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PHYSICS & SOCIETY

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Note from the Editor

As I write this, the news headlines this week are captivating people around the globe and are of interest to this Forum. NASA's New Horizon spacecraft successfully completed its flyby of Pluto sending its high resolution images back to Earth after a journey of more than three billion miles in less than a decade. Earlier in the week, the US announced that it had reached an agreement with Iran to limit its nuclear weapons development capability in return for a lifting of economic sanctions. Whenever there are headlines like this, friends and family ask me many questions (as I'm sure they are asking you) about the engineering challenges of sending a probe so far, the scientific questions we might answer with the data, and the overall cost of such a mission. Similarly, people have asked me about what it takes to create a nuclear weapon from uranium or plutonium.

In this issue of *Physics and Society*, we have two articles that focus on reducing the threat of nuclear weapons. First, Alex DeVolpi completes the second part of his two-part piece on the feasibility of using reactor-grade plutonium for a warhead. In our second article, Harold Feiveson and colleagues discuss their work on "Unmasking the Bomb," which looks at "practical policy initiatives to cap, reduce and eventually eliminate the global stockpile of weapon-usable fissile material in the world."

In the News of the Forum section, I am so pleased to recognize the 2015 FPS Award winners. The Joseph A. Burton Forum award goes to E. William Colglazier for his work on radioactive waste management. The Leo Szilard Lectureship Award Recipient is Ashok Gadgil for his work on sustainable energy. In addition, at every April APS meeting the Forum's Executive Committee meets and also holds a Business meeting session at the conference. For those of you that were not able to attend, I've included the link to the minutes of both meetings as well as to the minutes from past years. Finally, our book review by Leonard Solon is on *Serving The Reich: The Struggle For The Soul Of Physics Under Hitler*, by Philip Ball.

In the January 2015 article "Nuclear Waste Confidence: Is Indefinite Storage Safe" the NEPA was erroneously identified as the National Environmental Protection Act. It should have been identified as the National Environmental Policy Act. My thanks to the authors for alerting me to this and to Ken Maxey for identifying the error.

As always, I am looking for people that would like to publish articles of interest to our readership. Please let me know if you or one of your colleagues would like to submit an article for an upcoming newsletter. Happy reading and enjoy the summer! ■

—Andrew Zwicker
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IN THIS ISSUE

FPS Business Meetings

As a reminder, at every April APS meeting the FPS Executive Committee meets in person and there is an FPS Business meeting session that is advertised as part of the Conference. On April 12, 2015, the Executive Committee met from 8:00 am to 9:30 am. Immediately following the conclusion of this meeting was the Business Meeting, from 9:30 am to 10:00 am. For those who were not able to attend, the minutes from these meetings (and from previous years) are posted online at: http://www.aps.org/units/fps/governance/minutes/index.cfm

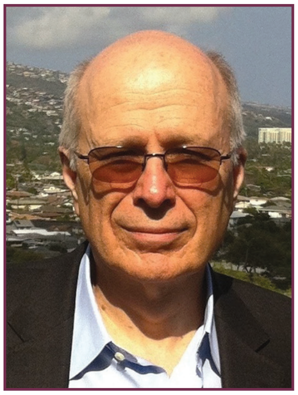
FPS Awards Recipients

JOSEPH A. BURTON FORUM AWARD

To recognize outstanding contributions to the public understanding or resolution of issues involving the interface of physics and society. The award consists of $3,000, a certificate citing the contributions of the recipient, and an allowance for travel to the meeting of the Society at which the award is presented. It will be awarded annually.

Establishment & Support: The Joseph A. Burton Forum Award is named in recognition of the many contributions of Joseph Burton to the society and to the APS as its Treasurer from 1970 - 1985. The award was endowed in 1997 through a donation from Mrs. LeRoy Apker. The award stems from the former Forum Award for Promoting Public Understanding of the relationship of Physics and Society, established by the Forum on Physics and Society in 1974.

2015 JOSEPH A. BURTON FORUM AWARD RECIPIENT



E. WILLIAM COLGLAZIER
Department of State

Citation: "For his contributions to scientific and public understanding of radioactive waste management, and to U.S. policy on science and technology and global scientific engagement for the betterment of society."

DR. E. WILLIAM COLGLAZIER served as the fourth Science and Technology Adviser to the Secretary of State from 2011 to 2014. His role was to provide scientific and technical expertise and advice in support of the development and implementation of U.S. foreign policy.

From 1994 to 2011, he was Executive Officer of the National Academy of Sciences (NAS) and the National Research Council (NRC) where he helped to oversee the studies that provide independent, objective advice on public policy issues. He received his B.S. in physics in 1966 and his Ph.D. in theoretical physics in 1971 from the California Institute of Technology, and prior to 1994 worked at the Stanford Linear Accelerator Center, the Institute for Advanced Study in Princeton, the Center for Science and International Affairs at Harvard's Kennedy School of Government, and the University of Tennessee.

While at Harvard, he also served as Associate Director of the Program in Science, Technology, and Humanism of the Aspen Institute. In 1976-77, he was an AAAS Congressional Science Fellow for Congressman George Brown. He is past chair of the Forum on Physics and Society of the APS and Fellow of the AAAS and APS.

Selection Committee: Valerie Thomas, Chair; M.M. May; R.V. Ramana; L. Krauss

LEO SZILARD LECTURESHIP AWARD

To recognize outstanding accomplishments by physicists in promoting the use of physics for the benefit of society in such areas as the environment, arms control, and science policy. The lecture format is intended to increase the visibility of those who have promoted the use of physics for the benefit of society. The award consists of $3,000, a certificate citing the contributions of the recipient, plus $2,000 travel expenses for lectures given by the recipient at an APS meeting and at two or more educational institutions or research laboratories in the year following the award. The lectures should be especially aimed at physicists early in their careers.

Establishment & Support: This annual award was established in 1974 by the Forum on Physics and Society as a memorial to Leo Szilard in recognition of his concern for the social consequences of science. The award was endowed in 1998 by donations from the John D. and Catherine T. MacArthur Foundation, the Energy Foundation, the David and Lucille Packard Foundation and individuals. It was also expanded to a lectureship format to promote awareness of the application of physics to social problems and to increase the visibility of those engaged in such activities.

2015 LEO SZILARD LECTURESHIP AWARD RECIPIENT

ASHOK GADGIL
Lawrence Berkeley National Laboratory

Citation: "For applying physics to a variety of social problems and developing sustainable energy, environmental and public health technologies, as well as demonstrating how these could be scaled up, thus contributing to improved life for millions."

ASHOK GADGIL has a doctorate in physics from UC Berkeley. He is Director of the Environmental Energy Technologies Division of Lawrence Berkeley National Laboratory, and a Professor of Civil and Environmental Engineering at UC Berkeley. He has substantial experience in technical, economic, and policy research on energy efficiency and its implementation — particularly in developing countries. For example, the utility-sponsored compact fluorescent lamp leasing programs that he pioneered are being successfully implemented by utilities in several east-European and developing countries. He has several patents and inventions to his credit, among them the "UV Waterworks," a technology to inexpensively disinfect drinking water in the developing countries, for which he received the Discover Award in 1996 for the most significant environmental invention of the year, as well as the Popular Science award for "Best of What is New – 1996". In recent years, he has worked on ways to inexpensively remove arsenic from Bangladesh drinking water, and on fuel-efficient stoves for Darfur.

Dr. Gadgil has received several other awards and honors for his work, including the Pew Fellowship in Conservation and the Environment in 1991 for his work on accelerating energy efficiency in developing countries, the World Technology Award for Energy in 2002, the Tech Laureate Award in 2004, the Heinz Award in 2009, the European Inventor Award in 2011. He serves on several international and national advisory committees dealing with energy efficiency, invention and innovation, and issues of development and the environment. He is also a member of the STAP roster of experts of the Global Environmental Facility. In the 2004-5 academic year, Dr. Gadgil was the MAP/Ming Visiting Professor in Civil and Environmental Engineering at Stanford University.

At Lawrence Berkeley National Laboratory, Dr. Gadgil is part of a group of researchers conducting experimental and modeling research in Indoor Airflow & Pollutant Transport. He has authored or co-authored more than 85 papers in refereed archival journals and more than 100 conference papers.

Selection Committee: Valerie Thomas, Chair; M.M. May; R.V. Ramana; L. Krauss

Physics and Society is the non-peer-reviewed quarterly newsletter of the Forum on Physics and Society, a division of the American Physical Society. It presents letters, commentary, book reviews and articles on the relations of physics and the physics community to government and society. It also carries news of the Forum and provides a medium for Forum members to exchange ideas. ***Opinions expressed are those of the authors alone and do not necessarily reflect the views of the APS or of the Forum.*** Contributed articles (up to 2500 words), letters (500 words), commentary (1000 words), reviews (1000 words) and brief news articles are welcome. Send them to the relevant editor by e-mail (preferred) or regular mail.

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***Physics and Society* can be found on the web at www.aps.org/units/fps.**

Unmaking the Bomb: A Fissile Material Approach to Nuclear Disarmament and Nonproliferation

Harold A. Feiveson, Alexander Glaser, Zia Mian and Frank von Hippel

Adapted from the introduction to Unmaking the Bomb: A Fissile Material Approach to Nuclear Disarmament and Nonproliferation (MIT Press, 2014)

INTRODUCTION

It is seven decades since the first nuclear explosion. On 16 July 1945, in the Alamogordo Desert in southern New Mexico, the United States tested the plutonium bomb that it exploded 24 days later over Nagasaki. A bomb of much simpler design made from highly enriched uranium (HEU) was used against Hiroshima on 6 August 1945.

Announcing the atomic bombing of Hiroshima, President Harry Truman made public the enormous effort involved in making the fissile materials for new bombs:[1]

> We now have two great plants and many lesser works devoted to the production of atomic power [fissile materials]. Employment during peak construction numbered 125,000 and over 65,000 individuals are even now engaged in operating the plants. Many have worked there for two and a half years. Few know what they have been producing.

Since then, the technologies for uranium enrichment and plutonium separation pioneered by the United States have been mastered by eight other weapon states and also many other states, some of whom have considered but decided not to build nuclear weapons. Only one state (South Africa) has made and then renounced these weapons.

During the Cold War, the weapon states collectively produced for weapons over 2,000 tons of HEU and about 250 tons of separated plutonium. The number of nuclear warheads peaked at over 65,000. Warhead stockpiles have fallen, but 25 years after the Cold War's end there remain about 10,000 operational warheads and components for many more. About 90 percent belong to Russia and the United States. The United Kingdom, France, China, Israel, India, Pakistan, and North Korea (in historical order) have about 1,000 warheads between them.

The fissile material problem is larger than this, however. Despite nuclear arsenal reductions, the global stockpile of fissile material as of 2014 was about 1,845 tons of HEU and plutonium. The ongoing dismantlement of tens of thousands of warheads has left large national stockpiles of excess fissile materials that have to be rigorously secured, and also, if not eliminated, could be used for weapons again.

Also, more HEU and plutonium was produced than was used for weapons. Hundreds of naval-propulsion reactors and research reactors are fueled with HEU, and more plutonium has been separated for civilian purposes than for weapons. All of this material is weapon-usable. There is in fact enough fissile material in the world today for about 200,000 simple fission weapons.

We wrote our book, *Unmaking the Bomb*, to provide a roadmap for practical policy initiatives to cap, reduce and eventually eliminate the global stockpile of weapon-usable fissile material in the world. It builds on analysis and reports prepared for the International Panel on Fissile Materials (IPFM). The Panel's reports and the book offer a fissile material perspective on how to enable deep reductions of nuclear warheads, make nuclear disarmament more difficult to reverse, raise the barriers to nuclear weapon proliferation, and prevent possible nuclear-weapon acquisition by terrorist groups.

HOW THE NUCLEAR WORLD EMERGED

The fact that the U-235 nucleus can be fissioned, releasing tens of millions of times more energy than the same weight of chemical explosives, was discovered in December 1938 in Germany, just before World War II. In March 1940, fearing a German atomic bomb, two refugee physicists at Birmingham University in England wrote a technical memo alerting the British government that an explosive nuclear fission chain reaction might be possible in a mass of nearly pure U-235 and allow for the production of a "super-bomb."[2]

Uranium-235 makes up only 0.7% of natural uranium. The remainder is U-238 plus trace amounts of U-234 from the alpha decay of U-238. The two physicists noted, however, that "effective methods for the separation of isotopes have been developed recently" that could allow U-235 separation from natural uranium on a sufficiently large scale to permit construction of an atomic bomb. Their memo eventually galvanized the establishment of the U.S. nuclear-weapon program.

While the U.S. effort to design the atomic bomb, led by Robert Oppenheimer at Los Alamos, has captured most attention from historians, the largest investment of resources and people in the "Manhattan Project" was the effort in Oak Ridge, Tennessee to enrich uranium in U-235. Three different techniques were developed, but the one the U.S. adopted at the end of the war and used during the Cold War was gaseous diffusion. Gaseous uranium hexafluoride is pumped through thousands of porous barriers with the stream becoming slightly more enriched in U-235 at each stage because the molecules carrying the lighter U-235 atoms pass through the barriers more quickly than U-238. In 1941, a second material able to undergo a fission chain reaction was discovered, plutonium-239. Pu-239 has a half-life of 24,000 years and does not exist in significant concentrations in nature. It can be produced, however, by the capture of neutrons by uranium-238 nuclei in a nuclear reactor and the rapid beta decay of the resulting U-239 nuclei to neptunium-239 and then to Pu-239.

To produce plutonium for weapons, three high-power reactors were set up at the Hanford Site in central Washington State in late 1944 and early 1945. According to General Leslie Groves, the man in charge of the Manhattan Project, an isolated location was chosen for the production reactors because “no one knew what might happen, if anything, when a chain reaction was attempted in a large reactor.” One fear was “some unknown and unanticipated factor” might lead a reactor “to explode and throw out great quantities of highly radioactive materials into the atmosphere.”[3]

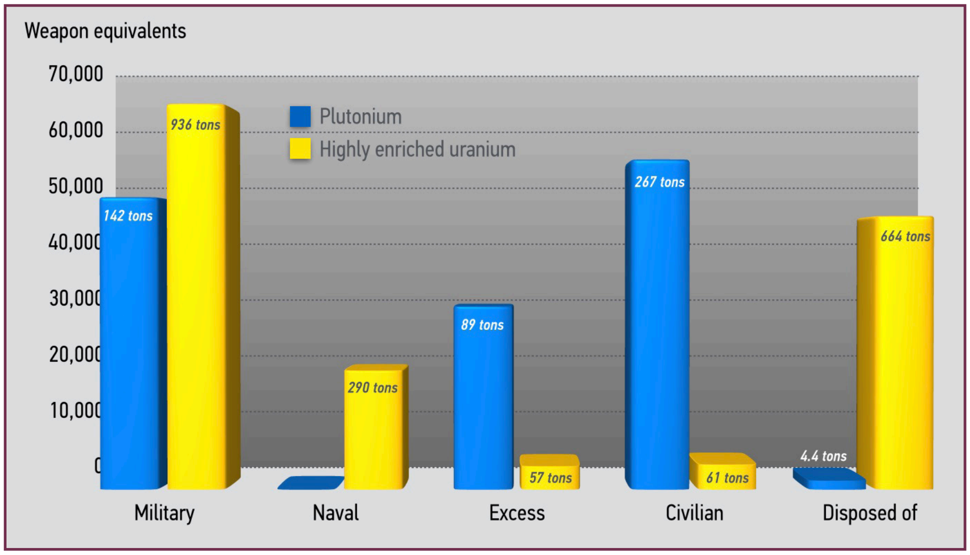

Figure 1. Global stocks of HEU and separated plutonium in metric tons, by category, as of 2014.[4] Also shown are their weapon-equivalents (using an average of 3 kg of weapon-grade plutonium, 5 kg of reactor-grade plutonium, 15 kg of highly enriched uranium per warhead). The global stockpile of fissile material is now more than 200,000 weapon-equivalents.

The plutonium has to be separated from the highly radioactive fission products in neutron-irradiated uranium. This is done remotely behind thick concrete radiation shielding in a chemical “reprocessing” plant. Once the plutonium is separated, it can be handled relatively easily in a “glovebox” which protects workers from inhaling carcinogenic plutonium oxide particles.

The Hiroshima bomb contained about 60 kilograms of HEU, while the Nagasaki bomb contained only about 6 kg of plutonium. This was because the Manhattan project developed two different types of nuclear-weapon designs. A simple “gun-type” design was developed for HEU. A much more difficult but efficient “implosion” design was developed for plutonium after it was discovered that the slow gun-type assembly would not work for plutonium. Pu-240 was being produced along with the Pu-239 and neutrons from Pu-240’s high rate of spontaneous fission would prematurely initiate a chain reaction.

Modern thermonuclear weapons (“hydrogen” bombs), also pioneered by the United States, use a “primary” fission explosion to trigger a much more powerful “secondary” fusion-fission explosion. These weapons generally contain an average of about 3 kg of plutonium in the “pit” of the fission primary and 15–25 kg of highly enriched uranium in the thermonuclear secondary.

The Soviet Union patterned its first fissile material production facilities, and its first weapon design, on those of the United States. Later, in the early 1960s, the Soviet Union broke new ground by shifting to gas-centrifuge technology for uranium enrichment. Uranium hexafluoride gas is spun at high speed inside a long cylinder so that the molecules carrying the heavier U-238 atoms are pressed more tightly against the wall. Combined with a circulation of the gas along the centrifuge rotor, this effect can be used to extract slightly enriched and depleted uranium streams from the machine. By connecting many such centrifuges in series and parallel, uranium can be enriched to any desired enriched level, from the 3–5% U-235 used in light-water reactor fuel to “weapon-grade” containing more than 90% U-235. Modern commercial uranium enrichment relies on this technology.

Britain’s nuclear weapon program was led by physicists who had participated in the U.S. wartime program. France followed Britain in its choice of technologies and scale. Many of China’s nuclear experts were trained in the Soviet Union, which also provided expert advisors and designs for fissile material production facilities, although the Soviet experts were withdrawn before China’s uranium enrichment and plutonium production facilities were completed. These five states are now recognized as nuclear-weapon states under the 1968 Non-proliferation Treaty (NPT).

Today, four additional states also have nuclear weapons. Israel received a complete plutonium production complex from France. India received assistance from the United States and Canada in building a plutonium production complex, nominally for a plutonium breeder reactor development program. Pakistan clandestinely purchased key technologies, components and materials from Europe’s gas-centrifuge production complex and received the design of a tested warhead from China. North Korea used the published design of a 1950s UK plutonium-production reactor and obtained

Unmaking the Bomb *continued on page 6*

gas-centrifuge technology from Pakistan. South Africa in the 1980s produced six nuclear weapons employing HEU. In 1990-91, it dismantled the weapons, placed the recovered HEU under international safeguards, and joined the NPT as a non-nuclear-weapon state.

GLOBAL STOCKS

There is considerable uncertainty about global fissile material stockpiles—only the United States and the United Kingdom have made public declarations of their inventories of military fissile materials. Estimates for the other nuclear weapon states carry uncertainties of 20-40 %.[5]

An estimated 940 tons of HEU and 140 tons of plutonium remain available for weapon purposes—mostly in Russia and the United States. Another almost 900 tons of HEU and 80 tons of plutonium have been declared excess for weapons use, of which over 660 tons of HEU have been eliminated by downblending it to low-enriched uranium for power-reactor fuel. The United States has allocated about 150 tons of its excess weapons HEU as a reserve for its military naval propulsion reactors.

France, Japan, Russia and the United Kingdom have declared a combined total of 260 tons of separated civilian plutonium as of the end of 2013, and about 70 tons of HEU are dedicated to civilian research reactor fuel. Starting after President Eisenhower's Atoms for Peace speech in 1953, the United States and Soviet Union distributed HEU-fueled research reactors to 30 non-weapon states during the 1950s and 1960s. Many of these reactors have been shut down, and the United States and Russia have sought to convert the others to low-enriched uranium fuel.

THE NUCLEAR WEAPON – NUCLEAR ENERGY LINK

The U.S. Atoms for Peace initiative also led to the founding of the International Atomic Energy Agency in 1957 with a mandate both to promote peaceful uses of nuclear technology and to monitor nuclear materials in non-weapon states to assure that they were not diverted to weapons uses. This approach to managing the proliferation risks of civilian nuclear energy programs was codified in the NPT.

Today, there are two principal civilian nuclear "fuel cycles." The United States and most of the 30 or so countries with nuclear power plants use natural or low-enriched uranium (LEU) fuel containing 3–5% uranium-235 "once-through." The discharged spent fuel is stored pending final disposal. This fuel system has the critical nonproliferation advantage that weapon-usable fissile material is nowhere easily accessible. LEU, defined as uranium containing less than 20% U-235 cannot be used for weapons without further enrichment and the plutonium in the spent fuel is not separated. There is no weapon-useable fissile material in such a system.

If a country acquires an enrichment plant to produce LEU fuel, however, the plant could be converted rapidly to produce weapon-grade uranium. This possibility has been at the heart of international concern about Iran's uranium enrichment program. The proliferation danger of national enrichment and reprocessing programs was recognized at least as early as 1946 when the U.S. proposed international control.[6] Today, multinational control may be more realistic.[7]

A small number of countries have chosen a second nuclear fuel system, in which plutonium is separated for use as a reactor fuel. From the earliest days of the nuclear era, interest in civilian reprocessing was driven by the dream of breeder reactors that would produce more fissile material than they consumed, typically by converting uranium-238 into plutonium. Efforts at breeder reactor commercialization by over half a dozen countries largely failed, despite five decades of research, development and demonstration projects and a combined cost in excess of $100 billion.

The United States, United Kingdom, and Germany abandoned their breeder reactor efforts in the 1980s and 1990s, and France and Japan postponed theirs. Only Russia and India—joined in 2010 by China at a pilot scale—now separate plutonium with the intention of using it as fuel for prototype plutonium breeder reactors.

Despite the breeder dream having faded, France, Japan and the United Kingdom continued reprocessing. France and Japan decided to mix their separated plutonium with depleted uranium in mixed-oxide (MOX) plutonium-uranium fuel for existing light water reactors. This fuel cycle is much more costly than the once-through fuel cycle and also complicates radioactive waste disposal and in both countries the future of reprocessing is being debated. In 2012, with its nuclear utility refusing to renew its reprocessing contracts, the UK decided to end reprocessing when it completed existing contracts.

HEU (defined as uranium containing 20% or more U-235) in naval fuel cycles also is a security risk. The single largest illicit diversion of fissile material thus far may have been the several hundred kilograms of weapon-grade uranium that were secretly transferred in the 1960s from the NUMEC naval fuel fabrication facility in the United States to Israel with the cooperation of the plant's owner.[8] In 1993, a much smaller amount of HEU submarine fuel was stolen from a Russian storage facility.[9] This incident helped focus attention on the need to secure Russian nuclear materials after the collapse of the Soviet Union.

The United States, Russia, the United Kingdom, and India fuel nuclear submarines with HEU, and the United States and Russia also operate HEU fueled ships. France, however, fuels its submarines and nuclear-powered aircraft carrier with LEU. It is believed that China also uses LEU fuel. Brazil, which is planning to be the first non-weapon state to have nuclear-powered submarines, also has chosen to use LEU. If the countries that use HEU fuel converted to LEU, much more military HEU could be eliminated.

Two hopeful signs are that Russia has recently developed an LEU-fueled reactor to power its future nuclear-powered icebreakers, and the U.S. Congress has become interested in the possibility of funding an R&D Program to develop LEU fuel for future U.S. nuclear-powered submarines and aircraft carriers.[10]

ELIMINATING FISSILE MATERIALS

The most effective and enduring way to deal with the dangers from fissile materials is to stop producing them and dispose of them as irreversibly as possible. This will require new policy and technology initiatives.

A Fissile Material Cutoff Treaty (FMCT) to end the production of fissile material for weapons was first proposed in the 1950s by the United States as a means to cap the relatively smaller Soviet fissile material stockpile and was rejected. The idea was revived at the end of the Cold War and has been under consideration at the United Nations Conference on Disarmament in Geneva since 1993. In recent years, with international attention focused on fighting Islamist militants, Pakistan has successfully stalled the start of talks as a way to buy time to build up its fissile material stockpile.

Under an FMCT, the IAEA would monitor enrichment and reprocessing plants to determine that any enriched uranium and separated plutonium produced is not used for weapons. If it were agreed, the storage and use of pre-existing fissile materials that the weapon states have declared excess for all military purposes too could be monitored.[11] If the use of plutonium and HEU fuels were abandoned, an FMCT could be broadened further into a ban on the production and use of fissile materials for any purpose. This last option would have the largest nonproliferation impact.

The disposal of HEU is relatively straightforward. It is blended with natural or slightly enriched uranium to produce LEU that can be used as reactor fuel. Russia and the United States together have down-blended over 650 tons of highly enriched uranium. Given the size of current arsenals, much more HEU could be declared excess by Russia and the United States and sent for down-blending.

The disposal of plutonium has proven more costly and complicated, and has made little progress since the United States and Russia concluded a Plutonium Management and Disposition Agreement in 2000 that committed each party to dispose of at least 34 tons of weapon-grade plutonium. Russia plans to use its excess separated plutonium in prototype breeder reactors. The United States planned to fabricate most of its excess plutonium into MOX fuel for use in light-water reactors but the MOX fuel fabrication facility that the Department of Energy has been building in South Carolina became so costly that the Obama Administration decided that it is “unaffordable.”

There are less costly options for plutonium disposal. These include mixing the plutonium into the concentrated fission-product wastes from which it was originally separated as those wastes are embedded in glass for disposal in a deep geological repository. Another option is dilution and immobilization of the plutonium in a durable matrix and disposal in 3–5 kilometer deep boreholes.[12]

CONCLUSION

International efforts to reduce nuclear weapon stocks and to prevent proliferation and nuclear terrorism have been operating largely in parallel. The fissile material perspective presented here provides a common basis for these efforts. If we are to reduce the threat from nuclear weapons, we must deal with the dangers posed by the production, stockpiling, and use of fissile materials. Unmaking the bomb requires eliminating the fissile materials that make nuclear weapons possible.

Confidence in and verification of nuclear disarmament will be far easier in a world where there is no production or use of separated plutonium or highly enriched uranium and where fissile material stocks have been eliminated. Together, these efforts would make it more difficult and more time-consuming for any country to make fissile materials for nuclear weapons and would make it easier for the international community to detect and respond to what would be a clear threat to international peace and security. ■

- Harold A. Feiveson, Alexander Glaser, Zia Mian and Frank von Hippel
Program on Science and Global Security, Princeton University

ENDNOTES

1 *White House Press Release on Hiroshima, Statement by the President of the United States, August 6, 1945.*

2 *Otto Frisch and Rudolph Peierls “On the Construction of a Super-bomb' based on a Nuclear Chain Reaction in Uranium”, Memorandum, March 1940.*

3 *Quoted in Richard Rhodes,* The Making of the Atomic Bomb *(New York: Simon & Schuster, 1986), p. 496.*

4 *International Panel on Fissile Materials,* Global Fissile Material Report 2015.

5 *For details on the published estimates used, see International Panel on Fissile Materials,* Global Fissile Material Report 2010: Balancing the Books—Production and Stocks, *http://fissilematerials.org/library/gfmr10.pdf*

6 *U.S. State Department,* A Report on the International Control of Atomic Energy, *1946, www.fissilematerials.org/library/ach46.pdf*

7 *Alexander Glaser, Zia Mian and Frank von Hippel, “After the Iran nuclear deal: Multinational enrichment,”* Science, *19 June 2015.*

8 *Victor Gilinsky and Roger J. Mattson, “Did Israel steal bomb-grade uranium from the United States?,* Bulletin of the Atomic Scientists, *17 April 2014.*

9 *Oleg Bukharin and William Potter, “Potatoes were guarded better,”* Bulletin of the Atomic Scientists, *May/June 1995, pp. 46-50.*

10 *H.R.1735, National Defense Authorization Act for Fiscal Year 2016, Section 3142, Research And Development of Advanced Naval Nuclear Fuel System Based on Low-Enriched Uranium.”*

11 *International Panel on Fissile Materials,* Global Fissile Material Report 2008: Scope and Verification of a Fissile Material (Cutoff) Treaty, *www.fissilematerials.org/library/gfmr08.pdf*

12 *Frank von Hippel and Gordon MacKerron, Alternatives to MOX: Direct-disposal Options for Stockpiles* of Separated Plutonium, *International Panel on Fissile Materials, 2015, www.fissilematerials.org/library/rr13.pdf.*

Demilitarizing Weapon-Grade Plutonium: Part II

CONTROVERSY ABOUT PROLIFERATION RISK

Alexander DeVolpi

In Part I of this review about plutonium, various proven technical and institutional means for reducing nuclear proliferation were described. Enormous public value, in terms of nuclear-arms reduction and nonproliferation, can be derived from systematic demilitarization of fissile materials. Moreover, billions of taxpayer dollars can be recovered from commercial sales of materials no longer needed for weapons.

Nevertheless, unjustified and prolonged concern has been perpetuated about reactor-grade plutonium (RGPu). Much of the concern began with US government censorship of a 1962 nuclear-explosive test. Regarding its "nuclear yield," the Department of Energy (DOE) has been evasive, simply asserting that "high-irradiation-level [RGPu] can be used to make nuclear weapons."[1] In 1994 DOE mentioned that the test yield had an upper limit of 20kt. In contrast, DOE has released much more substantive information about most other 1000 US nuclear explosions.

Some disturbing inferences about the still-limited data come to mind:[2] (1) The material supplied might not have been "reactor grade," but could have been more potent "fuel grade" or higher, and/or (2) The test yield and success might have been deliberately overstated by the government. This information management was evidently intended to avoid skepticism about the "successful" label attached to the 1962 test.

Specific questions were raised about the DOE assertions nine years ago in Physics & Society.[3] The World Nuclear Association has stated that the test device had at least 85% Pu-239 — a much higher fissile concentration than spent fuel from operating civilian reactors. Other nations have disagreed with the DOE "spin": France, in particular, "scorned the US affirmation that it successfully exploded a weapon made with [RGPu]"[4]

DO.E, by its own security criteria and practices, could have disclosed additional data. Abundant detail has been declassified for many US tests: For example, the 12 March 1968 "Buggy" series consisted of five simultaneous detonations using metallic HEU or weapon-grade plutonium (WGPu), with each explosive yield given as 1.08kt. Similar specifics have been released about numerous experiments going back to 1946.

The information still withheld by DOE can hardly add more proliferation value than data already divulged for other nuclear-explosive experiments. Moreover, the missing data would probably fortify awareness about inherent difficulties in weaponizing civilian plutonium, thus discouraging potential proliferators. It might even help formulate more cost-effective controls, without the need for relaxing nuclear-fuel-cycle safeguards.

In 1953 Britain conducted a test series (Operation Totem in Australia) using RGPu, reporting an 8-10kt explosive yield with relatively high fissile Pu-239 content estimated at 87-91%. The results were unacceptable: According to an official UK book (classified "Secret" in the US), the British never made weapons out of RGPu, even though they had lots of it.

For nearly a half century, controversy has lingered about RGPu. The implications affect civilian and military nuclear policy regarding arms control, demilitarization, international nonproliferation, and fuel management. Although the US government still implies nuclear weapons could be made from RGPu, that questionable posture has been documented only by ambiguous statements from the Atomic Energy Commission and its successors (ERDA, now DOE). Disagreeing are many experienced industry and laboratory nuclear physicists and engineers who recognize that impure plutonium has evidently not been incorporated in weapons for nuclear arsenals.

STATISTICAL LIMITS AND NUCLEAR INSIGHTS

DOE's publicized declarations are not compliant with proper statistical characterizations of technical data. The agency has repeatedly asserted the 1962 test yield to be between zero and 20 kt. This implies a broad Gaussian (or Poisson) distribution with mean 10kt, and min/max between zero and 20kt. Absent additional information, almost any centrally-distributed FWHM could statistically match that meager data. However, warheads intended for a military arsenal are subject to unique standards: Neither expensive resources nor military effectiveness have evidently been squandered by the nine established nuclear-weapon states; their governments would not fabricate warheads with minimal yield and inconsistent military value.

The long-prevailing worldwide suspension in nuclear weaponization strongly refutes decades-old doom-and-gloom forecasts by individuals, such as Amory Lovins, Frank von Hippel, Ed Lyman, as well as by non-government organizations like the Union of Concerned Scientists — and even by a few prominent Americans once associated with the Manhattan Project. Vague terms, especially "weapons usable," have often been deliberately exploited, and proper statistical boundaries are usually omitted. Too many forecasts depend almost entirely on existential threats of disaster. Tipoffs to such obfuscation are frequent mention of imprecise nouns, such as "capability" or "possibility," and use of the vague term "weapons usable."

Thousands of professional engineers and physicists in hundreds of nations have embraced nuclear power. Nuclear has had the best safety record of any major industry, irrespective of poor decisions and management at Chernobyl and in Japan. As indicated in the movie Pandora's Box, some prominent environmentalists have come to recognize benefits offered by nuclear power, especially the absence of air/ground/water pollution from particulates, ozone, aerosols, and CO2.

When President Jimmy Carter banned reprocessing of spent fuel, it was without French or British support. His decision had a politicized tone, and it's doubtful that it reduced international momentum for reprocessing. More than 1700 tons of civil plutonium have now been produced worldwide, much of it for recycle in reactors. MOX now comprises almost 5% of nuclear fuel in power reactors. It also provides a path for converting WGPu (from military sources) into commercial electricity.

Despite equivocations by former US weapon designers — such as Ted Taylor, Bob Selden, and Carson Mark — the military-arsenal requirement for high fissile fraction has been frequently reaffirmed. Mark told me directly that "You can't design around predetonation." Public literature advises that an arsenal-quality weapon requires small critical mass and low spontaneous-fission rate. That's also been acknowledged explicitly or implicitly by other weapon states: Arsenal-qualified weapons utilize only isotopically high-grade materials. As pointed out by a highly experienced former DOE Assistant Secretary, a "credible nuclear deterrent must have reliable, deliverable WEAPONS that can be stored safely and are ready to use."[5] Individuals or organizations who invoke the vague term "weapon-usable" instead of "weapon-grade" are being deliberately ambiguous.

Professional engineers and scientists in civilian or naval nuclear programs (or test and training reactors) routinely apply their nuclear experience and calculations to prevent accidental criticality, that is, to preclude explosive yields. Government and industrial installations have become highly proficient at understanding energy releases from super-critical masses.

During the highly publicized Progressive Case, around 1980, some secrets about nuclear weapons were deliberately or inadvertently placed in the public domain.[6] In addition, DOE officials pursued actions that drew attention to (or led to) disclosure of government-classified nuclear information regarding nuclear weapons and their design. Later, a detailed document was circulated about an unconsummated secret Swedish weaponization program that utilized only weapon-grade fissile materials.

In short, nuclear-weapons states have evidently based their projects on indigenous work and espionage, not on inferior materials. During World War II, Soviet scientists inferred the secret Manhattan Project's purpose, citing an analogy "the dogs that didn't bark." Because of the sudden wartime lapse in Western nuclear physics and engineering publications, the analogy made sense. But now, with globalized information, it's increasing difficult for any nation to clandestinely develop nuclear weapons without causing "dogs" to bark.

NUCLEAR EXPLOSIVES AND PROLIFERATION

DOE has repeatedly asserted that "Virtually any combination of plutonium isotopes ... can be used to make a nuclear weapon." Nevertheless, during WGPu production, deleterious Pu-238 and Pu-240 isotopes unavoidably accumulate, causing self-generated heat and neutrons. Without careful design and management, premature initiation would substantially reduce the potential explosive yield. Other complications can also be caused by excessive radiation and heat. Even so, a comparatively small (1kt) explosion would inflict terrible destruction within a radius roughly one-third of the Hiroshima zone. Indeed, a proliferating state or subnational group might theoretically be capable of inducing a destructive RGPu nuclear detonation using first-generation designs, materials, and technologies. But no weapon state has evidently introduced such unreliable devices into their arsenals.

Plutonium alone cannot be used in the simplest nuclear-weapon design ("gun type"): Potential proliferators with limited access to sophisticated technology would find enriched uranium to be a better choice than reactor plutonium. Either material can be used in a more sophisticated "implosion-type" device. In any event, according to former US weapons designers,[7] Achieving "the size and weight of a modern weapon while maintaining performance and confidence ... would require one or more full-scale nuclear tests...."

Nations have thus invested in WGPu rather than RGPu. For example, in the 1980s the US considered spending billions of dollars on a special isotope-separation facility to enrich RGPu; that funding magnitude attests to the disutility of low-quality plutonium. Another obstacle is increased complexity (in weapons design, fabrication, and deployment). It's highly unlikely that a rogue state or a sub-national group would be able to improvise an explosive using RGPu.

North Korea is the most recent nuclear-weapon state. Defying its NPT obligations, they probably produced WGPu in a "research" reactor. Uranium-enrichment facilities were also built. Beginning 2006, underground nuclear explosions in North Korea have been detected by international networks.

Iran in 1957 entered into an Atoms-for-Peace agreement with the US. Nearly a half-century later, Iran's uranium-enrichment facilities became subject to an IAEA inquiry that uncovered violations of NPT safeguards. The IAEA concluded in November 2011 that Iran likely had undertaken research and experiments geared to developing nuclear-weapon capability. Since then, comprehensive multilateral negotiations have been underway for an international inspection regime that would closely monitor agreed limits on Iran's nuclear program.

Iraq's only "research" reactor was destroyed in 1981 by an Israeli air strike just before fuel was loaded. Consequently, Iraq went underground with electromagnetic isotope separation of indigenous uranium. When war broke out in 1990, just a few separators had been installed, but clearly Iraq had violated NPT obligations. Subsequently its nuclear capacity was rendered harmless.

Israel's nuclear weaponization has chronically distorted international nonproliferation policy. Never having joined the international nonproliferation regime, Israel has apparently manufactured nuclear weapons with either passive or active support from other nations. WGPu could have been produced in their Dimona "research" reactor, which has never been opened to outsiders or to the IAEA.

Demilitarizing Plutonium *continued on page 10*

Pakistan, a fairly recent nuclear-weapon state, has tested long-range missiles. Its neighbor, India, has for many years had a vast indigenous program for nuclear power and weapons. Both nations have remained outside of international safeguards.

A book-length technical evaluation of safeguards and nonproliferation has been written by a retired leading scientist of the Karlsruhe Nuclear Research Center.[8] Also, a Russian group has conducted a thorough analysis.[9] Dr. Kessler's assessment shows that RGPu nuclear-explosive devices would be impaired by the high temperatures resulting from self-generated alpha decay and spontaneous fission. Kessler determined limits above which hypothetical nuclear weapons are not feasible on technical grounds, concluding that light-water-reactor plutonium with a burnup of 35 to 58 GWd/t cannot be used for making nuclear weapons. (Today's light-water reactors attain fuel consumption in excess of 50 GWd/t.)

Conflictive nonscientific views about plutonium weaponization have been publicized with publications and presentations that lack statistical boundaries. Such indifference to appropriate methodology weakens credibility. For example, Amory Lovins' heralded 1980 predictions about (1) nuclear-power's demise, (2) weapon-proliferation tendency, and (3) plutonium-demilitarization ineffectiveness are notably unfulfilled. Thirty-five years have passed since Nature and Foreign Affairs published his predictions, but those journals haven't felt obliged to print long-overdue corrections.[10]

CLOSING REMARKS

Nuclear proliferation has significantly slowed down — now much less than alarmists had predicted. Nearly a century has passed since the nuclear genie emerged — half a century since Nazi Germany and the US government became interested in uranium fission. The first critical reactor and first nuclear bombings occurred in the mid-1940s. The radiation age dates back longer.[11] Radiation hazards and proliferation potential are now better understood and significantly diminished.

Meanwhile, the world suffered frequent and consequential non-nuclear calamities: dams breached, mines caved in, air pollution increased, bridges collapsed, fuel-tank cars exploded, world and regional wars fought, infectious outbreaks spread, and humans starved.[12]

Thus, the perspective of time and context now validates some favorable observations, supported by preponderant evidence. No more than three or four dozen individuals have verifiably died in connection with civilian nuclear-power accidents. Mortality from conventional power sources (such as hydro, coal, and gas) far exceeds that of nuclear electricity. Meantime, reactors and nuclear controls have benefitted from a safety-conscious culture and from first-class weapon-design facilities.

Fissile materials, when rendered unsuitable for potential military use, can indeed be considered demilitarized. Demilitarization lastingly diminishes the risk of nuclear-weapon proliferation and any danger that sub-national groups or individuals might make nuclear explosives. Exaggeration of nuclear-proliferation risk is simply not justified.

Sensible and responsible nuclear policies include the extraction of usable energy and the reduction of waste: At least six nations have commercialized excess MOX, thus minimizing public expenditures, effectively turning "swords into plowshares." Uranium and plutonium demilitarization employ rather straightforward technologies with little technical risk. (Incidentally, destroying US chemical weapons is estimated to cost ~$35B — comparable to demilitarization of all nuclear-weapons.) As pointed out years ago, nuclear recycling is not going away; the choice now is simple: manage it poorly, or manage it carefully and safely.[13]

During the Cold War, more than 100,000 nuclear warheads were manufactured; the US recently disclosed that it still has 4,717 stockpiled weapons. Warhead demilitarization continues to be necessary and optimal for future arms control and nonproliferation, while recovering many billions of dollars in "sunk costs." ■

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Serving The Reich: The Struggle For The Soul Of Physics Under Hitler

By Philip Ball (University of Chicago Press, Chicago, 2014), ISBN 13:978-0-226-20457-4, ISBN 13:978-0-226-20460-4 (e-Book), 303 pgs. $30.00

This important book, first published in England in 2013 and made available in the United States by the University of Chicago Press in 2014, warrants careful reading by everyone who wants to understand the decisive implications of the discovery (more correctly, the identification) of uranium fission in Nazi Germany in 1939. Fission had been produced experimentally by Enrico Fermi and his colleagues in 1934 but was ascribed incorrectly to neutron capture by uranium- 238.

Most of the scientific information cited by the author is well known to physicists, but it's constructive for readers, especially physicists, to have the data integrated in this fascinating historical narrative. The main focus is not science but how science was subsequently handled by the scientists working for the authoritarian Nazi regime. Nearly every Nobel prize winner in physics and chemistry in the 20th century is mentioned along with many others including important scientists such as Lise Meitner, Robert Oppenheimer, and Otto Frisch.

One of the book's principal individuals is the Dutch scientist Peter Debye (1884-1966), 1936 Nobel laureate in Chemistry, director of Germany's Kaiser Wilhelm Institute of Physics from 1934 until leaving for the United States in January 1940. He was welcomed by Cornell University (Ithaca, New York) as a tenured professor in the Department of Chemistry, where he was honored with a bronze bust in the department entrance hall and where he remained for life. However, his prior elevated position under the Nazi regime came under controversial and negative scrutiny from several sources. One comment: "A Cornell chemist, a Nobel laureate, Roald Hoffman, who lost most of his Ukrainian Jewish family in the Holocaust ...said with respect to the bronze bust 'I would propose that it be moved where it belongs, into the faculty lounge'--the latter location obviously a delicate euphemism."

More negative to Debye's reputation was the opinion of the most prestigious of scientists, Albert Einstein (1879-1955) who had left Germany in 1933 after vicious anti-Semitic attacks by Nobel laureates Philipp Lenard (1905) and Johannes Stark (1919), early advocates of the Nazi movement. Ironically Einstein's Nobel prize in 1921 was for his quantum explanation of the photoelectric effect which had been experimentally studied and puzzled over by Lenard in prior years. Einstein's view of Debye's character as reported by the FBI says: "Einstein advised that he had not heard anything wrong concerning Debye but he knows the man well enough not to trust him; that he Einstein would accept the things as a scientist as being true but would not accept things that Debye says as a man as necessarily being true ...he said he believes Debye is not a person of high loyalty and will do anything for his own advantage ...."

This judgment appears to be supported by the fact that Debye never formally resigned as director of the Kaiser Wilhelm of Physics and seemed to keep the option of returning open in the event of a German victory. It is of interest that the same year (1936) that Debye won the Nobel prize for chemistry, that Victor Hess, the Austrian physicist who discovered what is later designated cosmic rays, won the Nobel prize in physics. After the Anschluss of 1938 which incorporated Austria into the Reich, Hess, a Jew, was arrested for refusing to accept Nazi rule. He immigrated to the United States where he became a distinguished member of the Fordham University faculty in New York City.

The book's second principle individual, addressed at length, is Max Planck (1858-1947), 1918 Nobel laureate, whose theoretical analysis of black body radiation must be regarded as the pioneering study which led to quantum mechanics. In an amusing footnote, the author writes: "it is sometimes said that Planck made two great discoveries--the second being Einstein."

Planck's personal life was marked by tragedy. One son was killed in the first World War. Two daughters-in-law died in childbirth. A second son was executed for joining the unsuccessful conspiracy to assassinate Hitler in 1943. That a person of such outstanding attributes of character, intellect, scientific accomplishment and morality could apparently tolerate living in equilibrium with the Nazi regime, which he opposed, is difficult to comprehend. Philip Ball's explanation is essentially that Planck rigidly obeyed government law--even grossly unjust Nazi law which he manifestly deplored. Such obedience was built into Planck's cultural perspective. Ball's hypothesis is plausible but hard to accept.

In April 1942 Werner Heisenberg (1901-1976), 1929 Nobel laureate, replaced Debye as the new director of the Kaiser Wilhelm Institute of Physics which had not had a formally designated head since Debye's leaving for the United States. In that capacity, he became titular leader of Germany's effort in the application of uranium fission research. According to Heisenberg and his defenders after the war, his effort was not directed toward making an atomic bomb but toward a failed effort to secure a uranium critical assembly leading to a nuclear reactor for generating electric power.

Quite a different view of Heisenberg's objective is reflected in a draft of a letter written by Niels Bohr to Heisenberg but never sent. It addresses Heisenberg's 1941 visit to Bohr's laboratory in Copenhagen in German occupied Denmark. Wrote Bohr: "It made a strong impression on both Marguerite (his wife) and me, and on everyone at the institute that you expressed your definite conviction that Germany would win and that it was therefore quite foolish for us to maintain the hope of a different outcome of the war and to be reticent as regards all German offers of cooperation. I also remember

Book Reviews *continued on page 12*

quite clearly our conversation in my room at the institute, where in vague terms, you spoke in a manner that could only give me the firm impression that, under your leadership, everything was being done in Germany to develop atomic weapons." Bohr added in another draft: "You informed me that it was your conviction that the war, if it lasted sufficiently long, would be decided with atomic weapons and I did not sense even the slightest hint that you, Heisenberg, and your friends were making efforts in another direction."

Despite his universal prestige, Bohr with a Jewish mother was always in considerable danger and in 1943, the Germans began the arrest of prominent Danish Jews who up until then had been relatively free from persecution. Bohr escaped Denmark and finally ended in Las Alamos at the end of the year. He said later: "They didn't need my help in making the bomb." However, Robert Oppenheimer who headed the scientific work at Las Alamos observed: "He made the enterprise seem hopeful."

As the war in Europe came to its conclusion, the principal German scientists either directly or thought to be associated with atomic bomb development were rounded up by the Americans and English. They were confined in a country house called Farm Hall in the town of Godmanchester. Among the ten scientists confined in Farm Hall were Heisenberg and Otto Hahn. It is somewhat surprising, coming from an all encompassing authoritarian political environment, that the group apparently did not suspect all their discussions and conversations were bugged by hidden microphones. Upon hearing of the atomic bombing of Hiroshima on the 6th of August 1945, Hahn who had received the Nobel prize in chemistry in 1944 for his pioneering work in uranium fission research, but had little connection with the Nazi atomic work, said to an unbelieving Heisenberg: "You're just second raters and you might as well pack up." Heisenberg at this point did not use his later prevarication that he and other German scientists were opposed to bomb making (unlike their inhumane and thoughtless American and English counterparts!) but replied: "All I can suggest is that some dilettante in America who knows very little about it had bluffed them in saying 'If you drop this, it has the equivalent of 20,000 tons of high explosives' and in reality doesn't work at all."

There is no question that the American success in securing the atomic bomb was in large measure the contribution of individuals like Enrico Fermi (who not Jewish himself, left Axis partner fascist Italy to not endanger his Jewish wife), Hans Bethe, Edward Teller and many others who escaped Nazi dominated Europe. Of course one must mention the famous letter of Einstein to President Roosevelt drafted by him, Leo Szilard and Teller which almost belatedly set the Manhattan Project in motion.

All Jewish physicists representing 25% of the profession in Germany were expelled, imprisoned (or worse). It is this reviewer's opinion, not explicitly stated by the author, that there is little question that the remaining German physicists would have been capable of developing the bomb. The myth that there was not adequate funding for the program is refuted by the author. He points out that the Peenemunde V-1, V-2 rocket program was comparable to the large cost of the Manhattan Project. The rockets killed 15,000 people in Britain and Belgium and something of the order of 20,000 slave laborers in the deplorable manufacturing process. In my opinion, Werner von Braun who headed the ghastly project does not deserve the adulation he still receives from many quarters because of his later help in the American space program. One wonders whether he should not have been called to account as a war criminal.

The detailed account given by Ball in this carefully researched work leads one to believe that Hitler's physicists could well have reached the fission bomb first and Nazi Germany could have prevailed in World War II with unspeakable consequences. ■

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