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Legacy of U.S. Nuclear Weapons Testing in the Marshall Islands during 1946-1958[1]

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1. Relevant data

a. Radioactive contamination – overall indicators

The explosive power of the 67 nuclear tests that the United States carried out in the Marshall Islands was about 108.5 megatons – about 100 times greater than all the atmospheric tests done at the Nevada Test Site.[3] The 1 March 1954 "Bravo" 15-megaton thermonuclear bomb test (at Bikini) alone was almost 15 times the explosive power of all Nevada atmospheric tests. The amounts of residual radioactivity resulting from these tests, decay corrected to 2020 are approximately as follows:[4]

- Cesium-137 (half-life, 30.1 years): 90,000 terabecquerels; cesium mimics potassium in the body.

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[1] This paper was reviewed by Bernd Franke (Insitut für Energie- und Umweltforschung (ifeu), Heidelberg, Germany) and Dr. Tilman Ruff (Board member, International Physicians for the Prevention of Nuclear War). Its contents, including its conclusions and any errors that may remain, are entirely the responsibility of the author.

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[3] Frederick Warner, Rene JC Kirchmann (eds). Scientific Committee on Problems of the Environment, International Council of Science (SCOPE 59). *Nuclear test explosions: Environmental and human impacts*. Chichester, UK: John Wiley & Sons, 2000. Chapter 3 in this document, by B. B. Bennet, L. E. De Geer, and A. Loury is at SCOPE 1999, Chapter 3 lists nuclear tests – see Table 3.1, which lists the date and yield of each test. Bikini total: 76.8 megatons; Enewetak total: 31.7 megatons, giving a Marshall Islands total of 108.5 megatons. Nevada atmospheric tests total 1.05 megatons. The U.S. Department of Energy has an official list of nuclear test with more details, such as the name and purpose of each test. U.S. Department of Energy, United States Nuclear Tests: July 1945 through September 1992, DOE/NV-009 Rev. 16, September 2015 at https://nnss.gov/wp-content/uploads/2023/08/DOE_NV-209_Rev16.pdf; hereafter DOE Test List 2015.

[4] Calculated from data in Chapters 2 and 3 of International Physicians for the Prevention of Nuclear War and Institute for Energy and *Environmental Research. Radioactive Heaven and Earth: The Health and Environmental Effects of Nuclear Weapons Testing In, On, and Above the Earth*. New York: Apex Press 1991, at http://ieer.org/wp/wp-content/uploads/1991/06/RadioactiveHeavenEarth1991.pdf. Hereafter IPPNW and IEER 1991.

- Strontium-90 (half-life, 28.8 years): 50,000 terabecquerels; strontium mimics calcium in the body and goes to the bone.
- Plutonium-239 (half-life, 24,110 years): 160 kilograms of unexploded plutonium-239. This is essentially undecayed so far.

In addition, smaller but still significant amounts of even longer-lived radionuclides will continue to exist in the environment essentially forever, circulating repeatedly through ecosystems –technetium-99 (half-life: 211,000 years); cesium-135 (half-life: 2.3 million years); and iodine-129 (half-life: 15.7 million years).[5] While the individual doses from these very long-lived residual radionuclides would likely be very small, the cumulative population doses over the generations could be very large. Much of this radioactivity is still in the Marshall Islands, while the rest is dispersed globally, though unevenly. The larger tests created hotspots far and wide. For instance, the 1954 Castle test series created hotspots as far away as Colombo, Sri Lanka and Mexico City, Mexico.[6] The BRAVO test in that series created the most severe fallout within the Marshall Islands, irradiating Rongelap and Ailinginae at close to lethal levels of fallout.[7]

b. Selection of the Marshall Islands test sites

There was deep disrespect in leading U.S. quarters in the selection of the test sites. The political and diplomatic facts are well documented and are not repeated here.[8] Less well known is that the sites were chosen despite radiological and health cautions that were already understood. The very first nuclear bomb test on 16 July 1945 in New Mexico created intense and widespread fallout. In his assessment of the radiological situation, the Trinity test's chief of radiological safety, Col. Stafford L. Warren (who was also a medical doctor), recommended that a future test of similar yield (21 kilotons) should not be done within 150 miles (240 kilometers) of human habitation. The criterion of distance was violated in the

[5] As a rule of thumb, it is reasonable to assume that quantities of radioactivity have decayed to very low levels after five to ten half-lives.

[6] Robert J. List. *World-wide Fallout from Operation CASTLE*. Washington, D.C.: U.S. Department of Commerce, 17 May 1955 at https://www.osti.gov/servlets/purl/4279860-EGhXto/ - see maps on pdf pages 20 and 21. The cumulative Castle test series fallout values are decay-corrected to 1 July 1954; the tests were conducted between 1 March 1954 and 14 May 1954. Hence the radioactivity in the fallout actually experienced between the times of the tests and 1 July 1954 was considerably greater than the cumulative decay-corrected values shown due to the intense radioactivity of short-lived radioisotopes, like iodine-131 (half-life 8 days): the vast majority of I-131 would have decayed away by 1 July 1954.

[7] Radiation doses estimates are available in various publications. The official external dose estimates, based on measurements in the aftermath of the tests, were published in Alfred J. Breslin and Melvin E. Cassidy, *Radioactive Debris from Operation Castle: Islands of the Mid-Pacific, Health and Safety Laboratory*, 18 January 1955 at https://www.osti.gov/servlets/purl/4274357; hereafter Breslin and Cassidy 1955. Table 1 (pdf p. 44) lists cumulative radiation doses from the Castle test series and also the dose from each test till the date of the next one. The cumulative dose in Rongelap atoll was the highest for any inhabited place (As a place, Rongerik atoll had a higher dose, but it was not inhabited at the time of the Castle series). Of the 2.02 gray external dose estimated for Rongelap, 1.80 gray was due to the BRAVO test.

[8] Some of them are recounted and referenced in Arjun Makhijani, *Summary of the Health and Environmental Impacts of U.S. Nuclear Testing in the Marshall Islands*, prepared for the International Campaign to Abolish Nuclear Weapons, June 2022; corrected January 2024; hereafter Makhijani 2022.

selection of Bikini and also the Nevada Test Site.[9] The yield criterion was also violated. The largest atmospheric test conducted at the Nevada Test Site was 74 kilotons, about three-and-a-half times the Trinity test yield.[10] It was massively violated for Bikini. The largest test there was over 700 times more powerful than the Trinity Test and its fission yield (which mainly determines fallout radioactivity) was over 400 times greater.[11]

An official 1948 assessment, two years after the first tests at Bikini ("Operation Crossroads"), found that the Marshall Islands sites did not "in the main" meet the necessary meteorological criteria for testing nuclear weapons:

> From a meteorological standpoint, there are three basic requirements for a suitable site for atomic bomb experiments. These are:
>
> a. There should be a reasonable frequency of occurrence of cloud or weather conditions to meet the operational requirements for the experiment….
> b. Wind conditions from the surface to stratospheric levels should be such that there can be no possibility of subjecting personnel to radiological hazards or surrounding land or water area to unintentional radioactive contamination….
> c. The mechanism of meteorological processes for the site should be adequately understood and the weather predictions for the site demonstrated to be of a high and reliable accuracy.
>
> The Marshall Islands in the main do not meet these meteorological requirements.[12]

Only five tests, totaling about 0.15 megatons (out of 108.5 megatons), had been conducted at Bikini and Enewetak up to the time this assessment was made. The tests continued regardless.

Conclusion #1: *The Marshall Islands was known in advance to be generally unsuitable for nuclear weapons testing from the meteorological and radiological standpoints by official criteria and actual testing experience. Yet the United States carried out massive nuclear weapons testing there amounting to 70% of the total explosive power of all its nuclear tests worldwide even after the unsuitability was known in practice and officially understood.*

c. Affected area

Thyroid doses provide a good technical basis for making a judgment about impact of fallout since they are primarily from very short-lived isotopes of iodine, notably iodine 131 (half-life: 8 days). Further,

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[9] For details as to the selection of the Nevada Test Site and the Marshall Islands see IPPNW and IEER 1991, op. cit. Chapter 4 is on the Nevada Test Site; Chapter 5 is on the Marshall Islands.

[10] The largest atmospheric test at the Nevada Test Site was named "Hood"; it was carried out on 5 July 1957 and had an yield of 74 kilotons – DOE Test List 2015, pdf page 32, item 93. Test Hood is explicitly named as the "Highest yield NNSS atmospheric test". The name of the test site was changed for from the "Nevada Test Site" to the "Nevada National Security Site" (NNSS) in 2010, DOE Test List 2015, pdf page 12.

[11] Steven L. Simon et al., "Radiation doses and cancer risks in the Marshall Islands associated with exposure to radioactive fallout from Bikini and Enewetak Nuclear Weapons Tests: Summary", *Health Physics*, Vol. 99, No. 2, August 2010; hereafter Simon et al. 2010. Table 1 provides total yields and fusion yields of 20 of the 67 tests conducted in the Marshall Islands. Fission yields can be calculated from the data provided. The paper was based on research done at the National Cancer Institute.

[12] U.S. Air Force Colonel evaluation of the site 21 August 1948 as quoted in IPPNW and IEER 1991

whole body doses can be roughly inferred from thyroid doses. Since thyroid doses have been estimated for both the Marshall Islands and the continuous United States ("the lower 48 states") they also provide a comparative indication of who has been officially regarded as impacted.

The Castle test series of six tests (1 March 1954 to 14 May 1954)[13] had almost 45% of the total explosive yield of all tests in the Marshall Islands. Aerial and ground-based measurements in the Marshall Islands show that the entire Marshall Islands received fallout. [14] The highest cumulative external doses, about 2 gray [15] were estimated for Rongelap and Rongerik. Cumulative external doses in the southern atolls were in the range of a few milligray, going down to about 2 milligray in the southern-most atolls.[16]

A later independent evaluation by Sanford Cohen & Associates (SC&A),[17] presented to the Senate Committee on Energy and Natural Resources in May 2005 argued persuasively that the whole body doses were at least twice the published government estimates. According to the testimony the studies with lower estimates

- "neglected the dose from the passing plume";
- "neglected the whole body dose from fallout that deposited directly on the persons' skin and clothing";
- "did not consider the unique exposure geometry associated with fallout"; and
- "made assumptions regarding the time of arrival of the plume and the duration of fallout that did not give the benefit of the doubt to the people of the Marshall Islands." [18]

According to the testimony by Dr. John Mauro, one of the authors of several independent reports prepared by SC&A for the Marshall Islands Nuclear Claims Tribunal and other official bodies, the higher dose estimates were consistent with medical evidence, such as blood counts, collected by the U.S. government.[19]

Organ doses and whole body doses are approximately related to each other in the context of exposure to fallout. Thus, whole body doses may be roughly estimated from thyroid doses and vice versa. Thyroid doses are highly dependent on age. For infants and children exposed to fallout in the immediate

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[13] Dates are at the location of the test site.

[14] Breslin and Cassidy 1955 op. cit., Table 1 (pdf p. 44) and Figure 27 (pdf p. 48).

[15] U.S. regulations and many studies and reports use rad, millirad, rem, and millirem instead of international system of units (SI system) of gray, milligray, sievert, and millisievert. The values in those reports and regulations have been converted to international units in this paper: 1 rad = 0.01 gray; 1 rem = 0.01 sievert. U.S. reports also use curies for quantities of radioactivity; those values have been converted to the SI system: 1 curie = 37 gigabecquerels.

[16] Alfred J. Breslin and Melvin E. Cassidy, op. cit. 1955, Table I (pdf page 44) and Figure 27 (pdf p. 48).

[17] Disclosure: I was an Associate (a consultant designation) of Sanford Cohen & Associates (SC&A) from 2004 to 2018 as part of a team that provided scientific and technical support to the presidentially-appointed Advisory Board on Radiation and Worker Health that oversees the U.S. government's compensation program for workers who contracted cancer as a result of their radiation exposure due to work relating to nuclear weapons production and testing for the contractors of the Atomic Energy Commission and its successor agencies (including the U.S. Department of Energy). I had no role in any of the studies referenced in Dr. Mauro's testimony or in Dr. Mauro's testimony.

[18] Dr. Mauro's written testimony as published in: *Oversight Hearing before the Committee on Resources and the Committee on International Relations, Committee on Resources Serial No. 109-15 and Committee on International Relations Serial No. 109-21*, U.S. House of Representatives, 25 May 2005, page 88 (pdf p. 94). Hereafter Congressional Hearing Record 2005.

[19] Congressional Hearing Record 2005, op. cit., pages 88 and 89 (pdf pages 94 and 95)

aftermath of a nuclear test, thyroid doses can be inferred to be on the order of 30 to 100 times the average external dose[20] (such as that estimated in the wake of the Castle test series), depending on age and other factors, with the largest factor applying to infants. On this basis, we may infer that infants in the least exposed southern-latitude atolls received average thyroid doses on the order of 100 to 200 milligray due; in the middle and northern latitude atolls, thyroid doses to infants can be inferred to range from of 1 gray to tens of grays.[21] These figures relate to the Castle series alone. Almost 30% of the fission yield of U.S. Marshall Islands tests was due to the other tests during 1946-1958 that were estimated by NCI to deposit fallout on the Marshall Islands.[22]

For comparison, thyroid exposures due to nuclear testing at the Nevada Test Site have also been large in many areas; the county-wide average thyroid doses in the most affected places have been estimated by the NCI to be between 120 and 160 milligray. The national average thyroid dose was about 20 milligray.[23] The NCI report notes that thyroid doses to infants (3 months old) and children (5 years old) from any particular test would be 3 to 7 times average population thyroid doses.[24] On this basis the highest county-wide average doses to infants would be on the order of 1 gray for infants (rounded). Those counties were in Idaho and Montana.

The average thyroid doses in the counties in Nevada, Utah, and Arizona, where U.S. downwinders have been extended compensation under the 1990 Radiation Exposure Compensation Act (RECA), were on the order of 10 to 120 milligray;[25] inferred thyroid doses for infants would be in the 70 to 800 milligray range (rounded). While RECA was not based on thyroid doses,[26] the thyroid doses are on the high side. Infants in southern-latitude atolls of the Marshall Islands (where exposures were the lowest) had comparable thyroid exposures. Thyroid doses were far higher in northern latitude atolls. But the southern-latitude atolls and most northern-latitude atolls have not been provided with medical care or even health screening by the U.S. government.

Finally, the above dose estimates are averages. The National Cancer Institute has stated that "[a]ny specific person could have received a dose many times lower or higher than the estimated [average] doses."[27] This would be true of both Marshallese and U.S. exposed populations.

Conclusion #2: *There is clear evidence that (i) the southern atolls of the Marshall Islands were impacted by fallout sufficiently for infants and children to have thyroid doses comparable to their counterparts in counties in the United States who are eligible for compensation under the 1990 Radiation Exposure Compensation Act and (ii) exposures in the rest of the Marshall Islands were far higher. Yet the vast majority of atolls have not received medical care or health monitoring as impacted persons.*

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[20] See Table 5.6 in Bernd Franke, *Review of Radiation Exposures of Utrik Atoll Residents*. Heidelberg, Germany: ifeu-Institut für Energie- und Umweltforschung, GmbH, prepared for Sanford Cohen & Associates, 2002. Both government and independent estimates of external and thyroid doses in Utrik are cited in this table.

[21] Derived from Table 1 (pdf page 44) in Breslin and Cassidy 1955, op. cit.

[22] Calculated from Table 1 of Steven L. Simon et al. 2010, op. cit.

[23] National Cancer Institute. *Estimated Exposures and Thyroid Doses Received by the American People from Iodine-131 in Fallout Following Nevada Atmospheric Nuclear Bomb Tests*. Washington, D.C.: U.S. Department of Health and Human Services, 1997, at https://www.cancer.gov/about-cancer/causes-prevention/risk/radiation/i131-report-and-appendix Table ES-1 and pdf p. 54 (p. TS.10). Hereafter NCI 1997

[24] NCI 1997 pages ES-2 and ES-4.

[25] Read off from Figure ES.1 on page ES.3 in NCI 1997

[26] The NCI study was published seven years after the passage of the Act.

[27] NCI 2004 page 10 (pdf page 11). Underlining in the original.

2. Health impacts

Cancer is generally recognized as a major adverse health outcome of radiation exposure; the generally accepted hypothesis in science and regulation for solid cancers is that the number of cancers is proportional to population dose and that there is no threshold of exposure below which the risk is zero. This is called the "linear no-threshold" hypothesis. There are also a number of other impacts, many of which have been ignored or downplayed in regulation not only in the Marshall Islands but generally.

The following impacts are briefly discussed below:

- Cancer incidence;
- Thyroid-related non-cancer impacts and impacts during pregnancy notably the first trimester;

a. Cancers

The National Cancer Institute made estimates of cancer incidence in the Marshall Islands due to fallout in its 2004 report, which was prepared for the Senate Committee on Energy and Natural Resources. About 44% of the approximately 500 excess cancers were estimated to occur in Rongelap, Ailinginae, and Utrik; another 43% were estimated to occur in the "other northern atolls" (Ailuk, Mejit, Likiep, Wotho, Wotje, and Ujelang) with the rest, about 13%, in the southern atolls;[28] this points to carcinogenic risk throughout the Marshall Islands. The NCI estimated that, overall, cancer incidence would increase by 9% in the 1950s Marshallese population of about 14,000. This rate would be equivalent to six million excess cancers in the U.S. population of the mid-1950s.

In 2010, the National Cancer Institute published in a revised set of dose estimates, stating that the 2004 values were overestimates in several ways. The estimated number of excess cancers was lowered to 170.[29] Even that lower number would be the equivalent of 2 million excess cancers in the mid-1950s U.S. population.

Neither estimate takes systematic account of the independent studies and the testimony mentioned above that provided evidence of systematic underestimates of radiation doses in the NCI 2004 study. The independent dose estimates, cited above, would result in cancer estimates greater than 500 cases.

b. Non-cancer impacts

A number of non-cancer impacts are to be expected, especially in the northern atolls, including but not limited to Rongelap, Utrik, and Ailinginae, which were most impacted by BRAVO fallout. High thyroid doses can destroy part of the thyroid and cause hypothyroidism which can lead to severe health problems especially in children. The potential impacts include physical and mental growth deficiencies and Hashimoto's disease, which is an auto-immune disorder.[30]

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[28] NCI 2004, Table 3. Percentages calculated from the numerical estimates in this table. The estimate in the table is 532 cancers but about 500 in the text.

[29] Simon et al. 2010, op. cit.

[30] Mayo Clinic, "Hypothyroidism (underactive thyroid)", at https://www.mayoclinic.org/diseases-conditions/hypothyroidism/symptoms-causes/syc-20350284

Serious impacts on pregnant women are also to be expected, including early failed pregnancies, organ malformations, and what the International Commission on Radiological Protection (ICRP) has called "severe mental retardation" and defined as "an individual unable to form simple sentences, to solve simple problems in arithmetic, to care for himself or herself, or is (was) unmanageable or institutionalized ."[31] The ICRP based this conclusion on epidemiological data of children who were *in utero* at the times of the atomic bombings of Hiroshima and Nagasaki and survived. The analysis found that there was no radiation dose threshold for such an effect; in other words, a low dose would produce a low risk and a higher dose would produce a proportionately higher risk. The risk coefficient was estimated at 0.4 occurrences per gray; this means that a cumulative population dose of roughly 2.5 gray experienced in a short time would be expected to produce one such case with high probability in that population.[32]

There is evidence that other teratogenic impacts, like early failed pregnancies, neural tube defects, and organ malformations, occur above 0.1 gray of external radiation during the early part of pregnancy. These thresholds are postulated based on external radiation. In reviewing the ICRP analysis the U.S. National Academies 1988 report on alpha radiation concluded that the threshold would be 0.01 Sv for internal radiation due to radionuclides that deposit their energy in a small volume ("high linear energy transfer" radiation).[33] Further discussion of thresholds for different endpoints, such as non-clonal aberrations in clonal progeny, can be found in my 2022 memorandum to a National Academies committee on low-level radiation research.[34]

There are also multi-generational impacts. The large number of radionuclides, from tritium to plutonium that cross the placenta, indicates such impacts. Further, ova develop when females are in their mothers' wombs. As a result, exposure of the mother can have multi-generational impacts. These issues have been studied far less than the nature of the risks and their importance would indicate.[35] That is an observation that is general and not confined to people exposed to nuclear weapons testing fallout, though it includes them.

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[31] International Commission on Radiological Protection, *Development Effects of Irradiation on the Brain of the Embryo and Fetus*, Publication No. 49, 1986 p. 20 at http://journals.sagepub.com/doi/pdf/10.1177/ANIB_16_4 ; hereafter ICRP 49.

[32] I discussed these issues in more detail in a memorandum to a National Academies committee in 2022. Arjun Makhijani, "Memorandum to the National Academies committee on the current status and development of a long-term strategy for low-dose radiation research in the United States", Institute for Energy and Environmental Research, January 2022 at https://ieer.org/wp/wp-content/uploads/2022/01/Arjun-Makhijani-memorandum-to-National-Academies-committee-on-low-level-radiation-2022-01-10.pdf ; hereafter Makhijani 2022a. It should be noted that very short-term exposures during the bombings of Hiroshima and Nagasaki have been central to estimation of the cancer risk of radiation – including the conclusion of no-threshold for the risk. But a downward adjustment of the numerical value is generally made in official risk estimates when the same total dose is experienced at low dose rates over long periods. Most of the dose experienced by the most highly exposed Marshallese was in a short period – though longer than the very short principal exposure period during the bombings of Hiroshima and Nagasaki. Hence the qualification "roughly" has been added to provide context for the Marshallese exposures.

[33] Committee on the Health Risks of Ionizing Radiations, Board on Radiation Effects Research. *Health Risks from Exposure to Radon and Other Alpha Emitters*. National Research Council of the National Academies. Washington, DC: National Academies Press, 1988, p. 392. See also discussion in Makhijani 2022a.

[34] Makhijani 2022a.

[35] See Makhijani 2022a for further discussion and evidence that the formal evaluation of these issues has been deferred for decades at least in the United States, despite formal public requests that they be addressed.

Conclusion #3: *Given the level of thyroid radiation doses to infants and children, a risk of developmental and immunological impacts on exposed infants and children existed throughout the Marshall Islands, especially in the mid-latitude and northern latitude atolls. These adverse health outcomes deserve far more attention and study and, when they occur, health care.*

Conclusion #4: *The level of radiation exposure in the mid-latitude and northern-latitude atolls, presents high likelihood that cases of severe brain damage due to exposure during pregnancy in the form of what the International Commission on Radiological Protection (ICRP) has called "severe mental retardation". This conclusion is based on an epidemiological analysis published by the ICRP. To date, no general regulation to protect the embryo and fetus exists even though the ICRP concluded as far back as 1986 that such severe brain damage occurs with no dose threshold to the excess risk.*[36]

Conclusion #5: *The level of radiation exposure in the mid-latitude and northern-latitude atolls, presents significant risks of other teratogenic impacts, such as early failed pregnancies and organ malformations, that have not yet been adequately examined or acknowledged.*

Conclusion #6: *Multi-generational impacts of exposure to internal radiation have been studied far less than their risk and importance indicates. That is a general observation about states and industries that cause anthropogenic radiation exposures, including those due to atmospheric nuclear weapons testing.*

3. Remediation[37]

There is residual radioactivity in varying amounts throughout the Marshall Islands, the more so in Bikini and Enewetak atolls where the tests were carried out and the northern atolls, and Rongelap, Ailinginae, and Utrik, that received the heaviest fallout. Contamination of locally produced food with cesium-137 (half-life 30.1 years) is one of the principal enduring impacts. Food impacts other exposure pathways; pregnant women are affected. Children, especially female children, have a far greater risk of cancer than adults for the same exposure.[38] The risks of cancer and of the teratogenic damage that is estimated to occur with no threshold will continue; such risks can be significantly mitigated by well-designed remediation programs.

Remediation must include sound ocean and lagoon ecosystem assessments and must include impact on diets and on the economic prospects. Existing diet studies can be complemented by new ones. Both land and lagoons are still contaminated. Nuclear explosions have destroyed coral reefs. The extensive damage to and disturbance of ecosystems requires detailed assessments – far more than have been done to date. Existing studies can provide a basis for

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[36] Radiation doses to women who declare their pregnancies in radiation regulated work places, such as nuclear power plants, or uranium processing plants are limited to 5 milligray in the United States and to 1 milligray in many other countries.

[37] Remediation and associated resettlement issues (among others) are discussed in Arjun Makhijani, Daryl Kimball, and Lilly Adams, *Issues Relating to Nuclear Testing Impacts on the Marshall Islands: Health Risks, Environmental Monitoring, Remediation, Ocean Ecosystem Assessment, Resettlement and Capacity Building*, Arms Control Association, Institute for Energy and Environmental Research, and Union of Concerned Scientists, 1 November 2022, with two cover letters.

[38] Committee to Assess Health Risks from Exposure to Low Levels of Ionizing Radiation, Board on Radiation Effects Research. *Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII – Phase 2*. National Research Council of the National Academies. Washington, DC: National Academies Press, 2006

some action in the short-term and also point to future research requirements, including whether more radionuclides need study and the areas the studies should cover. Evidently, the Marshallese people should be integrally involved. These studies should realistically assess bioconcentration of radionuclides such as strontium-90 and iodine-129 across food webs, oceanic ecosystems, and terrestrial agricultural systems.

Sufficient understanding for some actions already exists. For instance, cesium-137 uptake by plants is significantly reduced by application of potassium fertilizer when soils are potassium-deficient. In such cases, fertilization can be a complement to measures to reduce the residual radioactivity by bioremediation and/or removal of soil.

Bioremediation and removal of contaminated soil can reduce local contamination; but they will also result in radioactive waste. What should be done with these radioactive materials is a critical scientific, policy, and political question. The Runit dome (discussed below) presents an important (negative) object lesson.

Contamination is often spread over large areas at low concentrations, interspersed with areas of higher concentrations as well as hot spots. Removal of all the radioactivity is usually not possible; even if it were it would usually be counterproductive since such "cleanup" would leave a barren landscape. As a result, even well-designed remediation is likely to leave some residual radioactivity, with the concomitant risk.

It is worth considering the Runit Dome built by the United States on Runit island in Enewetak Atoll as a remediation measure. It was part of an effort by the U.S. government in the 1970s to promote the resettlement of Enewetak Atoll, which had been evacuated in 1947 to enable nuclear weapons testing. The remediation was geared to limiting exposure to plutonium and other transuranic radionuclides, deposited unevenly across the atoll on various islands, including Runit. The cleanup levels were set according to the envisaged use. The strictest level, 1.5 becquerels per gram (Bq/gram), was set for islands were people would live and higher limits up to 15 Bq/gram were set for other islands, depending on anticipated activities. Soil above 15 Bq/gram was to be removed. That soil was mixed with cement and placed "inside an unlined nuclear test crater, the Cactus Crater, on the north end of Runit Island." A concrete dome was built to cap the waste pile.[39]

None of the cleanup efforts were directed at the lagoon of Enewetak Atoll, an important resource for traditional food and economic activities. In round numbers, waste in the dome is estimated to contain about a quarter of a kilogram of plutonium compared to almost 30 kilograms that remain in the lagoon.[40] The Atomic Energy Commission, in advocating for the (rejected) option of dumping the contaminated soil into the ocean contrasted the "few hundred

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[39] Defense Nuclear Agency, *Fact Sheet: Enewetak Operation*, April 1980 at https://www.dtra.mil/Portals/125/Documents/NTPR/newDocs/ENEWETAK/1980-DNA%20Fact%20Sheet_Enewetak%20Operation.pdf

[40] Calculated from radioactivity data in U.S. Department of Energy, *Report on the Status of the Runit Dome in the Marshall Islands: Report to Congress*, June 2020, p. 6 at https://www.energy.gov/sites/prod/files/2020/06/f76/DOE-Runit-Dome-Report-to-Congress.pdf; hereafter DOE 2020.

grams" to be disposed of the Cactus crater with "at least a hundred kilograms of plutonium [that] had already been dumped in the ocean from 1947 to 1974."[41]

Two test craters were considered for disposal. The first was the Lacrosse test crater, which was larger and was considered to have a more suitable geology but was off the island and hence less accessible. The second was the Cactus crater which was easier of access but had a more complex geology that "aroused some doubt" as to the robustness and longevity of the containment. In the event, the Cactus crater was chosen; it was cheaper.[42]

The concrete dome has cracks; the Department of Energy contends that it is still "an effective and erosion resistant seal for the encapsulated radioactive material within the containment structure". [43] The lifetime of the dome's concrete must be contrasted with the half-life of plutonium, which is more than 24,000 years. The fact that the bottom of the crater is not lined also needs to be factored into the hydrological and ecological dynamics. The structure rises and falls with the tides and contains groundwater. The Department of Energy estimates that

> The key pathway for exposure to radioactive materials contained in the Cactus Crater containment structure is from leakage of contaminated groundwater entering the local marine environment, and the subsequent uptake of dome derived fallout contamination into the marine food chain.[44]

In sum, despite the effort and expense, the Runit dome is leaking and Runit island itself remains uninhabitable. All this is aggravated by climate change, which is already a huge presence in the Marshall Islands. Typhoons as a complicating factor were, of course, well understood; in fact three typhoons occurred during the cleanup operations, leading to additional costs.[45]

The above considerations point to the critical need for an overall, science-based remediation plan developed with the full participation of the Marshallese people. Putting radioactive waste in unlined bomb craters in a marine environment, as was done with the Runit dome, is decidedly inadvisable, the more so given climate change. The issue of the location of the disposal of wastes is as important as ensuring that remediation results in measurable and durable ecological improvement.

It would be reasonable for the United States to take responsibility for the radioactive and any other toxic waste created by its military activities in the Marshall Islands by (i) paying for remediation activities that are mutually agreed upon and (ii) removing those wastes from the Marshall Islands to much more secure storage and disposal.

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[41] As cited in Defense Nuclear Agency, The Radiological Cleanup of Enewetak Atoll, December 1981, pdf page 115; at https://www.dtra.mil/Portals/125/Documents/NTPR/newDocs/ENEWETAK/1981-DNA_The%20Radiological%20Cleanup%20of%20Enewetak%20Atoll-web.pdf ; hereafter Defense Nuclear Agency 1981

[42] Defense Nuclear Agency 1981, op. cit., pdf page 428.

[43] DOE 2020, op. cit., p. iii.

[44] DOE 2020, op. cit., pdf page 11.

[45] Defense Nuclear Agency 1981, op. cit. pdf page 518.

The example of the 1966 accident that involved the loss of four thermonuclear weapons over Spain is one of the most relevant for future remediation.[46] Two of the four bombs were recovered and were in good condition. But the conventional explosives in the other two ignited; as a result plutonium was dispersed plutonium over a considerable area near Palomares, a village on the Spanish Mediterranean Coast; contaminated land included "farms and cropland".[47] There were extensive surveys; continuous air monitoring was established. A remediation plan was agreed upon with the Spanish government. The cleanup involved scraping up soil contaminated with plutonium above a certain concentration level; it was then packaged for shipment to the United States. Lower levels of contamination were dealt with locally; for instance, contaminated fruits and vegetables were buried in Spain. The repatriated waste was shipped to the Atomic Energy Commission's Savannah River Site in South Carolina where there was already a large amount of radioactive waste. (Plutonium and tritium for use in nuclear weapons were produced in reactors at the Savannah River Site during the Cold War.)

Another pertinent example, not only for remediation, but also of close cooperation between scientists of the United States and the affected country, is provided by January 1968 crash near Thule in Greenland, an autonomous territory that is part of Denmark. It was also of a B-52 bomber carrying four thermonuclear weapons.[48] It crashed onto the sea ice off Thule; in this case the plutonium from all four bombs was dispersed on ice and snow in the middle of the Greenland winter.

The U.S. commander of the recovery operation "preferred to store the contaminated snow and ice in surplus 25,000 gallon tanks and then bury them in the permafrost."[49] In contrast, Danish scientists wanted heavily contaminated snow and ice to be gathered up and removed from Greenland. Moreover, the Danes also wanted consideration of ecosystem protection rather than just allowing the snow and ice to melt and wash the plutonium into the sea (one of the options considered). U.S. and Danish scientists collaborated in the assessment. They agreed that over 50% of the contamination on the snow and ice would be removed; they estimated the likely amount at about 80%. The rest would be left behind; for that portion an ecological surveillance and monitoring program would be put in place. The recovered snow and ice was stored in the 95 cubic meter tanks, then transferred to smaller containers and shipped to the Savannah River Site. There it was "buried beside the barrels of contaminated soil collected at Palomares, Spain."[50] Debris was sent to the Atomic Energy Commission's sites at Hanford (in Washington State) and the Pantex plant (near Amarillo, Texas).[51] Despite the large effort at remediation, considerable amount of plutonium remains in the marine environment.[52]

The contrast of the Spanish and Danish examples with the Runit dome is further sharpened by the fact that the option of repatriating the waste that was put into the Cactus crater on Runit was considered

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[46] This paragraph is based on Defense Nuclear Agency Field Command, *Palomares Accident Summary Report*, 15 January 1975 at https://www.osti.gov/opennet/servlets/purl/16478624.pdf ; hereafter Palomares Report 1975.
[47] Palomares Report 1975, pdf page 50.
[48] History and Research Division, *Project Crested Ice: The Thule Nuclear Accident, Volume I*, Strategic Air Command Headquarters, 23 April 1969 at http://www.gwu.edu/~nsarchiv/nukevault/ebb267/03.pdf ; hereafter SAC 1969
[49] SAC 1969, pdf page 39.
[50] SAC 1969, pdf pages 16 to 40 and pdf page 49.
[51] John C. Taschner, *Nuclear Weapon Accident near Thule Air Base, Greenland: 21 January 1968*, 2005 at https://www.osti.gov/opennet/servlets/purl/1735362.pdf with diagrams and photographs at https://www.osti.gov/opennet/servlets/purl/1428068.pdf
[52] A 2002 doctoral dissertation estimated the marine inventory to be 3.8 kilograms of plutonium-239/240. Mats Eriksson, *On Weapons Plutonium in the Arctic Environment (Thule, Greenland)*, Lund University, April 2002, p. 31.

during the extensive analysis and preparations for preparing some part of Enewetak Atoll for resettlement. This option was supported by the people of Enewetak and the Nevada Operations Office of the Atomic Energy Commission. It was rejected because it "was uneconomical, would generate considerable political resistance, and would adversely affect the entire project." The added expense of disposal on the continental United States compared to disposal on Runit was estimated at about $9 million.[53]

Finally, the matter of remediation standards is also critical. Several U.S. radiation protection standards should be mentioned. The overall limit for public exposure to anthropogenic radiation is 1 mSv/ year from all anthropogenic sources (specified at 10 CFR 20); only medical and sewer-related exposures are exempted. The 1 mSv/year limit has been applied to the Marshall Islands. The Superfund remediation guideline for developing remediation plans for highly contaminated sites (chemical and/or radioactive) a *lifetime cancer risk* between 1 in 10,000 and 1 in 1,000,000 a standard specific to cleanup (specified at 40 CFR 430(e)(2)(i)(A)(2)). The U.S. Environmental Protection Agency (EPA) interprets the upper end of this risk range (rather loosely) as implying a dose of 0.15 millisievert/year. Doses from civilian nuclear facilities have their own regulated limits: the whole body dose limit is 0.25 millisievert/year; the same limit applies to all organs, except the thyroid, for which there is a higher limit of 0.75 millisievert/year (see 40 CFR 190.10(a)).

For a given intake, organ doses from radionuclides like strontium-90 and plutonium-239 that target specific parts of the body are much higher than whole body doses. As a result a standard that specifies the same numerical dose limit for organ doses as for the whole body is in effect much more stringent than only a whole body standard in many situations, including those involving exposure to residual radioactivity from fallout. The drinking water standard (at 40 CFR 141.66) specifies a limit of 0.04 mSv/year from anthropogenic beta and gamma emitting radionuclides. Finally, the United States also has a disposal standard for "low-level" radioactive wastes that are disposed of in near-surface facilities. Those dose limits are specified at 10 CFR 61.41; they are 0.25 mSv/year to the whole body or the most exposed organ, except 0.75 mSv/year to the thyroid.

In their 2020 letter to Senators Fischer and Heinrich, two Marshallese ministers asked for a tighter 0.15 millisievert/year guidance that the EPA has derived from Superfund cancer risk limits to be applied to Marshall Islands remediation efforts.[54] The Department of Energy rejected this demand in January 2021.[55]

Finally, post-cleanup capacity to monitor food and the general environment by the Marshallese themselves in close to real time is essential to the health security of people living in areas with residual contamination. This is necessary both to ensure that doses are kept within the regulatory limits and that they will be kept as low as is reasonably possibly below those limits. This capacity will also serve as a safeguard against consequences of incomplete cleanup or unexpected findings of areas of contamination that were not previously identified.

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[53] Defense Nuclear Agency 1981, op. cit., pdf pages 112 to 114. He quoted phrase is on pdf p. 114.

[54] Letter from Casten H. Nemra (Minister of Foreign Affairs) and Kessai H. Note (Minister of Justice, Immigration, & Labor) to Senator Deb Fischer and Senator Martin Heinrich, 24 September 2020.

[55] Department of Energy letter to Foreign Minister Casten N. Nemra and Justice Minister Kessai H. Note, 21 January 2021.

Conclusion #7: *Remediation is very challenging when dispersed long-lived radionuclides are involved. Remediation standards in the United States are stricter than those that have been applied to the Marshall Islands. A stricter standards has been demanded by the Marshall Islands.*

Conclusion #8*: Some cleanup by removing debris and the contaminated layers of soil can reduce risk significantly if the waste is well managed to strict standards; this is a difficult task. Other risk reduction methods are also needed, including for lagoons and agricultural areas.*

Conclusion # 9*: The 1966 accidental dispersal of plutonium from a U.S. thermonuclear weapon in Spain provides a positive example of the U.S. taking responsibility for the contamination it created; it cleaned up and then repatriated much of it. The repatriation of waste from the 1968 weapons accident in Greenland provides a similar example. That incident also shows the value of the adversely affected country having its own scientists to participate in the assessment. On the other hand the Runit dome represents a negative example where remediation related wastes were dumped in a vulnerable way in the Marshall Islands, contrary to the wishes of the people of Enewetak.*

Conclusion #10*: Secure cleanup requires the buildup of Marshallese local capacity for monitoring the environment and food and water to ensure cleanup dose limits are adhered to and risks are kept as low as possible below the maximum exposure thresholds in the standards.*

4. Appendix

Two matters, one an unresolved issue about material from the Nevada Test Site taken to Enewetak and the other about hazardous materials, are important and are addressed in this appendix.

a. Nevada Test Site Material

There is an apparently unresolved matter of material from Nevada that was taken to Enewetak. The National Nuclear Commission of the Marshall Islands in its review of the DOE 2020 report to Congress stated that "…environmental monitoring by the weapons laboratory contractor fails to account for radionuclides and hazardous materials from sources other than weapons detonations brought into the Marshall Islands, including radioactive soil brought in from Nevada to conceal a misfired weapon in the Fig-Quince area of Enewetak…"[56]

A 2018 Los Angeles Times investigative report stated that 130 tons of radioactive material had been taken from the Nevada Test Site to the Marshall Islands in 1958. According to the report, the soil was to be used "as part of an experiment, to help scientists understand how soil types contribute to different blast impacts and crater sizes." A scientist from Lawence Livermore National Laboratory intimately involved in Marshall Islands testing evaluations stated that the material taken was not radioactive but clean.[57] Nuclear tests named Quince and Fig were in fact

[56] Attachment to a letter from Casten H. Nemra (Minister of Foreign Affairs) and Kessai H. Note (Minister of Justice, Immigration, & Labor) to Senator Deb Fischer and Senator Martin Heinrich, 24 September 2020.
[57] Suzanne Rust, "How the U.S Betrayed the Marshall Islands, kindling the next nuclear disaster", *Los Angeles Times*, 10 November 2018 at https://www.latimes.com/projects/marshall-islands-nuclear-testing-sea-level-rise/

conducted on Runit as part of Operation Hardtack I in 1958. The Quince test did not explode as planned.[58] It created plutonium contamination and hot spots. The area had to be cleaned up before the second test, planned at the same ground zero, could be carried out. Much of the contaminated soil and debris was removed and piled up on the lagoon side of Runit. The Fig test was then carried out.[59] The comprehensive 1981 Defense Nuclear Agency account of the cleanup notes that it did some cleanup Runit test locations, including the site of the Quince and Fig tests.[60] Thus, some of the radioactive contamination from these tests was put into the Runit dome. It therefore appears likely that some of the Nevada soil was put into the Runit dome in a contaminated state, whether or not it was initially radioactively contaminated.

To my knowledge, the matter remains officially unresolved; the Department of Energy's response to the letter by Marshallese government ministers Casten N. Nemra and Kessai H. Note did not mention the issue of Nevada soil. [61]

b. Hazardous materials

Though a non-nuclear matter, it is important to note the issue of hazardous materials, especially since was raised in the National Nuclear Commission's review of the 2020 Department of Energy report to Congress. The Department of Energy letter in response stated that "not aware of this non-radiological issue" relating to chemical or biological weapons and that it "did not find any further information in DOE records regarding this issue".[62]

However, there is publicly available declassified material that the Department of Defense conducted a test at sea off Enewetak Atoll as part of a series of chemical and biological weapon tests at sea called Project SHAD, which stands for "Project Shipboard Hazard and Defense". The tests were conducted over a period of several years, starting in 1963.

The specific test off Enewetak, numbered 68-50 and named "Speckled Start", was with a biological warfare agent.[63] The test was carried out in September and October 1968. According to the Department of Defense "The weapon system disseminated an aerosol over a 40-50 kilometer downwind grid, encompassing a segment of the Enewetak Atoll and an array of five

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[58] Defense Threat Reduction Agency Fact Sheet Operation Hardtack I, September 2021 at https://www.dtra.mil/DTRA-Mission/Reference-Documents/NTPR-Info/

[59] Wayne Bliss (of the U.S. Environmental Protection Agency), *Enewetak Fact Book (A Resumé of Pre-cleanup Information)*, Department of Energy, 1982, pdf page 109 at https://www.dtra.mil/Portals/125/Documents/NTPR/newDocs/ENEWETAK/1982-DOE-EPA_Enewetak%20Fact%20Book%20(Pre-Cleanup%20Infor)-xprsd.pdf . Note that the U.S. military gave its own names to the islands; Runit was called Yvonne. At various times radioactive material was also pushed into the lagoon and the ocean.

[60] Defense Nuclear Agency 1981,, op. cit., pdf pages 469 and 470.

[61] Department of Energy letter to Foreign Minister Casten N. Nemra and Justice Minister Kessai H. Note, 21 January 2021.

[62] Department of Energy letter to Foreign Minister Casten N. Nemra and Justice Minister Kessai H. Note, 21 January 2021.

[63] See the list of Project SHAD tests at http://mcm.dhhq.health.mil/cb_exposures/project112_shad/shadfactSheets.aspx

Army light tugs."[64] Official documents relating to Project SHAD have been publicly available for over two decades.[65]

The Department of Defense Fact Sheet on the 68-50 test stated that it was "providing this information, at the request of the Department of Veterans Affairs (VA), to assist the VA in providing healthcare services to qualified veterans and to assist veterans in establishing service connection for disability claims."[66]

From the nature of the comment by the National Nuclear Commission and the response of the Department of Energy, it would appear that issues relating to any residual biological warfare agent or its impact on health had not been discussed with the Marshallese government and people, including the people of Enewetak, at least as of 2020.

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[64] Department of Defense, Project Shipboard Hazard and Defense (SHAD): DTC Test 68-50, Version 05-23-2002, at https://web.archive.org/web/20130726040015/http://mcm.dhhq.health.mil/Libraries/CBexposuresDocs/dtc_68_50.sflb.ashx ; hereafter Department of Defense 2002.

[65] See the website named "Medical Countermeasures: Helping Protect America's Armed Forces from Illness and Disease": http://mcm.dhhq.health.mil/cb_exposures/project112_shad/shadfactSheets.aspx

[66] Department of Defense 2002, op. cit. Statement in the footnote to the document.