

PHYSICS & SOCIETY

A Publication of The Forum on Physics and Society A Forum of The American Physical Society

Note from the Editor

As I write this, spring has finally made an appearance after a long and cold winter here on the east coast. While a new season may be upon us, the debate over climate change is ever present. Whether it is a discussion related to a changing climate and public health, regulatory oversight of the coal industry, or a politician bringing a snowball onto the floor of the Senate, I would argue that as physicists we must be an active part of this conversation. With that in mind and, as I hope you already know, the APS is currently asking for our comments on the draft statement on “Earth’s Changing Climate.” The deadline to do so is May 6, 2015. Continuing the theme, we have in this issue a book review written by Joe Levinger of *Climate Change: What it Means for Us, Our Children, and Our Grandchildren*.

Also in the newspapers almost daily is the proposed accord with Iran and the ongoing threat of nuclear weapons. Our feature article in this issue is the first of a two part series by Alexander DeVolpi on “Demilitarizing Weapons Grade Plutonium.” Our second book review continues that theme with a review written by Cameron Reed of *Unmaking the Bomb: A Fissile Material Approach to Nuclear Disarmament and Nonproliferation*.

In the *News from the Forum* section, there is a summary written by our Past-Chair, Micah Lowenthal, of some of the

FPS-sponsored sessions at the March meeting. First we have one on “additive manufacturing,” the other on “artificial intelligence.” As a reminder, we are always looking for suggestions for session topics to sponsor so if you have an idea, information on who to contact can be found below. You will also find announcements on Fellowship nominations and for the Joseph A. Burton Forum Award and the Leo Szilard Lectureship Award.

Finally, one of the keys to the long-term health of the Forum is to have a constant influx of our younger colleagues — early-career scientists, graduate students and undergraduate students join in the activities of the Forum. Our presence online continues to grow thanks to our Social Media Editor Matthew Parsons. In this issue, Hannah Davinroy, a sophomore physics major at Princeton University interested in public policy has written an article on recent research results using a zero-knowledge protocol to detect nuclear weapons. If you know of a student or early-career scientist interested in our activities or you are one and would like to write for the newsletter, please contact me. I hope that we can have regular contributions from the next generation of physicists interested in the societal implications of our research. ■

—Andrew Zwicker
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PLEASE SUGGEST FPS INVITED SESSIONS FOR THE MARCH AND APRIL MEETINGS

FPS has several slots for invited sessions at the March 2016 and April 2016 meetings. If you have ideas for sessions (including speakers), or even better if you want to organize a session at one of the meetings, please contact FPS Program Chair (and FPS Chair-Elect) Ruth Howes, rhowes@bsu.edu. Decisions about sessions will be made in the early fall 2015, so please send in your ideas as early as you can.

PLEASE NOMINATE FELLOW AND AWARD CANDIDATES

FPS is responsible for nominating members for APS fellowship and for selecting candidates for the Joseph A. Burton Forum Award and the Leo Szilard Lectureship Award. The list of fellows and awardees is truly outstanding, but the only way that we can maintain this level of excellence and recognize deserving recipients is if you nominate them.

APS Fellowship

Any active APS member is eligible for nomination and election to Fellowship. The general criterion for election is exceptional contributions to the physics enterprise; e.g., outstanding physics research, important applications of physics, leadership in or service to physics, or significant contributions to physics

education. FPS nominates physicists for contributions in some aspect of physics and society. Fellowship is a distinct honor signifying recognition by one's professional peers.

<http://www.aps.org/programs/honors/fellowships/index.cfm>

*FPS Deadline for APS Fellowship Nomination:
Monday, June 1, 2015*

Joseph A. Burton Forum Award

To recognize outstanding contributions to the public understanding or resolution of issues involving the interface of physics and society.

<http://www.aps.org/units/fps/awards/burton.cfm>

Deadline: Tuesday, July 1, 2015

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.

<http://www.aps.org/units/fps/awards/szilard.cfm>

Deadline: Tuesday, July 1, 2015

Select talks from FPS sessions at the March 2015 APS Meeting

M.D. Lowenthal, Past-Chair of FPS

Artificial Intelligence: Existential Risk or Boon to Humanity?

March 4, 2015

STUART RUSSEL (UC Berkeley) said that artificial intelligence (AI) is about making computers intelligent, which means making them do the right thing, which means maximizing the expected utility. Why? AI developers usually say that we do it for its own value, and more is better, and there are no limits. Recently, there have been rapid advances in deep learning in speech, vision, and reinforcement learning; universal probability languages enable cross fields; long-term hierarchically structured behavior to address the billions of operations. We can no longer compete with machines in chess, poker, and 29 Atari video games like space invaders (learned by a computer

only from raw image data in a few hours). These methods have been applied successfully to nuclear explosion detection and identification. What if we do succeed? I.J. Good said that "the first ultraintelligent machine is the last invention humankind need ever make." An intelligence explosion takes place if AI itself can do AI research. It is crucial to get the objectives, values, and constraints right or the AI system will do incredibly well at solving the wrong or incomplete problem. A responsible approach could be to do research not in AI but in provably beneficial AI. One could try to seal the system away or limit its function to answering questions. Stepwise progress would be an adversarial approach with functional AI and superintelligent verifiers. The bottom line is that we need to give this thought now before the technology gets ahead of our ability to manage it.

Select Talks continued on page 3

GURUDUTH BANAVAR of IBM argued that developments in AI are going to be driven by social and economic values. The systems are made to meet needs and a business case must be made for each development. There have been major advances because of huge computing power, vast amounts of data, more powerful algorithms. For example, speech recognition error rates are getting to error rates in the range of human level performance. Watson's victory on Jeopardy! led to a whole new line of business at IBM on cognitive learning based on requests from health care, finance, travel and other sectors. They have developed debating technologies that examine articles (newspaper, review, and research) and relevant claims and assess probable useful arguments. In minutes, a computer extracts key arguments from four million articles. Similarly, computers can conduct image analysis and anomaly detection, such as a tumor in an ultrasound image leading to differential diagnosis and treatment recommendations. In short, Banavar said that we can create cognitive environments that enable people to be more effective.

GILL PRATT (DARPA) discussed the implications of cognitive computing and robotics for future defense systems. He began by noting that computers are capable of doing pattern matching and extrapolation for prediction, but asked whether that is thought. He argued that experts are modeling the brain, but we still know little about how it works. There has been progress on some of the challenges for which AI and robotics are well suited, but others remain stubbornly resistant to progress. Mobility of, for example bipedal robots, has improved to the point where a blind robot can have better balance than a human and can traverse complex terrain quickly and blindly better than humans. Autonomy has improved, but the capability is brittle and not adaptable. Looking at end uses, improvised explosive devices (IEDs) in Iraq and Afghanistan continue to be essentially as effective and harmful as they were 10 years ago, despite huge investment in robotics and sensors because of relatively simple improvements in the IEDs. At a more fundamental level, energy efficiency is a major challenge: human walking is very efficient (if terrain were flat, a human could walk from east coast to west coast without eating) and robots are 100 times worse. Human muscles are efficient because they are complex and adapt and distribute load to operate at the optimal efficiency. Neuromorphic chips are not faster than other processors, but they explore a territory of engineering tradeoffs inspired by neurons in the brain, which are optimized for energy (food is expensive) rather than simplicity (complexity in machines is expensive). Pratt identified opportunities for AI and robotics to address problems in climate change, health care, manufacturing, and a variety of others arenas. To do that, AI and robotics need to develop competency in unstructured environments, operate with intermittent communications (what do you do when the link breaks), surpass human performance, and reduce size, weight, and power demands.

BENJA FALLENSTEIN (Machine Intelligence Research Institute) said that smarter than human intelligence is not around the corner, but it probably will be and it is important to ensure that it is aligned with our interests. He asked, how do we specify beneficial goals and that systems actually pursue them, and how do we correct when we get it wrong?

He argued that we need a solid theoretical understanding of the problem and solution, using probability theory, decision theory, game theory, statistical learning, Bayesian networks, and formal verification.

Contemporary AI systems use simplified models of the world. If a goal is not specified perfectly for the environments in which the systems operate, then the outcomes can be very wrong. Fallenstein discussed the various probabilistic and theoretical approaches and their limitations, and he concludes that much work is still to be done before we can trust AI systems with smarter than human intelligence to act in what we would consider to be our interests.

Additive Manufacturing: Societal Impacts

March 5, 2015

MICHAEL CIMA (MIT) holds the first patent on 3d printing (1985). He gave an overview of additive manufacturing and the evolution of manufacturing methods, challenges that were encountered, and how they were overcome, such as inkjet printing of curves using a rastering print head. Additive manufacturing was thought of as a tool for design, "printing" the prototype, but businesses began to use it for small-run manufacturing, such as short-turnaround production of complicated engine manifolds for which the world demand is only a handful, but they are needed as soon as possible. Cima foresees that custom prototyping and printing services are more likely to take hold (they already exist) than a 3d printer in every home. He explained that some of the main remaining challenges have to do with materials, such as elastomeric polymers.

DAVID KEICHER of Sandia National Laboratories argued for the promise of printed electronics: it reduces the number of steps and gives you more flexibility with less tooling. Keicher listed different methods, from extrusion casting to direct-write printing using nanoparticles in an aerosol jet (SNL formulates a lot of its own nanoparticles of different materials). SNL uses "aerodynamic lenses" to focus printing make it less sensitive to pressure variations. These methods enable designers to create advanced tools for maintaining continuity of knowledge (ceramic tamper seals with simple continuity circuit built in) and other security-related missions.

Select Talks continued on page 4

PRABHJOT SINGH described GE's work using additive manufacturing, ranging from digital microprinting at 15-20 microns of ceramic metal to laser or electron-beam melting of metal in a powder bed. They have produced key parts of finished products, such as ultrasound transducers using printed piezoelectric transducer elements that are better than conventionally made elements, enabling designers to close in on 25MHz transducers, the "holy grail" of ultrasound. That said, even if additive manufacturing can be used, it must yield a net benefit in quality, time, and/or cost to be of interest to companies. GE made maternal fetal probes with additive technology that were not marketed because they offered no advantage over conventionally produced probes. A key advantage of additive technology was illustrated by new fuel nozzles for jet engines that previously were built by brazing 19-20 pieces together, but now can be made as a single integral part. Singh identified key needs, including sensors and non-destructive evaluation methods for certifying the quality of the pieces, ensuring that the process achieves the specified configurations and properties. Another challenge is to reduce the time required on three steps: design time; time on the manufacturing machine; and post-processing to achieve the right surface features and microstructure treatment.

BRUCE GOODWIN from Lawrence Livermore National Laboratory discussed how the combination of additive manufacturing and high-performance computing has the potential for enormous benefits to society but also latent disruptive impacts to national security. Additive manufacturing reduces waste and energy costs, relies on general purpose manufacturing equipment (rather than product-specific equipment), makes otherwise unbuildable technology, and reduces skill demand and factory footprint. Goodwin noted that a uranium processing machine in a 400sqft room replaces a one-mile long production line at Y12. It also enables durably transportable qualified CAD designs. All of this could make it much harder to detect proliferation of nuclear and other weapons (e.g., printing military grade high explosives). Uncertainty quantified high-performance computing can accelerate the engineering design cycle by an order of magnitude, and additive manufacturing can yield the same order of acceleration. Goodwin asks, So what's the problem? These tools take expertise out of the manufacturing and make the footprint small and hard to detect (small energy and material consumption and waste streams). Qualified digital build files are hard to control and contain everything you need to produce a working product. All of these factors could compromise trade sanctions. ■

POPA Ready to Hear from APS Membership on Climate Change Statement

By Tawanda W. Johnson, APS Press Secretary

During the week of April 6, APS members were sent an email with a link to a member website with the draft Statement on Earth's Changing Climate. The site enables every APS member to comment on the draft. APS members can also access the statement via this link: <http://apps3.aps.org/statements/statement.cfm> by using their APS Web username and password. The statement is not published in this article because it is not a public position of APS, and comments are only being collected via the APS website.

The draft statement is the result of a deliberative review of the APS Climate Change Statement (http://www.aps.org/policy/statements/07_1.cfm). The Panel on Public Affairs (POPA), which developed the draft statement, is eager to receive input from the Society's membership.

"We have taken great care throughout this process, including focusing on consensus building that has resulted in a solid, science-based statement," said William Barletta, POPA chair. "We now look forward to hearing from the Society's membership."

POPA began reviewing the APS Climate Change Statement and Climate Change Commentary in fall 2013, in accordance with APS policy that requires statements to be formally reviewed every five years. POPA then proposed a subcommittee to initiate the review, and the APS Board approved the charge to the Review Subcommittee.

As part of the process, the Review Subcommittee convened a workshop on Jan. 8, 2014, with six climate experts. "We used this meeting to delve deeply into aspects of the IPCC consensus view of the physical basis of climate science," said Barletta. "The Review Subcommittee's goal was to illuminate for itself, for the APS membership, and for the broader public both the certainties and boundaries of the current climate science understanding."

The Review Subcommittee presented the results of the workshop during the Feb. 7, 2014 POPA meeting. At POPA's meeting the following June 6, its Energy and Environment Subcommittee presented an initial draft of a new statement. POPA then began the process of finalizing a draft for consideration by the APS Board and Council. On Oct. 10, POPA reported out a draft of the statement.

The APS Council reviewed the statement in November. On Feb. 21, 2015, the Board voted unanimously to forward the statement to the APS membership. "APS members currently have the opportunity to ask questions about the process and submit comments about the statement. POPA will also update an online FAQ that members can access via the APS website," said Barletta.

Climate Change Statement continued on page 5

If you have questions about the process by which the statement was developed, you can submit them to: statements@aps.org. Although there will not be an opportunity to respond to every question individually, a list of Frequently Asked Questions will be updated on a regular basis and can be found via the following link: <http://www.aps.org/policy/statements/climate-review.cfm> along with additional resource material. The last opportunity to submit questions will be on April 29; the last update of the FAQs is scheduled for May 1.

The member comment period will close on May 6. Every APS member will have one opportunity to comment, and submissions are final. All the APS member comments will be reviewed by POPA, and the statement may be modified accordingly. The draft statement will then be presented to the Board and Council for discussion. If approved by the Council, the statement will become the official position of the APS.

EARTH'S CHANGING CLIMATE FAQs

Q: Why is APS revising its climate change statement?

A: The American Physical Society (APS) formally reviews its statements every five years. The APS Panel on Public Affairs (POPA) formed a subcommittee in fall 2013 to review its 2007 Climate Change Statement and 2010 Climate Change Commentary (http://www.aps.org/policy/statements/07_1.cfm). After reviewing the statement, commentary and recent scientific reports, POPA developed a single, concise statement on Earth's Changing Climate.

Q: Who wrote the statement?

A: The entire APS Panel on Public Affairs (POPA) membership was engaged in drafting the statement. The panel's membership as well as the charge to POPA and resource documents can be found on the APS Climate Change Statement review website: <http://www.aps.org/policy/statements/climate-review.cfm>

Q: What was the process to revise the statement?

A: A detailed description of the process is included in APS News and posted on the APS Climate Change Statement review website: (<http://www.aps.org/policy/statements/climate-review.cfm>) Briefly, the APS Panel on Public Affairs (POPA) adhered to the process outlined in the APS by-laws, starting with a standard review of the APS Climate Change Statement and Climate Change Commentary. Then, a POPA subcommittee convened a workshop to inform itself on aspects of the Intergovernmental Panel on Climate Change (IPCC) consensus view of the physical basis of climate science. That was followed by the drafting of a single, concise statement that was reviewed by POPA and the APS Council. The APS Board unanimously voted to send it to the membership for comment on Feb. 21, 2015.

Q: How does this draft statement compare to the 2007 statement and 2010 commentary?

A: In this draft statement on Earth's Changing Climate, APS "reiterates" its 2007 statement (http://www.aps.org/policy/statements/07_1.cfm) in stating that: the climate is changing, humans are contributing to climate change, and rising concentrations of greenhouse gases pose the risk of significant disruption around the globe. While there remain scientific challenges to our ability to observe, interpret and project climate change, APS continues to support actions – as it did in the 2007 statement – that reduce greenhouse gases and increase the resilience of society to climate change. A primary change is that the draft is succinct and does not require an associated commentary.

Q: What happens to the 2007 statement?

A: If the current draft is ultimately approved by the APS Council, it becomes the current position of the APS, and the 2007 statement is moved to the archive (<http://www.aps.org/policy/statements/archive.cfm>) on the APS Statement webpage.

Q: What will the APS do with the statement?

A: If the statement is approved, then the APS Council and Board will make a decision on whether to pursue any policy or outreach activities related to climate change. Those activities would be carried out by the Panel on Public Affairs (POPA) and the Physics Policy Committee (PPC).

Q: What is the status of this statement on Earth's Changing Climate?

A: The APS Statement on Earth's Changing Climate is a draft. The development of an APS statement is a deliberative process. During the last year, consistent with APS by-laws, the APS Panel on Public Affairs (POPA) developed the draft, the Council provided commentary on the draft, and the APS Board voted unanimously to forward the statement to the APS membership. All APS members now have an opportunity to review the statement and provide input during a 30-day comment period. The comments will be reviewed by POPA, and the statement may be modified accordingly. The statement will then be presented to the APS Board and APS Council for discussion. If approved by the Council, the statement will become the official position of the APS.

Q: Why is APS qualified to comment on the science of climate change?

A: A number of issues associated with climate change are fundamental physics topics, including the connection between greenhouse gas increases and warming, radiative transfer, spectroscopy, thermodynamics and energy balance. In addition, climate change is an area of interest for many APS members, including the more than 500 APS members who are in the APS Topical Group on the Physics of Climate. ■

Demilitarizing Weapon-Grade Plutonium: Part I

Alexander DeVolpi

REDUCING RISK OF NUCLEAR PROLIFERATION

Ongoing multinational demilitarization of stockpiled nuclear weapons has been reducing proliferation risk and offsetting those government expenditures that result from conversion (demilitarization) of uranium and plutonium to non-weapon-grade.

All together, ten nations (US, USSR, G.B., France, China, India, Pakistan, Israel, South Africa, and North Korea) have militarized nuclear materials. Several other nations once made technical inquiries into nuclear weaponization. There are now 9 nuclear-weapons states and 185 non-nuclear-weapon states.

As of mid-January 2015, 439 nuclear power plant units with an installed net electric capacity of about 377 GW are in operation in 31 countries. Under construction are 69 nuclear plants with an installed capacity of 66 GW in 16 countries. In addition there are numerous maritime reactors, as well as education, testing, and development reactors — perhaps 1000 in operation or standby, and others under construction or planned.

THE VALUE OF DEMILITARIZED PLUTONIUM

Civilian nuclear-power reactors are burning up weapons plutonium (and uranium), helping reduce federal budget expenses. In addition, the fissile demilitarization sequence provides enormous public value in terms of nuclear arms reduction and nonproliferation. Many billions of taxpayer dollars can be recovered from commercial sales of fissionable materials no longer needed for weapons.

This forum for *Physics and Society* has witnessed a half-century of ongoing discourse about issues dealing with the theoretical potential for making nuclear explosives out of “weapon-grade” plutonium.¹

Strongly inclined against weaponization of reactor-grade plutonium are a number of factors, such as fundamental nuclear physics and engineering calculations, supported by experimental data and public information. It is well understood that low-enrichment grades of uranium also do not constitute the fissile core of nuclear weapons because they would become heavy, unwieldy devices.

Nine countries altogether now possess about 16,000 nuclear weapons, reduced significantly since the peak of the Cold War. Both the US and Russia each still maintain roughly 1,800 of their nuclear weapons on high-alert status — ready to be launched for long-range attack within minutes of a warning. Most of the weapons are many times more powerful than the devastating atomic bombs dropped on Japan in 1945.

The failure of Cold-War powers to further reduce their

devastating arsenals had evidently incentivized a couple of other countries to acquire nuclear weapons. However, the rate of proliferation has indeed flattened out since North Korea independently developed nuclear-weapon technology.

WEAPONIZABILITY OF REACTOR-GRADE PLUTONIUM

A long-exercised dispute about “weaponizability” of reactor-grade plutonium revolves about semantic differences (see Part II, to be published in the next issue of *Physics and Society*). My own periodic reassessments since the late 1970s indicate that nuclear-source material qualifies only for a nuclear weapon if it can be manufactured, field-tested, and produced for the nation’s military arsenal. Nuclear materials of inferior quality are effectively demilitarized: They have not been usable in military-quality weapons.

The Cold-Warrior nations, by mutual agreement, have found it in their interest to reduce nuclear-weapon arsenals and to demilitarize stockpiles of fissile materials. Nuclear warheads in arsenals have turned out to be devices subject to precise and carefully managed explosive qualification for predetermined yield and reliability. Weapon-grade plutonium is typically about 93% Pu-239. Lacking confirmation is the allegation that lower-quality “reactor-grade plutonium” could be weaponized. That any military arsenal that would contain “poor” quality fissile material is far-fetched: Anything less than premium fissile material is unlikely to be utilized.

Regarding weaponization of “reactor-grade plutonium,” the US DOE (AEC/ERDA) has equivocated for nearly a half-century.² The explosive yield of a 1962 test in Nevada still remains secret; however, a great number of other test yields and details have been declassified. One must now consider the 1962 explosive to have been very low and disappointing from the viewpoint of weaponization.

In any event, all nuclear-weapon states are universally understood to have gone to the trouble and expense of producing weapon-quality fissile components in their arsenals. As for other scenarios using low-grade plutonium, some speculation includes radiation-dispersal devices with limited burst range. Remaining essential are national and internationalized nuclear treaties, safeguards, inspections, and surveillance on all radiative materials.

DEMILITARIZING URANIUM AND PLUTONIUM

A 15-year Megatons-to-Megawatts US-USSR program for demilitarizing 500 tonnes of weapon-grade uranium

Demilitarizing continued on page 7

(HEU) has proven to be an on-schedule winner — in mutual arms control, economics, and non-proliferation. About 20,000 Soviet nuclear warheads have been effectively converted to civilian reactor use, fueling half of our nuclear-power plants, which produce as much as 10% of US electricity. The program has readily paid for its federal budget outlays, and it has been reducing national and international nuclear risk (a swords-into-plowshares paradigm).

Under a subsequent bilateral agreement, the US and Russia were to dispose of surplus weapon plutonium from approximately 17,000 nuclear warheads. When operational, a mixed-oxide (MOX) conversion facility will be capable of turning 3.5 metric tons/yr of weapon plutonium and uranium into civilian-use fuel assemblies.

MOX is a blend of plutonium and natural uranium or depleted uranium which behaves similarly (though not identically) to the enriched uranium feed for which most nuclear reactors were designed. MOX is an alternative to low enriched uranium (LEU) fuel used in the light water reactors that predominate in international nuclear-power generation. MOX also provides a means of using excess weapon-grade plutonium (from military sources) to produce electricity

In the wholesale market, 34 tonnes of converted weapon plutonium might eventually fetch as much as \$3B, equivalent to \$30B in taxable retail sales in the United States. Even if costs did inflate for the 60+%-completed South Carolina MOX facility, there are multiple ancillary national and international benefits of plutonium conversion (to reactor fuel).

As long as the US carries out its previously negotiated treaty reduction, the RF is now on track to convert a matching amount of weapon plutonium into peacetime nuclear energy. That would correspond to irreversible reduction of ~10,000 US nuclear weapons. The plutonium is to be permanently diluted, irradiated, and rendered unusable for future weapons use. Relevant experience has been gained in Europe for burnup of both reactor and weapon plutonium.

Demilitarization, denaturing, and degradation are terms applicable to fissile materials rendered unsuitable for use in military-quality weapons. For practical purposes, extensively irradiated reactor-grade uranium and plutonium are effectively demilitarized, despite Jimmy Carter's unwarranted 1977 ban on US reprocessing. The unilateral decision had essentially no influence overseas.

DEMILITARIZATION THROUGH MOX BURNUP

The US has three times more weapon-grade plutonium in its national nuclear-weapon inventory than now needed, as well as much weapon-grade uranium. To move toward irreversible nuclear disengagement, both the US and Russia could continue their leadership, irreversibly demilitarizing weapon-grade fissile inventories.

Demilitarization of weapon plutonium gains other substantial benefits, reducing risk of international proliferation and nuclear terrorism. Burnup adds physical, chemical,

radiological, and isotopic barriers that reduce accessibility and utility. Once converted to MOX, reactor fuel is no longer usable in nuclear weapons, a technical proposition never contradicted by specific nuclear-test data.

No other proposed demilitarization technology has proven to be as effective and beneficial as conversion to and burnup of MOX. Earlier suggestions and inquiries into vitrification and/or burial did not withstand critical analysis.

US (and some overseas) reactors routinely consume weapons uranium that has been downblended to reactor grade, as well as some weapon plutonium converted to MOX. The industrial technology for demilitarizing weapon-grade materials is well established. For degrading fissile materials removed from nuclear weapons, commercial reactor burnup provides a means that is technologically realistic, proliferation secure, economically viable, and militarily irreversible. Using a rough estimate of 2000 tonnes HEU and 260 tonnes plutonium remaining in the world, demilitarization and utilization might net tens of billions of dollars on the open market.

MEGATONS TO MEGAWATT CONVERSION

The US-RF MOX conversion program would help both nations comply with international obligations toward worldwide reciprocal nuclear disarmament under Article VI of the Nuclear Non-Proliferation Treaty. Such a move would present a commendable example for other weapon states — the UK, China, and France.

Russia, Britain, and France have commercialized their excess MOX, so they don't necessarily have to draw upon substantial government subsidies. Demilitarization is a rather straightforward technology that has little technical risk, although environmental restrictions might indeed artificially elevate its cost. An early-generation reprocessing plant was built for extracting plutonium from spent fuel in the UK's atomic weapons program, partly under a US-UK Mutual Defence Agreement. It operated from 1951 until 1964, with an annual capacity of 750 tonnes of low-burn-up fuel. From 1971 to 2001 more than 35,000 tonnes were reprocessed.

THE "SPENT FUEL STANDARD" — PLUTONIUM ACCESSIBILITY

Four primary factors affect the theoretical usefulness of civilian spent fuel as a potential weapon material: (1) intense radioactivity of fission products (which decay with time); (2) the need for chemical separation of plutonium from fuel (which must be done by remotely operated equipment); (3) the isotopic composition of the plutonium (reactor-grade being less desirable material than weapon-grade); and (4) the difficulty of acquiring plutonium if the party in question does not already have spent fuel in its possession. Overcoming these factors depends on resources of the state or group trying to do so.

Demilitarizing continued on page 8

A goal of US plutonium disposition is to achieve the “Spent Fuel Standard” — that is, to make excess weapons plutonium as inaccessible and unattractive as is the much larger quantity of plutonium in commercial spent fuel. This raises two obvious questions: How difficult is it to recover plutonium from commercial spent fuel and use it in weapons, and how do the various proposed forms for plutonium disposition compare in this respect?

The difficulty of recovering plutonium from spent fuel or other disposition depends on resources of the state or group seeking to recover it. A weapon state with large reprocessing plants available, for example, could use those facilities to recover plutonium from spent fuel with relatively little difficulty. They could theoretically fabricate weapons from that plutonium: Time, cost, visibility, and effectiveness would be the principal complications. At the other end of the capability spectrum, a subnational group would need to accomplish several tasks: steal spent fuel without being caught, build a facility for chemically separating plutonium from the spent fuel without being detected, carry out hazardous processing without being stymied by unexpected difficulties, and then produce a nuclear weapon without prior experience.

Official DOE releases² have acknowledged increased complexity and cost in “designing, fabricating, and handling” nuclear-weapons made with reactor-grade plutonium. DOE statements also affirm that nations must be “willing to make large investments ... to acquire weapon-grade rather than reactor-grade plutonium.” However, lower-grade plutonium has long been available to many nations in large quantities for essentially no additional production cost. The DOE statement thus implicitly acknowledges that being “willing” has less to do than “ineffectiveness” of such hypothetical nuclear-explosive devices.

Although specific explosive yield data has been published for a great many nuclear-explosive tests, no such information has been provided on the 1962 test yield, despite the informative value it would have. Disregarding many calls for release of this clarifying data, its absence unavoidably hints that the test yield from the so-called reactor-grade explosion might have been disappointingly low.

In the absence of any nuclear-weapon state publicly declaring that it has made warheads with anything less than weapon-grade plutonium (and/or uranium), it must be concluded that reactor-grade plutonium is still not a viable choice for military-quality nuclear weapons.

Although reactor-grade plutonium requires safeguards and protection to the same standards as weapon-grade plutonium, disposing of excess plutonium through reactor burnup meets the “Spent Fuel Standard,” sufficient for non-proliferation goals. Burning surplus plutonium as MOX fuel in nuclear reactors is technically secure and economically advantageous. ■

— Alexander DeVolpi, retired reactor physicist from Argonne National Laboratory, Fellow APS

ENDNOTES

- 1 E.g.: (a) *Physics Today*, January 2015, page 9, referring to an article published July 2014, page 24; *Physics Today*, November 2010; (b) oftentimes in the pages of *Arms Control Today*; (c) in the peer-reviewed pages of *Ann. Rev. Nucl. Part. Sci.*, 36 83 (1986); (d) also, “Denaturing Fissile Materials,” invited review paper, *Progr. in Nucl. Energy* 10, 161-219 (1982); and (e) in my 3-volume book *Nuclear Insights: the Cold War Legacy*, Amazon.com (2009).
- 2 “DOE Facts Additional Information Concerning Underground Nuclear Weapon Test of Reactor-grade Plutonium,” US DOE, Office of Public Affairs, Contact: Sam Grizzle. (Also, “Nonproliferation and Arms Control Assessment of Weapons-Usable Fissile Material Storage and Excess Plutonium Disposition Alternatives,” U.S. Department of Energy report DOE NN-0007 (Jan. 1977).

A Zero-Knowledge Protocol for Nuclear Warhead Verification

Hannah Davinroy

INTRODUCTION

In times of an uncertain nuclear future, with the intersection of advancing technology for nuclear energy in the midst of a slew of diplomatic tensions, the questions of nuclear non-proliferation is as important as ever. Since the emergence of nuclear technology in the 1930s through the thaw of Cold War tensions in the 1990s, global politics have played a great role in the monitoring of nuclear technology. National governments and state-sponsored research laboratories remain necessarily guarded of their top-secret technology. In the 1990s, questions of verification and inspection during disarmament became more prominent. Many agree that while a “global-zero” might not be possible in terms of total operational nuclear warheads, a number in the hundreds per nuclear nation is realistic. The limitation of total deployed strategic warheads has been explored in disarmament deals like the New START Treaty ratified by President Obama and Russian Prime Minister Dmitry Medvedev in 2010. This disarmament, which requires a reduction in the total number of deployed strategic warheads, depends on the ability of each nuclear country – and even non-nuclear nations – to monitor the status of warheads as they remain deployed, are stored, or enter the dismantlement queue.

STATUS QUO VERIFICATION AND THE DESIRE FOR A ZERO-KNOWLEDGE SYSTEM

The creation of a verification system is both technologically very difficult and politically even more so. No country wants its nuclear secrets to be leaked. Though the current system of counting the number of deployed strategic warheads does not allow for the escape of any national secrets, this status quo method cannot provide an exact number without a significant uncertainty. In a game where an underestimation could cause catastrophic loss, the development of a new protocol is much desired. Alex Glaser – professor in Princeton’s Woodrow Wilson School of Public Policy, Boaz Barak – Principal Researcher at Microsoft New England, and Rob Goldston – former director of Princeton Plasma Physics Laboratory and professor of astrophysics at Princeton, have done just this. Scrutinizing the problem of verification without revealing secret technology, Glaser, Boaz, and Goldston apply the idea of zero-knowledge proof to the confirmation of disarmament. During a time with nuclear non-proliferation and inspection in the news every day and the framework of a US-Iran agreement being developed, Glaser and Goldston were enthusiastic to sit down and talk about the future of a zero-knowledge verification protocol.

The process includes the creation of a fingerprint, almost a reverse x-ray, of the contents of the test object – potentially a nuclear warhead. The test objects are then subjected to trans-

mission of a preloaded known number of 14MeV neutrons. The initial fingerprint, as created by the host, is then compared with the transmission pattern to confirm that the test objects are identical. Indeed, if multiple tests are run simultaneously and the fingerprints are randomized to the transmission pattern of the test object, the probability that they are not identical falls even more. Though in theory the noise of a transmission pattern could reveal information about the contents of the test object, Goldston points out, “With neutrons, you’re not going to get an exact number; you’re going to get statistically uncertain numbers so that the signal carries no information and the noise carries no information.”

The advantage of a technology that not only doesn’t reveal any sensitive information but also *does not measure the sensitive information in the first place* is obvious. Citing the possibility for verification methods to backfire and instead cause nuclear proliferation, Goldston says, “What we don’t want is the inspectors from the IAEA [International Atomic Energy Agency] to learn what the warheads consist of.” Not only would sensitive information give countries a stronger arsenal but indeed a stronger understanding of how to prepare countermeasures against a nuclear attack.

This zero-knowledge approach also creates a disincentive for countries to deceive the inspector. The falsification of a template or the use of non-identical test objects would put the host at serious risk. Glaser weighs in, “Built in there is a certain deterrent to cheat, because very likely, if I cheat, something is going to show up on the x-ray then the inspector will learn something. I may get away with it once, but over time it will fail, and that’s counterproductive because you have revealed the secret to the inspector.”

MAJOR ISSUE IF A SYSTEM IS DEVELOPED UNDER THE FRAMEWORK

With the proposed zero-knowledge method put forth by Goldston and Glaser, though it addresses the issue of doctoring both the fingerprints submitted by the host and the test objects, the issue of mistrust and concealed technologies remain. The way the method is proposed, the host will provide the verification system to the inspector. Glaser elaborated, “The bottom line is that electronics are very hard to authenticate to make sure that this electronic piece of equipment is doing what it is supposed to do. The problem is that the host, whoever owns the warhead, will insist that the electronic that is being used is his own.” The inspector must then have a very high level of trust that the system itself has not been falsified to give positive identification of a warhead when it was not a warhead, or vice versa. Though this poses a serious obstacle to the adoption of the zero-knowledge system, Goldston

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believes that international cooperation in the development of the technologies will overcome this. He says, “There’s a lot of argument that says we should work together, and they should see what we’re thinking about so when the [inspection system] arrives, they know what it’s supposed to be, they can inspect it and see that it really is what it’s supposed to be. And if it’s a relatively simple thing and everyone has developed it together than that will be an easier process.”

WHAT IS HAPPENING WITH ZERO-KNOWLEDGE TODAY

Though Glaser, Boaz, and Goldston have been refining their idea and addressing some of the loopholes, there has been relatively little progress – or really need for progress – since the publication of their paper, “A zero-knowledge protocol for nuclear warhead verification” in *Nature* in June 2014. “In the army they’re always saying, ‘Hurry Up and Wait,’” Goldston says, “For this it’s ‘Wait and Hurry Up.’ There’s enough money to play with the idea now, but suddenly the politicians will jump in and say, ‘What have you got?’”

For now, the goal is to continue to ready the research for application. Even after receiving a five-year grant from the National Nuclear Security Administration of the U.S. Department of Energy, the process is slow. “We’ve got enough money to do a very good proof of principle on how well this works, and we also know we won’t be taking our system and attaching it to a real, deployed warhead in the next five years, though there is the possibility that we could work with some special materials. The goal at the end of five years is to have done enough prototyping that you could start to build a real one.” Glaser was even more pessimistic about the creation of a workable prototype of their envisioned system, though more hopeful about a general zero-knowledge method, “For me it’s about injecting some new momentum and new ideas, maintaining some of the knowledge and hopefully generating some new knowledge.”

One of these areas of new knowledge is the emergence of non-electronic zero-knowledge methods. In particular, a non-electronic detector would create less opportunity of tampering by the host. Such technologies as superheated emulsions, or ‘bubbles’ could be arranged in a microscopic matrix in order to measure transmission patterns instead of electronic, and possibly faulty, detectors.

Though Goldston and Glaser make a strong argument for their zero-knowledge methods, the adoption of such verification processes will take many iterations and quite a long time. In the global context of uncertain national security, countries are paranoid, and as Goldston aptly put it, “Being fooled is high stakes.”

ADDITIONAL INFORMATION ON ZERO-KNOWLEDGE PROTOCOL

“Science on a Saturday” – General public talk on Zero-Knowledge Protocol given by Rob Goldston at the Princeton Plasma Physics Laboratory on Feb. 28, 2015.

Link: <http://www.pppl.gov/events/zero-knowledge-arms-control-proving-warhead-real-while-learning-nothing-about-it>

Glaser, Alexander, Boaz Barak, and Robert J. Goldston. “A Zero-Knowledge Protocol for Nuclear Warhead Verification.” *Nature* 510 (June 2014): 497. ■

Hannah Davinroy is a physics major at Princeton University. She plans to pursue a career in science policy, using her background in physics to tackle today’s national and international challenge. She believes that in times of an uncertain future with climate change, technological warfare, and threats to global health, policy makers with a background in science and scientists who dedicate themselves to furthering society are invaluable.

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

by Harold A. Feiveson, Alexander Glaser, Zia Mian, and Frank N. von Hippel (Cambridge, MA, The MIT Press, 2014) ISBN 978-0262027748 (hardcover), \$24.

All nuclear weapons require fissile materials – plutonium and/or highly-enriched uranium (HEU) – to function. As many of the world’s nuclear powers reduce their stockpiles of weapons, an issue that will come to the fore is that of securing and eventually disposing of the global supply of excess fissile materials. This book describes the history, production, current stockpiles, and uses of fissile materials, and sets out possible policies for reducing and eventually eliminating them. The centerpiece policy is a proposed Fissile Materials Cutoff Treaty (FMCT), which the authors argue would also complement nonproliferation efforts.

The authors of this volume are well-qualified to address the dangers posed by nuclear materials. All of them are associated with the Woodrow Wilson School of Public and International Affairs at Princeton University, and have between them decades of experience with the science and politics of nuclear weapons and fissile materials. All are also founders of the International Panel on Fissile Materials, an organization through which scholars and diplomats work to inform their governments of the dangers of fissile materials.

The book is fairly compact. Its roughly 185 pages of text include a preface, introductory chapter, and nine other chapters distributed in three sections titled *How the Nuclear World Emerged*, *Breaking the Nuclear Energy-Weapons Link*, and *Eliminating Fissile Materials*. An additional 90 pages offer appendices detailing the current global inventory of enrichment and nuclear fuel-reprocessing plants, extensive notes, glossary, bibliography, and a comprehensive index.

The introduction offers an overview of the fissile materials situation. For weapons alone the world’s nuclear powers collectively produced over 2,000 metric tons (MT) of HEU and about 250 MT of Pu. In addition to weapons materials there are supplies of HEU in civilian and military research and naval reactors, as well as some 260 MT of plutonium that have been separated from spent civilian power-reactor fuel rods. The present stockpile of weapons-useable fissile materials amounts to about 1,900 tons, enough for over 100,000 nuclear weapons.

Chapter 2 supplies background material: a survey of the discovery of nuclear fission, the concept of critical mass, techniques for enriching uranium and synthesizing plutonium, reactor designs, the dangers of spent reactor fuel, fission and fusion bombs, and the proliferation danger posed by reactor-grade plutonium and centrifuge technologies. This will be familiar ground to readers of nuclear history, but I did learn one fact: that the global inventory of separated weapons-useable neptunium could be on the order of a ton!

Chapter 3 reviews the history of HEU and plutonium production in every country that ever possessed nuclear weapons. The largest producers were the United States (about 960 MT total) and Russia (~1,400), but quantities on the order of tens of tons were also produced by the “smaller” nuclear powers. This chapter also reviews the various routes by which nuclear technology and expertise have spread since Hiroshima and Nagasaki. In addition to espionage and inter-governmental exchanges for either development of weapons or “peaceful” trade, much proliferation can be traced to President Eisenhower’s “Atoms for Peace” initiative which distributed reactors fueled with HEU to a number of nations. Chapter 4 offers a sort of executive abstract of Chapter 3, summarizing stocks of fissile material by country and intended use. As of the end of 2012 global stockpiles of HEU and separated plutonium amounted to about 1,380 and 490 tons, respectively. There are, however, significant uncertainties in these numbers (equivalent to several thousand weapons) as only the non-weapons states are required to report material holdings to the IAEA and allow verification visits. The authors stress the need for more detailed declarations of materials and independent analyses of the operating history of production facilities.

Section II explores the connections between fissile materials, nuclear power, and nuclear proliferation. As remarked above, “Atoms for Peace”-type programs prompted much “latent” proliferation: dozens of countries now have available the technology, materials, and expertise to make nuclear weapons if they decided to. The authors advocate eliminating HEU and plutonium from civilian fuel cycles and phasing out spent-fuel reprocessing. More controversial will be their notion that countries may have to give up some control of nuclear technologies in favor of a regime in which nuclear power is generated by “a globally agreed set of rules that apply equally to all states.” However, they leave unstated what sort of overseeing agency would be involved.

Chapters 6 and 7 examine separated plutonium and HEU. The approximately 260 tons of “civilian” plutonium is the legacy of fuel-reprocessing efforts initiated in anticipation of breeder-reactor programs. But the growth of nuclear power has been less dramatic than predicted 40 years ago, and estimates of recoverable uranium ores have grown substantially; breeders and reprocessing are now no more economical than once-through fuel cycles. The case of HEU is trickier because of the spectrum of venues involved and the enormous investments in existing systems. Numerous civilian research reactors utilize HEU; there are also medical-isotope production reactors, reactors for testing new core designs, and high-neutron-flux reactors for testing weapons components. In many of these installations the HEU fuel can be replaced with “high-density” low-enriched uranium (LEU) fuel, but a particular concern is naval-propulsion reactors: both the U.S. and Britain use “lifetime core” designs intended to operate for 30-40 years without refueling. The Department of Energy has

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indicated that a shift to LEU might eventually be practical, but this would be a decades-long conversion involving future generations of vessels.

Section III moves the discussion into the political arena. Chapter 8 explores the possible scope and verification requirements of a FMCT. The UN General Assembly has agreed to a resolution calling for banning fissile production for nuclear weapons, but discussions have been blocked by Pakistan. In theory, a FMCT would prohibit production of fissile materials for weapons and enrichment of uranium except under safeguards, prohibit separation of plutonium, and require the decommissioning or conversion to civilian use of military fissile materials production plants. Verification procedures could be based on existing IAEA protocols along with “managed access” to military facilities to monitor for clandestine diversion of materials to weapons use.

Chapter 9 examines disposal scenarios for fissile materials. For HEU the most sensible option is down-blending into fuel for power reactors as exemplified by a U.S. program to purchase 500 tons of excess Russian HEU which was down-blended to LEU and sold to American utilities. Separated plutonium can be mixed with depleted uranium oxide to form mixed-oxide fuel (MOX), but MOX fabrication plants have been plagued by cost overruns and poor production records. The best approach for Pu may be burial in deep (~ 5 km) sealed-off boreholes. A striking statistic is that even if they were to retain 5,000 operational warheads each, the U.S. and Russia could respectively declare as excess roughly one-half and three-quarters of their weapons materials.

In their summary and conclusions, the authors urge all countries possessing fissile materials to cap and reduce civilian and military stockpiles and to approach regulation as if the world is preparing for nuclear disarmament. One striking statement: “In time, a decision might be made to forgo nuclear power entirely;” however, the authors offer no comments on the attendant issues of cost, environmental impact, and resource consumption.

Overall, the authors convinced me that the world's stockpile of fissile material is adequate to supply civilian and military needs well into the future and that no more needs to be produced. But I am skeptical that a FMCT would meaningfully complement arms-reduction efforts. The nuclear powers can recycle weapons materials into new warheads for decades to come. The U.S. and Russia are reducing their numbers of deployed warheads, but military planning still includes nuclear postures. Life-extension and weapons-platform programs carry huge budgets, political clout, and bureaucratic inertia.

The world took decades and trillions of dollars to get into its current fissile-materials situation, and will take more decades, more trillions, and a very different international environment to get this genie back into the bottle. But we have to try, and a FMCT would be a strong place to start. This book should be read and carefully considered by every serious student of the world nuclear situation. ■

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Climate Change: What it Means for Us, Our Children, and Our Grandchildren

Edited by Joseph F. C. DiMento and Pamela Doughman, MIT Press, Cambridge MA, Second Edition 2014, 343 pages.

Mark Twain said “Everyone talks about the weather, but nobody does anything about it.” I look back over the past two centuries of the industrial revolution, during which we poured huge quantities of carbon dioxide and other greenhouse gases into the atmosphere, and think “we are doing something about the weather—we’re making it worse!” But my retort misses the important distinction, made in the Introduction by DiMento and Doughman. They carefully distinguish between day to day “weather” and its average over a long time, called “climate.” Weather fluctuates and cannot be predicted accurately for weeks into the future. Climate changes gradually and, they argue, can be predicted.

Almost two centuries ago Fourier asked why Earth’s average temperature is 15oC, far above the freezing -18oC expected from the balance between solar radiation we receive and energy radiated by Earth (Chapter 2). Fourier’s answer to his question was the “greenhouse effect.” He also coined that expression. Since Fourier’s work the greenhouse effect has intensified: Carbon dioxide in our atmosphere has doubled from about 200 parts per million to the current 400 ppm. The authors point out the huge greenhouse effect on Venus, and contrast it with the negligible greenhouse effect on Mars.

In Chapter 4 Naomi Oreskes—a professor in the history of science and author of the well-known book *Merchants of Doubt*—discusses in detail “The Scientific Consensus on Climate Change: How Do We Know We’re Not Wrong.” I found her careful analysis convincing. All experts on our climate agree that our temperature has increased some 1oC, caused by a doubling of carbon dioxide, with further increases in temperature and in carbon dioxide anticipated. Among the serious effects are severe flooding and storm surges.

Let’s modernize Mark Twain’s epigram to read “Everyone talks about climate change, but nobody does anything about it.” In Chapter 5 DiMento and Doughman tell us about the multitude of international conferences in the last third of a century, with no binding agreements. Why have we failed? How can we reach agreements between industrialized countries which have polluted the atmosphere and underdeveloped countries striving to catch up. There has been some progress, by a few countries and in some states. In the U.S., California and New York have indeed “done something about it.” As I write this review, I hear on PBS that the U.S. and China just agreed to do something about climate change.

This book is a good survey of greenhouse gas production, and resulting problems of climate change. My one objection is that it omits one significant source of greenhouse gases: the rapid increase in population. The industrial revolution led both to an increase in the per capita production of greenhouse gases, and to an increase the number of people. Both must be controlled. ■

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