure groundwater aquifer is not distinguishable from the concentrations of fallout radionuclides in the wider marine environment and present a minimal added risk. The consistency of the ^{129}I data measured for the different water bodies indicates that this radionuclide is a good candidate for future monitoring of potential discharges of Cactus Crater-derived contaminants into the lagoon.

The groundwater collected from CD-17 indicated a pH of 12.2 as compared to a pH of 8.1 for seawater. This high level of pH was likely caused by the concrete material in the crater fill.

Rainfall is also having a clear influence on groundwater salinity and is likely driving short-term changes in water quality. In general, the measured salinity of groundwater in CD-17 has been highly variable, ranging from 0.7-16.7 percent saline but has remained relatively fresh compared with groundwater contained in CD-16 and ARU-2, which range between 21-30.4 percent saline. This difference in salinity implies that there is some level of rainwater infiltration into the waste pile under the Cactus Crater Containment Structure.

DOE also analyzed groundwater samples for heavy metals, including beryllium, to address concerns raised by the Enewetak Atoll leadership. No beryllium was detected in the Cactus Crater Containment Structure groundwater. Other than the high pH, none of the standard water quality results were outside of EPA parameters (see Table 4, Section VIII).

V. Health Risk Assessment

The most likely scenario for radiological contamination release from the Cactus Crater Containment Structure is the flow of contaminated groundwater from the Structure that may form localized contamination areas in and around outflow points in the lagoon and increase the level of radionuclide uptake into marine biota, especially for some sessile (fixed in one place) organisms. Consumers of these marine foods may have a higher risk of cancer from intakes of Cactus Crater-derived radionuclides compared to those people who refrain from eating marine foods from this area. Under this scenario, groundwater quality, radionuclide dispersion away from the site boundary in the groundwater aquifer, and the subsequent uptake of fallout radionuclides in the marine food chain will be variously affected by local forcing events scaling from days (e.g., diurnal tides) to seasonal storms, and possibly from the longer-term impacts of sea-level rise.

The Runit Island groundwater monitoring program suggests that fallout contamination may be leaching into the groundwater aquifer beneath the Cactus Crater Containment Structure due to the pump test results, which have indicated that the groundwater and lagoon water are in communication. The groundwater then may be considered a point source for potential migration of fallout radionuclides away from the site boundary and into the marine environment. Any outfall of Cactus Crater-derived fallout contamination into the marine environment is likely to take place at discrete outflow points in the lagoon and could potentially provide an additional source-term for uptake of fallout radionuclides, such as ^{137}Cs, into aquatic plants and animals. ^{137}Cs is known to accumulate in edible portions of fish and other marine organisms (Noshkin et al., 1997).

Under existing conditions, there is no clear evidence at present that dispersion of Cactus Crater-derived radioactivity is having a measurable impact on the radiation environment in offshore lagoon waters due to the contamination present in the lagoon. Elevated levels of $^{239+240}$Pu contamination observed in the Enewetak Atoll lagoon appear to be dominated by Pu from the lagoon sediments and not from the flow of Cactus Crater-derived contamination into the lagoon. As previously discussed, the inventory of TRU activity encapsulated in the Cactus Crater Containment Structure is dwarfed by the inventory of TRU activity in atoll lagoon sediments (Davisson et al., 2012; Hamilton, 2013; Noshkin and Robison, 1997). .

To assess individual personal risk more directly, DOE has maintained a personal whole body counting radiological monitoring program on Enewetak since 1977 and a plutonium urinalysis bioassay program since 2001. These monitoring programs are available at no cost to all residents. The individual results are provided to each participant and the overall results, with personal information removed, are made publicly available. The individual monitoring programs provide an effective tool to assess intakes of ^{137}Cs from all possible exposure pathways in the RMI, not just that associated with leakage of Cactus Crater-derived fallout contamination into the lagoon. A large proportion (greater than 50 percent) of the resident population on Enewetak now participate in the program.

The cohort on Enewetak with the highest potential for uptake of dietary ^{137}Cs appears to be adult males, especially those individuals who visit the northern islands to fish or participate in recreational or resource development activities. The average level of internally deposited ^{137}Cs in the adult male population on Enewetak 1977-2018 has rarely exceeded 1 kBq. This amount of ^{137}Cs for an adult male equates to an annual effective dose of around 5 millirem per year, which is below the RMI government cleanup standard of 15 mrem per year for the public (see Figure 8, Section VIII).

VI. Conclusion

DOE completed two visual studies of the Cactus Crater Containment Structure on Runit Island in 2013 and 2018. These studies assessed the condition of individual concrete panel cap segments that protect the mound of encapsulated contaminated soil and radioactive debris below from erosion. Although the studies revealed that some concrete panels contained visual defects consisting mostly of cracks and spalled concrete panel seams and corners, DOE determined they were not structural in nature or likely to present any additional hazard associated with the spread of radioactive contamination into the environment. Additionally, nondestructive and core sample testing results show that the exterior concrete cap is not significantly compromised and was serving its intended purpose of providing an effective barrier to reduce natural erosion of underlying waste pile materials.

The Runit Island groundwater monitoring program suggests that fallout contamination is leaching into the groundwater aquifer beneath the Cactus Crater Containment Structure due to the pump test results, which have indicated that the groundwater and lagoon water are in communication. The groundwater then may be considered a point source for potential migration of fallout radionuclides away from the site boundary and into the marine environment. Under existing conditions, there is no clear evidence at present that dispersion of Cactus Crater-derived radioactivity is having a measurable impact on the radiation environment in offshore lagoon or surrounding ocean waters due to the contamination present in the lagoon. Elevated levels of $^{239+240}Pu$ contamination observed in the lagoon water column appear to be dominated by plutonium from the lagoon sediments and not from the flow of Cactus Crater-derived contamination into the lagoon.

Based on the visual studies and the data observed from the Runit groundwater monitoring program, DOE has determined that there is no significant change in the health risks to the people of Enewetak from the contaminants within the Cactus Crater Containment Structure.

Further refinement and expansion of the groundwater monitoring program on Runit Island will allow for a more accurate assessment of any site-specific risks posed by the Cactus Crater Containment Structure through development of a conceptual model describing the effects of forcing events such as severe weather conditions and storm surge on water quality and the export of Cactus Crater-derived radioactive contaminants into the lagoon. DOE has initiated collaboration with a team of hydrogeologists and engineers from the USACE to design and install additional groundwater monitoring resources to improve future data and provide a more detailed picture of groundwater flow and characteristics in and around the Cactus Crater Containment Structure as risk assessments are made. In addition, the existing individual monitoring program based on whole-body counting and plutonium urinalysis bioassay will continue to provide valuable information to determine the overall health risk of the people of Enewetak from internal exposure to key fallout radionuclides in the environment from all possible exposure pathways.

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VIII. Figures and Tables

Fig. 1. Reconstituted CD-17 NAS Borehole on the Cactus Crater Containment Structure (after NAS, 1980)

Table 1. Runit Island groundwater sample collection (2013-2018)

Date of Collection	Sample Code	Salinity (‰)	Description	Targeted Analyses
CD-17 NAS Borehole, Cactus Crater Containment Structure				
6/3/2013	13EX-0114	4.8	0.5 µm filtrate	^{137}Cs, Pu isotopes
9/2/2013	13EY-0226	2.0	0.5 µm filtrate	^{137}Cs, Pu isotopes
12/15/2015	15EY-0300	4.2	0.5 µm filtrate	^{137}Cs, Pu isotopes (supplemental analysis of gross alpha, gross beta, tritium, ^{14}C, ^{36}Cl, ^{90}Sr, ^{129}I, ^{236}U and a suite of metal ions and other standard water quality measures)
8/9/2016	16EY-3571	14.1	0.5 µm filtrate	^{137}Cs, Pu isotopes, ^{129}I, selected tritium & ^{236}U
8/13/2016	16EY-3578	11.4	24-h cycle, 1206 h, 0.5 µm filtrate	^{137}Cs, Pu isotopes, ^{129}I, selected tritium & ^{236}U
8/13/2016	16EY-3585	10.8	24-h cycle, 1600 h, 0.5 µm filtrate	^{137}Cs, Pu isotopes, ^{129}I, selected tritium & ^{236}U
8/13/2016	16EY-3592	12.1	24-h cycle, 2005 h, 0.5 µm filtrate	^{137}Cs, Pu isotopes, ^{129}I, selected tritium & ^{236}U
8/13/2016	16EY-3599	15.6	24-h cycle, 2400 h, 0.5 µm filtrate	^{137}Cs, Pu isotopes, ^{129}I, selected tritium & ^{236}U
8/14/2016	16EY-3606	15.6	24-h cycle, 0408 h, 0.5 µm filtrate	^{137}Cs, Pu isotopes, ^{129}I, selected tritium & ^{236}U
8/14/2016	16EY-3613	11.5	24-h cycle, 0800 h, 0.5 µm filtrate	^{137}Cs, Pu isotopes, ^{129}I, selected tritium & ^{236}U
8/14/2016	16EY-3620	14.7	24-h cycle, 1235 h, 0.5 µm filtrate	^{137}Cs, Pu isotopes, ^{129}I, selected tritium & ^{236}U
8/18/2016	16EY-3556	16.5	Low Tide, 0949 h, 0.5 µm filtrate	^{137}Cs, Pu isotopes, ^{129}I, selected tritium & ^{236}U
8/18/2016	16EY-3563	16.7	High Tide, 1604 h, 0.5 µm filtrate	^{137}Cs, Pu isotopes, ^{129}I, selected tritium & ^{236}U
10/3/2018	18EY-0497	0.7	0.5 µm filtrate	^{137}Cs, Pu isotopes, ^{129}I, selected tritium & ^{236}U
CD-16 NAS Borehole, 15-meters from the Base of the Cactus Crater Containment Structure on the Lagoon Side				
8/31/2013	13EY-0221	28.3	0.5 µm filtrate	^{137}Cs, Pu isotopes
8/13/2016	16EY-3630	28	0.5 µm filrate	^{137}Cs, Pu isotopes, ^{129}I, selected tritium & ^{236}U
10/3/2018	18EY-0484	21	0.5 µm filrate	^{137}Cs, Pu isotopes, ^{129}I, selected tritium & ^{236}U
ARU-2 Control Borehole, located approximately 100 meters SSW of the Cactus Crater Containment Structure				
8/31/2013	13EY-0218	30.4	0.5 µm filtrate	^{137}Cs, Pu isotopes
8/13/2016	16EY-3631	28	0.5 µm filtrate	^{137}Cs, Pu isotopes, ^{129}I, selected tritium & ^{236}U
10/3/2018	18EY-0487	24.4	0.5 µm filtrate	^{137}Cs, Pu isotopes, ^{129}I, selected tritium & ^{236}U

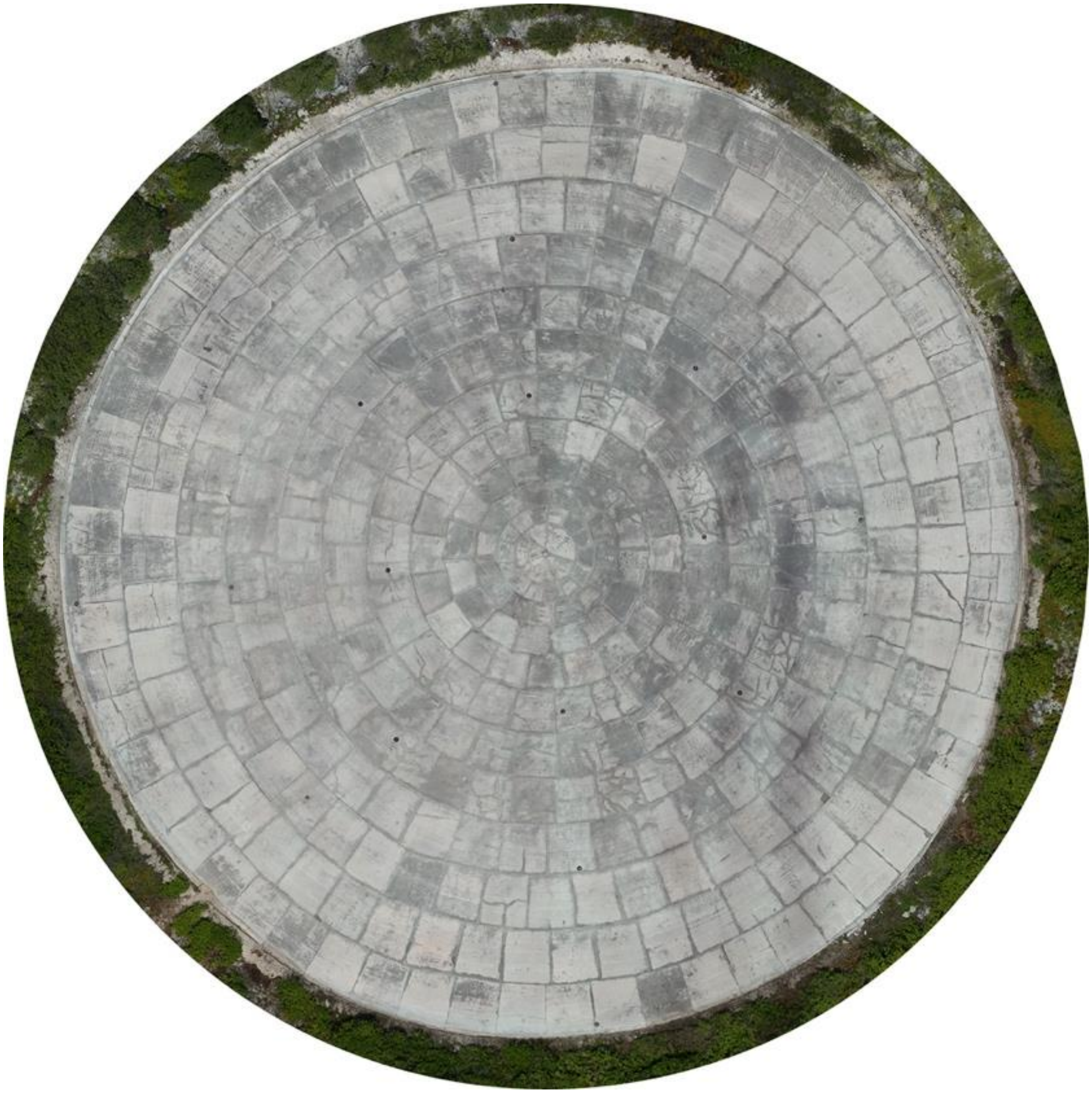

Fig. 2. 3D Model Output from the UAS Survey of the Cactus Crater Containment Structure

Table 2. ^{137}Cs and $^{239+240}$Pu analysis in groundwaters samples surrounding and on the Cactus Crater Containment Structure

Sample Code	Date of Collection	Plutonium Isotopes				Cesium Isotopes		
		Units	$^{239+240}$Pu	^{240}Pu/^{239}Pu atom ratio	Method Code	Units	^{137}Cs	Method Code
CD-17 NAS Groundwater Borehole, Cactus Crater Containment Structure								
13EX-0114	6/3/2013	mBq L^{-1}	3.4 ± 0.1	0.104 ± 0.006	LLNL_AMS	Bq L^{-1}	4.4 ± 0.1	LLNL, Gamma
13EY-0226	9/2/2013	mBq L^{-1}	5.7 ± 0.1	0.095 ± 0.005	LLNL_AMS	Bq L^{-1}	2.24 ± 0.05	LLNL, Gamma
15EY-0300	12/15/2015	mBq L^{-1}	0.77 ± 0.02	0.123 ± 0.006	LLNL_AMS	Bq L^{-1}	2.48 ± 0.05	LLNL, Gamma
16EY-3571	8/9/2016	mBq L^{-1}	1.43 ± 0.02	0.127 ± 0.004	LLNL_AMS	Bq L^{-1}	2.9 ± 0.1	LLNL, Gamma
16EY-3578	8/13/2016	mBq L^{-1}	0.63 ± 0.01	0.126 ± 0.004	LLNL_AMS	Bq L^{-1}	2.8 ± 0.1	LLNL, Gamma
16EY-3585	8/13/2016	mBq L^{-1}	1.21 ± 0.02	0.125 ± 0.004	LLNL_AMS	Bq L^{-1}	2.8 ± 0.1	LLNL, Gamma
16EY-3592	8/13/2016	mBq L^{-1}	0.46 ± 0.01	0.124 ± 0.005	LLNL_AMS	Bq L^{-1}	2.6 ± 0.1	LLNL, Gamma
16EY-3599	8/13/2016	mBq L^{-1}	1.53 ± 0.02	0.131 ± 0.004	LLNL_AMS	Bq L^{-1}	3.2 ± 0.1	LLNL, Gamma
16EY-3606	8/14/2016	mBq L^{-1}	1.47 ± 0.02	0.122 ± 0.003	LLNL_AMS	Bq L^{-1}	2.5 ± 0.1	LLNL, Gamma
16EY-3613	8/14/2016	mBq L^{-1}	1.47 ± 0.02	0.122 ± 0.003	LLNL_AMS	Bq L^{-1}	2.8 ± 0.1	LLNL, Gamma
16EY-3620	8/14/2016	mBq L^{-1}	1.93 ± 0.03	0.124 ± 0.004	LLNL_AMS	Bq L^{-1}	3.2 ± 0.1	LLNL, Gamma
16EY-3556	8/18/2016	mBq L^{-1}	1.84 ± 0.03	0.129 ± 0.004	LLNL_AMS	Bq L^{-1}	2.8 ± 0.1	LLNL, Gamma
16EY-3563	8/18/2016	mBq L^{-1}	2.03 ± 0.03	0.128 ± 0.004	LLNL_AMS	Bq L^{-1}	2.8 ± 0.1	LLNL, Gamma
18EY-0497	10/3/2018	mBq L^{-1}	0.81 ± 0.01	0.094 ± 0.004	LLNL_AMS	Bq L^{-1}	0.9 ± 0.1	LLNL, Gamma
CD-16 NAS Borehole, 15-meters from the Base of the Cactus Crater Containment Structure on the Lagoon Side								
13EY-0221	8/31/2013	mBq L^{-1}	0.91 ± 0.02	0.064 ± 0.004	LLNL_AMS	Bq L^{-1}	0.25 ± 0.01	LLNL, Gamma
16EY-3630	8/13/2016	mBq L^{-1}	0.40 ± 0.01	0.075 ± 0.002	LLNL_AMS	Bq L^{-1}	1.3 ± 0.1	LLNL, Gamma
18EY-0484	10/3/2018	mBq L^{-1}	14.5 ± 0.36	0.070 ± 0.003	LLNL_AMS	Bq L^{-1}	0.19 ± 0.08	LLNL, Gamma
ARU-2 Control Borehole, located approximately 100 meters SSW of the Cactus Crater Containment Structure								
13EY-0218	8/31/2013	mBq L^{-1}	0.31 ± 0.01	0.064 ± 0.007	LLNL_AMS	Bq L^{-1}	0.85 ± 0.02	LLNL, Gamma
16EY-3631	8/13/2016	mBq L^{-1}	0.38 ± 0.01	0.076 ± 0.003	LLNL_AMS	Bq L^{-1}	0.48 ± 0.06	LLNL, Gamma
18EY-0487	10/3/2018	mBq L^{-1}	0.57 ± 0.01	0.071 ± 0.002	LLNL_AMS	Bq L^{-1}	1.4 ± 0.1	LLNL, Gamma

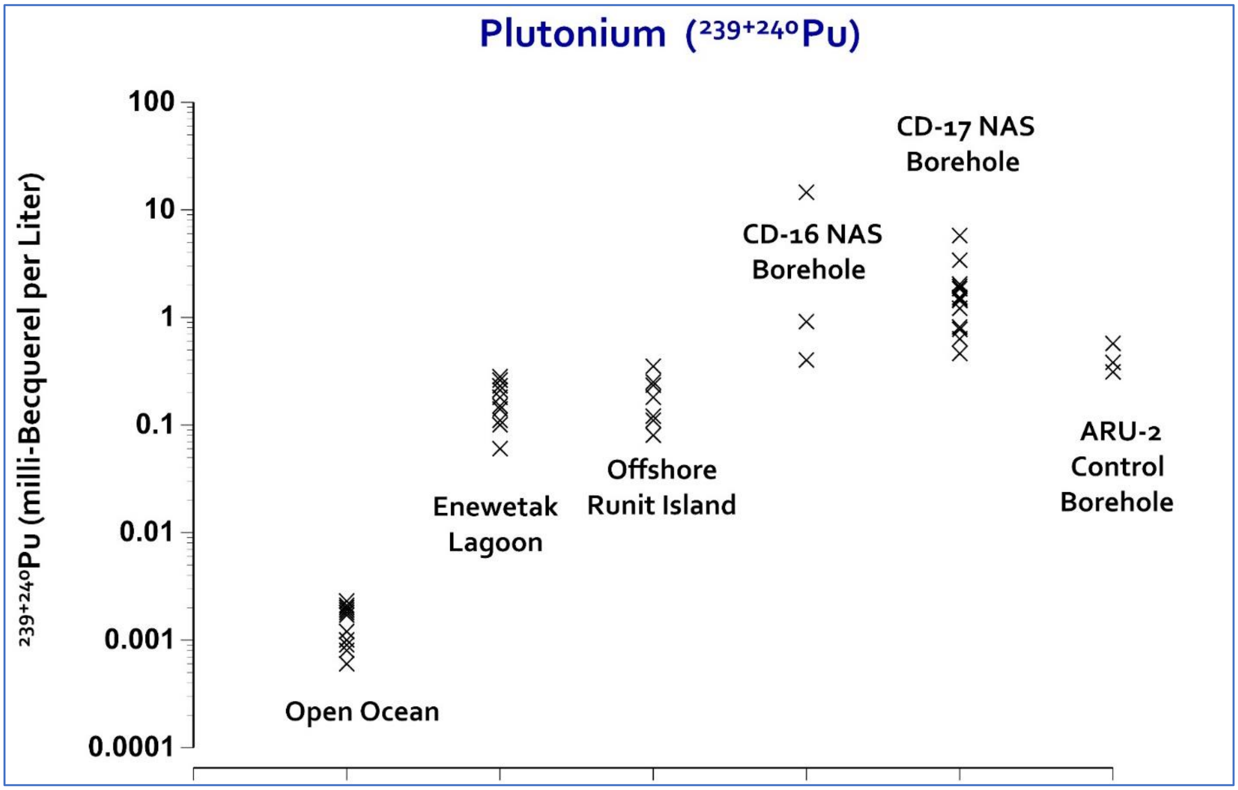

Fig. 3. Range of $^{239+240}Pu$ activity concentrations (mBq L^{-1}) observed in groundwater from Runit Island compared with that observed in seawater samples collected from Enewetak Lagoon and the Open Ocean

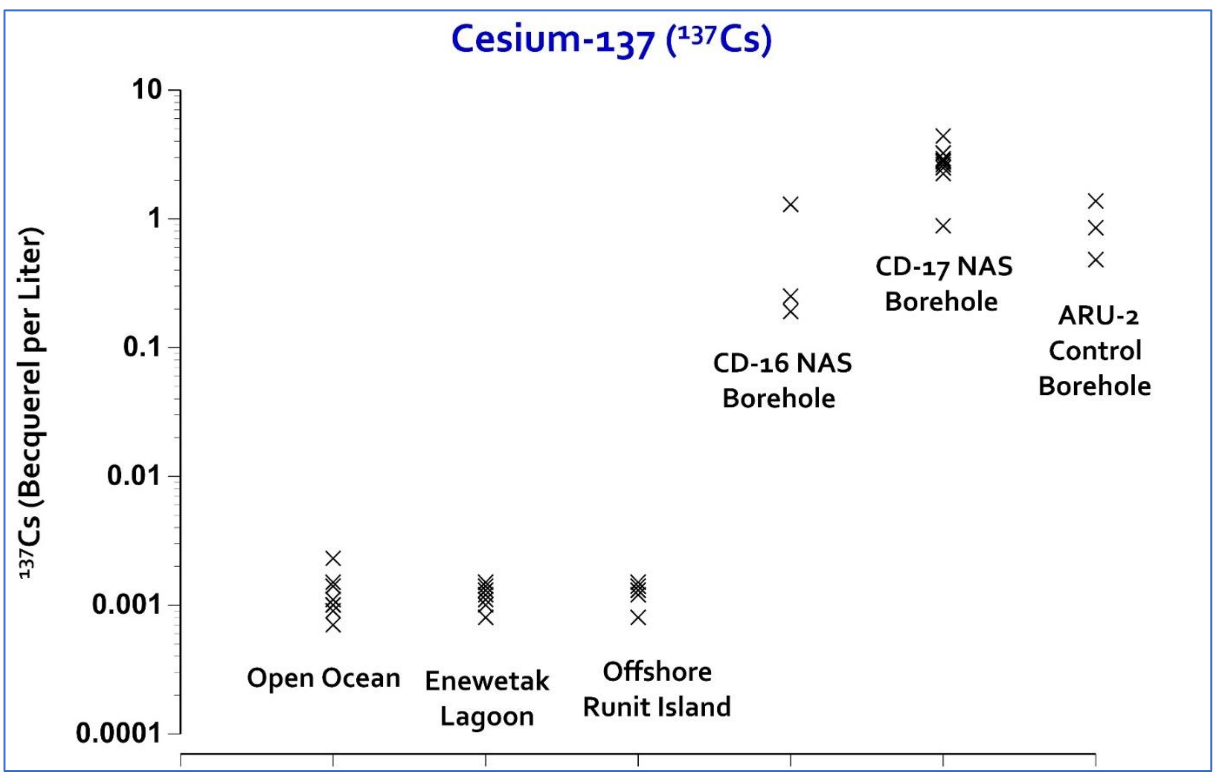

Fig. 4. Range of ^{137}Cs activity (Bq L^{-1}) observed in groundwater from Runit Island compared with that observed in seawater samples collected from Enewetak Lagoon and the Open Ocean

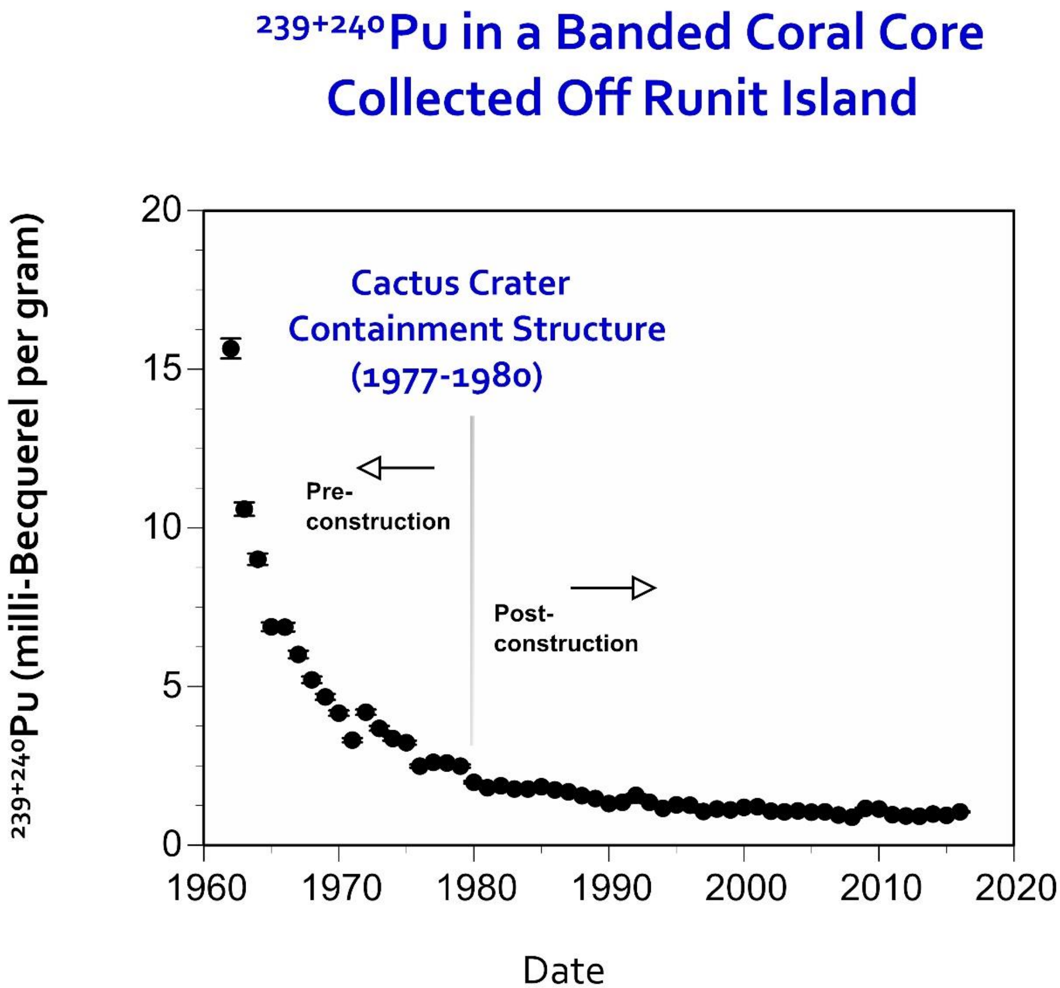

Fig. 5. Analysis of $^{239+240}Pu$ in a dated coral core collected off Runit Island (2016)

Table 3. Analysis of tritium (^3H), carbon-14 (^{14}C), chlorine-36 (^{36}Cl), strontium-90 (^{90}Sr), iodine-129 (^{129}I), cesium-137 (^{137}Cs), plutonium-239+240 ($^{239+240}Pu$), gross alpha and gross beta in CD-17 borehole groundwater from 2015

Water Quality Measure	Units	CD-17 Filtered Groundwater Value	U.S. EPA Maximum Contaminant Levels (MCLs) or other Applicable Standards for Drinking Water	Method Code or Instrumentation
^{36}Cl	mBq L^{-1}	84.2 ± 0.2	25,900	LLNL_AMS
^{14}C	mBq L^{-1}	1.99 ± 0.01	74,000	LLNL_AMS
^{90}Sr	Bq L^{-1}	5.98 ± 0.08	0.30	EPA 905
^{129}I	μBq L^{-1}	62 ± 3	37,000	LLNL_AMS
^{137}Cs	Bq L^{-1}	2.48 ± 0.05	7.4	LLNL_Gamma
$^{239+240}Pu$	mBq L^{-1}	0.77 ± 0.02	555	LLNL_AMS
Tritium	Bq L^{-1}	3.5 ± 0.1	740	LLNL_tritium
Gross Alpha#	Bq L^{-1}	<0.7	0.6	EPA 900.0
Gross Beta	Bq L^{-1}	21.0 ± 1.2	~0.3	EPA 900.0

Reference date = 12/05/15

A gross alpha standard for all alphas (not including radon and uranium)

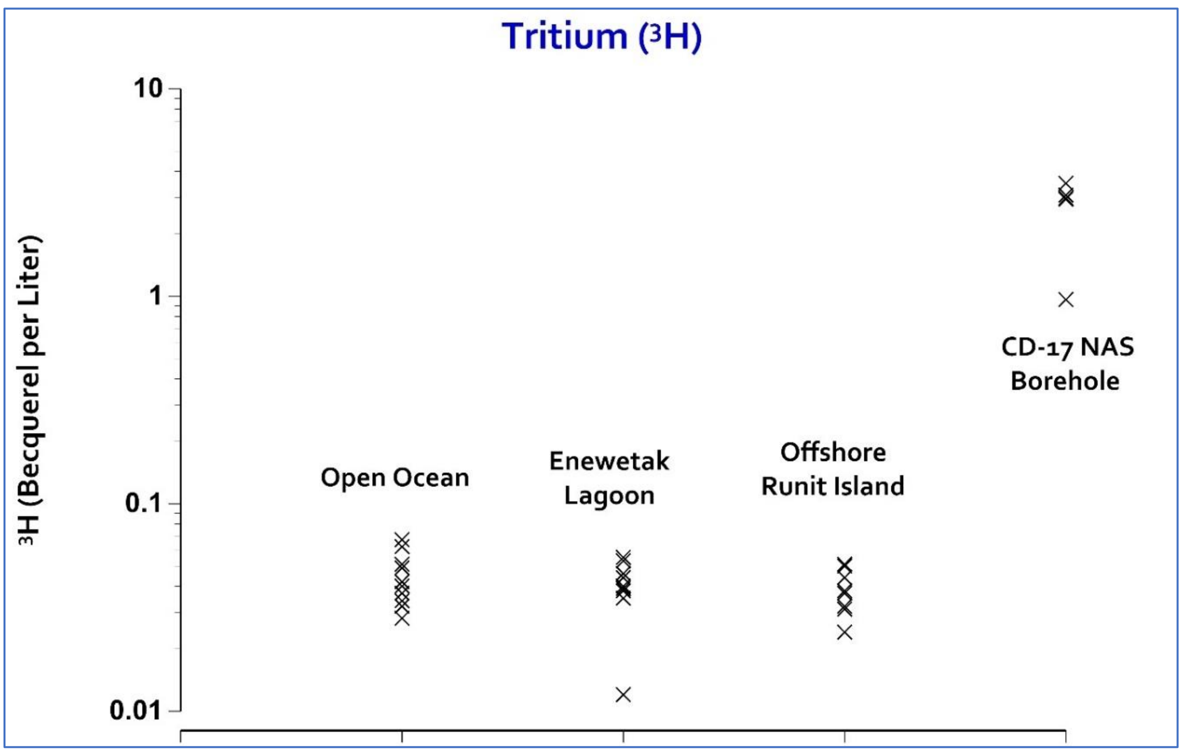

Fig. 6. Range of ^3H activity concentrations (Bq L^{-1}) observed in groundwater from the CD-17 borehole on *Cactus Crater* versus that observed in seawater samples collected from Enewetak Lagoon and the Open Ocean

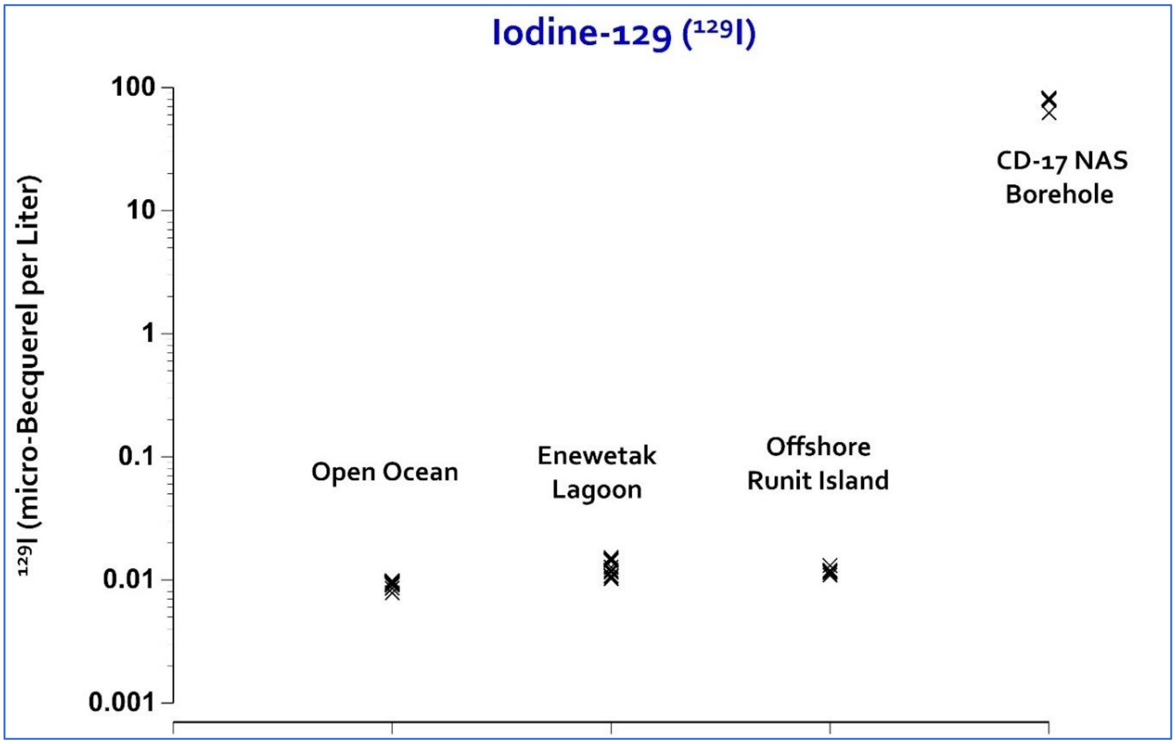

Fig. 7. Range of ^{129}I activity concentrations (μBq L^{-1}) observed in groundwater from the CD-17 borehole on *Cactus Crater* versus that observed in seawater samples collected from Enewetak Lagoon and the Open Ocean

Table 4. Water quality measures in groundwater collected from the CD-17 borehole

Water Quality Parameter	Units	Unfiltered Groundwater		Filtered Groundwater		Drinking Water Maximum Contaminant Levels (MCLs) or other Applicable Standards	Method Code or Instrumentation
		Value	MDC or RL	Value	MDC or RL		
pH	pH units	12.2	0.05	12.2	0.05	6.5-8.5	ThermoFisher Scientific
Total Hardness	mg L^{-1}	370	29	ND	6.6	<61 (considered Soft)	EPA 200.7, as $CaCO_3$
Sodium	µg L^{-1}	160,000	10,000	2300	1000	30,000-60,000	EPA 200.7
Arsenic	µg L^{-1}	1.2	1.0	ND	1.0	10	EPA 200.8
Beryllium	µg L^{-1}	ND	1.0	ND	1.0	4	EPA 200.8
Cadmium	µg L^{-1}	ND	1.0	ND	1.0	5	EPA 200.8
Chronium	µg L^{-1}	ND	10	ND	10	100	EPA 200.8
Copper	µg L^{-1}	ND	5.0	ND	5.0	1000	EPA 200.8
Lead	µg L^{-1}	ND	1.0	ND	1.0	15 (action level)	EPA 200.8
Selenium	µg L^{-1}	7.5	1.0	ND	1.0	50	EPA 200.8
Zinc	µg L^{-1}	_	_	ND	5.0	5000	EPA 200.8
Mercury	µg L^{-1}	_	_	ND	0	2 (inorganic)	EPA 245.1
Chloride	mg L^{-1}	210	10	1.4	10	250	EPA 300.0
Floride	mg L^{-1}	0.27	0.25	ND	0.25	4	EPA 300.0
Nitrate	mg L^{-1}	1.2	0.50	ND	0.50	10	EPA 300.0, as N
Nitrite	mg L^{-1}	ND	0.50	ND	0.50	1	EPA 300.0, as N
ortho-Phosphate	mg L^{-1}	ND	0.75	ND	0.75	_	EPA 300.0, as P
Sulfate	mg L^{-1}	43	7.5	ND	7.5	250	EPA 300.0
Sulfate Reducing Bacteria	CFU mL^{-1}	Absent		Absent		_	SRB-BART™ System, M122 (EMSL Analytical, Inc.)

Definitions:
ND - Indicates that the analyte was not detected at the reporting or detection limit
MDC - Minimum Detectable Concentration (Detection Limit)
RL - Reporting Limit

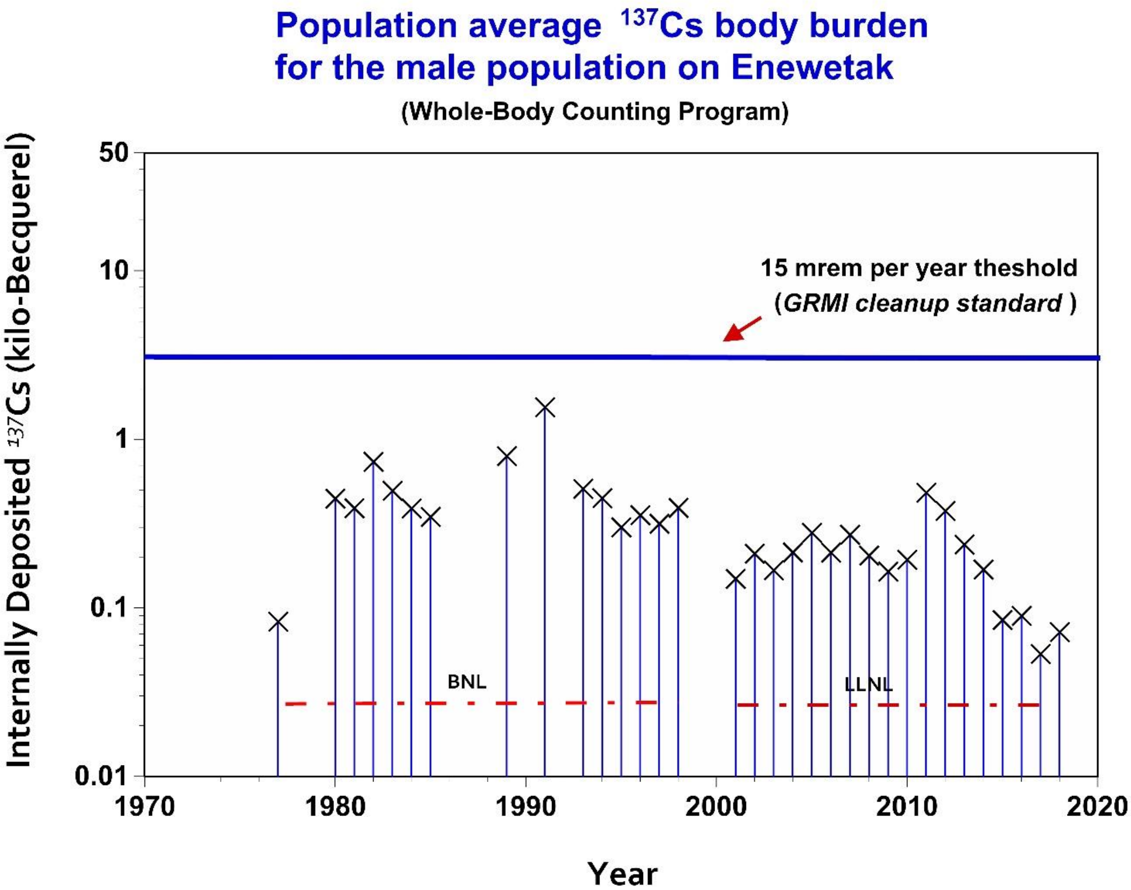

Fig. 8. Average body burden of ^{137}Cs (kBq) in the adult male population on Enewetak Atoll (1977-2018)

**Fig. 9. Cleanup of Cactus Crater Containment Structure
Before and After
(October 2018)**

UAS Photo of the Cactus Crater Containment Structure
(October 2018)