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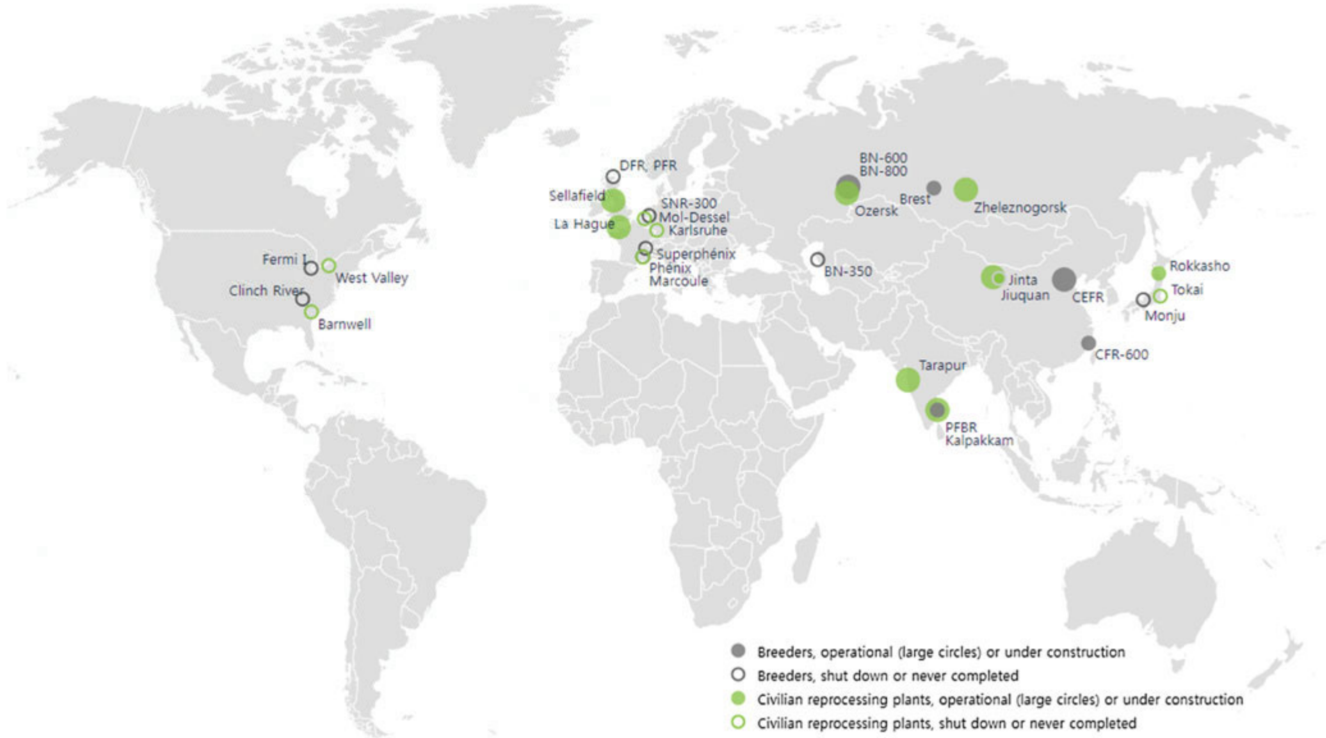


Global map of civilian reprocessing and breeder reactor sites

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Jungmin Kang

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*To our predecessors and allies who saw the danger and raised the warning.*
*And to the invisible hand of the market, which voted against the commercialization of plutonium.*

# Foreword by Mohamed ElBaradei

Plutonium, atomic number 94, was first separated in 1941 in Berkeley, California, in a quantity so small that it was difficult to see with the naked eye. By 2019, there are more than 500 metric tons of plutonium in civilian and military stocks in more than 10 countries around the world.

Named after the dark planet Pluto, plutonium has been characterized by some as the world's most dangerous nuclear material; Pu-239 has a half-life of 24,000 years and less than 8 kilograms is sufficient for a nuclear explosive device.

Plutonium use in the civilian nuclear fuel cycle has been passionately debated, with proponents sometimes uncharitably referred to as "plutonium eaters" and opponents on occasions derisively called "passive-aggressive." Those who advocated the use of plutonium emphasized its energy value ("one gram of recycled plutonium in a MOX fuel assembly generates the same quantity of electricity as burning 1–2 tons of oil") and promoted it as a valuable resource that should not be wasted. Those who opposed its use, on the other hand, stressed its toxicity and its long half-life, and highlighted its role as one of the key materials that can enable the acquisition of a nuclear-weapon capability, and hence advocated that its civilian use be stopped and it be disposed of as nuclear waste.

In the 1960s and 1970s, there were serious concerns that the global stocks of commercially recoverable uranium were limited. Uranium prices soared in the mid-1970s due to the effects of the 1973 OPEC oil embargo and a short-lived price cartel by some of the then-leading uranium-producing countries. At a time of high uranium prices, a plutonium fuel cycle was estimated to be competitively cost effective. Its proponents regarded plutonium as a "wonder fuel" that could generate a practically infinite amount of energy if produced in a closed fuel cycle, that is, uranium irradiated and discharged as spent fuel would be reprocessed to separate plutonium for fuels to be used in breeder reactors to create yet more plutonium. Over time, however, these optimistic expectations gave way to the realities of new sources of recoverable uranium at low prices, costly engineering challenges, and the complexities of safeguarding reprocessing and the related proliferation concerns. Reprocessing is one of the two most sensitive nuclear technologies from a proliferation perspective, along with uranium enrichment.

In October 2003, as the then-director general of the International Atomic Energy Agency (IAEA), in an op-ed titled "Towards a safer world" in *The Economist*, I proposed the multilateralization of all uranium-enrichment and plutonium-reprocessing facilities in view of the related proliferation concerns. I suggested that this should happen in three phases. First, any new uranium-enrichment and plutonium-reprocessing facilities should be set up exclusively on a multinational basis; second, over time convert all existing facilities to be operated under multinational auspices; and, third, negotiate a treaty on the prohibition of production of fissile material for nuclear weapons and place all existing stocks of military nuclear material under international monitoring. Unfortunately, not much has happened on this score, and much more work clearly needs to be done to curb the proliferation potential of these two most sensitive technologies. This includes the need to safely and securely dispose of plutonium and highly enriched uranium released from dismantled nuclear warheads under international monitoring. In this context, the Trilateral Initiative, and the Plutonium Management and Disposition Agreement, to place plutonium from dismantled Russian and US nuclear warheads under IAEA monitoring, need to be revived and implemented.

In light of the serious security and safety concerns surrounding the separation, use, and disposition of all isotopic mixes of plutonium, policy-makers, the media, and the public need to be better informed. Frank von Hippel, Jungmin Kang, and Masafumi Takubo, three internationally renowned nuclear experts, have done a valuable service to the global community in putting together this book, which both historically and comprehensively covers the "plutonium age" as we know it today. They articulate in a succinct and clear manner their views on the dangers of a plutonium economy and advocate a ban on the separation of plutonium for use in the civilian fuel cycle in view of the high proliferation and nuclear-security risks and lack of economic justification. They advocate instead dry storage of spent fuel after several years of pool cooling and its direct disposal in deep geological repositories when they become available.

There exists, however, no international consensus, and some states continue to pursue a commercial plutonium fuel cycle and forecast a sustainable future with new technologies. A comprehensive and sober discussion on the civilian use of plutonium needs to continue in the broader context of the role of nuclear energy in meeting the United Nations' sustainable development goals (SDGs), while reducing its proliferation potential. This book is a valuable contribution to that discussion.

Vienna, Austria

Mohamed ElBaradei
Director General, International
Atomic Energy Agency (1997–2009)
Nobel Peace Prize (2005)

# Acknowledgments

For more than four decades, we have been part of a small community of experts fighting to keep plutonium, a nuclear-weapon material, out of commerce. During that time, we have accumulated intellectual and other debts to colleagues who have been part of that fight.

- Thomas Cochran and Gus Speth, respectively, a physicist and a lawyer, when they worked at the US Natural Resources Defense Council, a nongovernmental organization, sued the US Atomic Energy Commission and forced it to publish in 1974 the analytical basis for its claim that plutonium was the fuel of the future. Cochran also made sure that, when the Carter administration launched the 1977 review that helped end the US breeder-reactor program, independent experts, including himself and von Hippel, were included in the steering committee;
- Harold Feiveson of Princeton University recognized the proliferation dangers in the proposed “plutonium economy” even before India’s 1974 nuclear test woke the world up to the issue;
- Edwin Lyman of the Union of Concerned Scientists has spent much of his professional life on plutonium issues and has become a leading expert;
- Theodore B. Taylor, a nuclear-weapon designer, went public in 1973 with his concerns that making a nuclear explosion with plutonium was no longer beyond the reach of terrorists; and
- Others who have made fundamental contributions to the debates over plutonium policy, especially Paul Leventhal in the United States; Yves Marignac and Mycle Schneider in France; M. V. Ramana in India; Tatsujiro Suzuki, Jinzaburo Takagi, and Fumihiko Yoshida in Japan; and Martin Forwood and William Walker in the UK.

Frank Niels von Hippel also owes an intellectual debt—as well as his first two names—to James Franck and Niels Bohr, who were among the first to understand the social responsibility physicists incurred with the world-changing discovery of nuclear fission.

Finally, we are grateful to Daniel Horner for his meticulous editorial work.

# Contents

# About the Authors

**Frank von Hippel** is a Senior Research Physicist and Professor of Public and International Affairs Emeritus with Princeton University's Program on Science and Global Security, which he co-founded, along with the International Panel on Fissile Materials and the journal *Science & Global Security*. During 1993–94, he served as Assistant Director for National Security in the White House Office of Science and Technology Policy.

**Masafumi Takubo** is a Tokyo-based researcher currently affiliated with Princeton University's Program on Science and Global Security. He has been working on nuclear-energy and nuclear-weapon issues in Tokyo as an activist and a researcher since the 1970s and manages the website Kakujoho.net ("Nuclear Information").

**Jungmin Kang** was trained as a nuclear engineer and has held research positions at Princeton, Stanford, and Johns Hopkins Universities and the Natural Resources Defense Council in the United States and the Korea Advanced Institute of Science and Technology in South Korea. During most of 2018, he served as the Chairperson of South Korea's Nuclear Safety and Security Commission.

# Abbreviations, Names and Units

| | |
|---|---|
| AGR | Advanced gas-cooled reactor (UK) |
| Areva | French government-owned company responsible for nuclear-fuel-cycle services and reactor construction, reorganized in 2018 with the fuel-cycle portion becoming Orano |
| ASN | Autorité de Sûreté Nucléaire, France's Nuclear Safety Authority |
| ASTRID | France's proposed Advanced Sodium Technological Reactor for Industrial Demonstration |
| BNFL | British Nuclear Fuels Ltd. |
| Bq | Becquerel, a unit of radioactivity: one disintegration per second |
| CEA | Commissariat à l'énergie atomique et aux énergies alternatives, France's Atomic Energy and Alternative Energies Commission |
| CIAE | China Institute of Atomic Energy |
| CNNC | China National Nuclear Corporation |
| Curie | A unit of rate of decay, originally defined as the radioactivity of a gram of radium, later redefined as $3.7 \times 10^{10}$ Bq |
| DAE | Department of Atomic Energy (India) |
| EDF | Électricité de France, France's nuclear utility, which also owns the operating nuclear power plants in the UK |
| ERDA | Energy Research and Development Administration (US, 1975–77) |
| FMCT | Fissile Material Cutoff Treaty |
| GWe | Gigawatts, $10^9$ watts, or 1,000 megawatts (electric) |
| HEU | Highly enriched uranium ($\geq$ 20% U-235) |
| HM | Heavy metal, either uranium or a mix of uranium and plutonium in nuclear fuel |
| Holtec | US manufacturer of spent-fuel canisters |
| IAEA | International Atomic Energy Agency |
| INFCE | International Nuclear Fuel Cycle Evaluation (1977–1980) |
| IPFM | International Panel on Fissile Materials |
| IRSN | Institut de Radioprotection et de Sûreté Nucléaire, France's Institute for Radiological Protection and Nuclear Safety |
| JAEA | Japan Atomic Energy Agency (does nuclear R&D) |

| | |
|---|---|
| JAEC | Japan Atomic Energy Commission |
| JAPC | Japan Atomic Power Company |
| KAERI | Korea Atomic Energy Research Institute |
| kg | Kilograms |
| km | Kilometers |
| kWh | Kilowatt-hours |
| LEU | Low-Enriched uranium (<20% U-235) |
| LWR | Light-water (power) reactor |
| MBq | Megabecquerels, $10^6$ Bq |
| MBq/m$^2$ | Megabecquerels per square meter, a measure of radioactive contamination |
| MOX | Mixed-oxide (fuel), in which plutonium is mixed with natural or with depleted uranium, the waste product from enrichment |
| MWe | Megawatts (electric) |
| MWt | Megawatts (thermal) |
| MWt-day | Cumulative energy expended in a day at a rate of one MWt |
| NAS | National Academy of Sciences (US) |
| NDA | Nuclear Decommissioning Authority (UK) |
| NNSA | National Nuclear Security Administration (part of US DOE) |
| NRA | Nuclear Regulation Authority (Japan, 2012–) |
| OECD IEA | International Energy Agency, which is part of the Organisation for Economic Co-operation and Development |
| Orano | France's government-owned fuel-cycle company (2018–) |
| PBq | Petabecquerels, $10^{15}$ Bq |
| PFBR | Prototype Fast Breeder Reactor (India) |
| PUREX | Plutonium Uranium Redox Extraction, the standard method for separating plutonium from irradiated uranium, originally used in the US nuclear-weapon program beginning in the 1950s |
| R&D | Research and development |
| SKB | Swedish Nuclear Fuel and Waste Management Company |
| TEPCO | Tokyo Electric Power Company (renamed in 2016 as Tokyo Electric Power Holdings, but with the same acronym) |
| THORP | Thermal Oxide Reprocessing Plant (UK) |
| ton | Metric ton, 1000 kg |
| Transuranics | Artificial elements with more protons than uranium (92) and therefore to the right of it on the periodic table, created by neutron absorption in uranium: neptunium (93), plutonium (94), americium (95), and curium (96) |
| UN AEC | United Nations Atomic Energy Commission (1946–49) |
| US AEC | United States Atomic Energy Commission (1946–1975) |
| US DOE | United States Department of Energy, responsible for designing, producing, and maintaining US nuclear weapons and cleaning up nuclear-weapon-material-production sites as well as energy R&D (1977–) |
| US NRC | United States Nuclear Regulatory Commission (1975–) |

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# Chapter 1
# Overview

One of the first tasks of the secret US World War II nuclear-weapon project was to design reactors to produce plutonium for bombs. This part of the project was headquartered at the University of Chicago, where, on 2 December 1942, a team led by Enrico Fermi and Leo Szilard, two European refugee physicists, created the first artificial steady fission chain reaction, which was sustained by neutrons traveling between lumps of uranium inside a "pile" of graphite.

After the operation of the pile confirmed their understanding of how a chain reaction could be achieved and controlled, the team worked with the DuPont company to design and build three hulking high-power plutonium-production reactors at the Hanford site on the Columbia River in remote eastern Washington state. These reactors produced the plutonium for the first test nuclear explosion in the southern New Mexico desert on 16 July 1945 and for the bomb that destroyed Nagasaki on 9 August 1945. After the war, 11 additional production reactors were built, and the 14 reactors together produced plutonium for the tens of thousands of additional nuclear weapons that the United States built during the Cold War.

In 1944, with the Hanford reactors about to go into operation, Fermi moved to Los Alamos, New Mexico, to work on the design of the plutonium bomb. In Chicago, Szilard and a few others in the reactor-design team started thinking about how to use nuclear energy to generate electrical power. They worried, however, that not enough high-grade uranium ore would be found to make fission energy into a significant energy source.[1] Chain-reacting uranium-235 constitutes only 0.7% of natural uranium. Virtually all of the rest is non-chain-reacting U-238.

## 1.1 Dreams of Plutonium Breeder Reactors

In the Hanford reactors, for every 10 atoms of U-235 consumed, about seven atoms of U-238 were being turned by neutron absorption into the artificial chain-reacting isotope plutonium-239. Neutrons released by the fissioning of the Pu-239 atoms could in turn convert more U-238 into Pu-239.



F. von Hippel et al., *Plutonium*,
https://doi.org/10.1007/978-981-13-9901-5_1