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From the Editor

We have in this issue two more articles in the series, started in July, written by recent Forum invited speakers and award recipients. These are the articles by Laura Grego and by Edwin Lyman. We are also announcing in this issue the recipients of two Forum awards. I hope to have articles written by these award winners in a forthcoming issue.

We have also an article by Alvin Sapperstein on a recent controversy concerning peer review which has recently been aired in "The Economist". I expect there will be more discussion of this issue as the European Community is moving towards making open access mandatory. What will that do to quality control?

We have also several Letters to the Editor, and two book reviews.

Our new media editor, Tabitha Coulter is in the process of organizing and updating the media presence of the newsletter. A news item on her activities is included.

This is your newsletter. We are dependent on contributions from our membership and their friends. I have a very broad definition of what is pertinent to "Physics & Society" and not at all afraid of publishing on unusual or controversial topics.

Oriol

Oriol T. Valls, the current P&S newsletter editor, is a Condensed Matter theorist.

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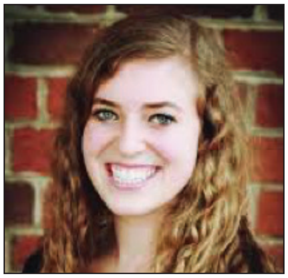
IN THIS ISSUE

FORUM NEWS

OUR MEDIA PRESENCE

Want a more interactive experience? We now have a blog and our own Facebook Page. Feel free to use them. They are not moderated, so please be careful and maintain a polite tone. However, as in the text Newsletter, do not shy away from controversial topics or opinions.



Tabitha Coulter, Media Editor

Head over to our new blog physicsandsocietyforum.wordpress.com or Facebook page @APSPhysicsAndSociety to share specific articles, leave comments, or post your own interesting physics and society stories! We're hoping to use these platforms to keep a more constant online presence, so please send any photos, event blurbs, media clips, interesting lectures and conferences.

For any other feedback and ideas on enhancing our media presence, contact our media editor at tabithacolter@gmail.com.

FORUM AWARDS

We are very pleased and proud to announce the new winners of Forum awards. They are

Zia Mian, Leo Szilard Lectureship Award

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For promoting global peace and nuclear disarmament particularly in South Asia, through academic research, public speaking, technical and popular writing and organizing efforts to ban the bomb.

Shirley Jackson, Joseph A. Burton Forum Award

jackson@rpi.edu

For distinguished application of her knowledge of physics to public service and increasing diversity in physics as Chair of the Nuclear Regulatory Commission, president of Rensselaer Polytechnic Institute and service on many government, charitable and corporate boards and committees.

LETTERS

Light Speed Day

Chemists celebrate Mole Day annually on October 23 from 6:02 AM to 6:02 PM in honor of Avogadro's number (6.02 x $10^{23)}$, which is a basic measuring unit in chemistry. 10/^{23} from 6:02 AM to 6:02 PM corresponds to 6.02 * 10^{23}.

Mathematicians celebrate e-Day annually on February 7 in recognition of the frequently used mathematical constant e, which is equal to 2.718. February 7 expressed numerically as 2/7 looks similar to 2.7. Also, mathematicians celebrate Pi Day annually on March 14 to commemorate the frequently used mathematical constant π, which is equal to 3.1416. March 14 expressed numerically as 3/14 looks similar to 3.14.

I propose that Light Speed Day be celebrated annually on October 8 from 3:00 AM to 3:00 PM to commemorate the frequently used constant for speed of light in a vacuum, $c = 3 * 10^8$ m/s. 10/8 from 3:00 AM to 3:00 PM corresponds to 3 * 10^8 m/s. This uses the same date and time format as Mole Day.

The intent of Light Speed Day is to give physicists something to celebrate and increase awareness of physics concepts among the general public. The constant c is not only the speed of light in a vacuum, but the maximum speed at which conventional matter and all known forms of information can travel in the universe according to special relativity. Although c is commonly associated with the speed of light in a vacuum, it is also the speed at which all massless particles and changes of the associated fields travel in a vacuum. The constant c interrelates space and time in the general and special theories of relativity and is used in the equation of mass-energy equivalence.

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Dear Editor:

In the July 2018 issue of the Forum, there was a very interesting article on the transformation to sustainable energy by Yeh. However there is one other carbon free sustainable option which I have been researching for 20 years, fusion breeding. A fast neutron reactor can breed fuel for a thermal reactor, but its breeding rate is low. It would take two fission breeders, at maximum breeding rate, to fuel a single light water reactor (LWR) of equal power. A fusion breeder could potentially breed about 10 times a much fuel, so a single fusion breeder could fuel many LWR's of equal power.

The nuclear cycle could be closed by by using a fast neutron reactor such as the Integral Fast Reactor (IFR) to burn the actinide wastes of a large number of thermal reactors of equal power.

I have written a review article on the subject, available open access, in the. fusion literature. It is:

Fusion Breeding for Midcentury Sustainable Power
Wallace Manheimer
Journal of Fusion Energy June 2014 (open access) vol 33, p 199

While I have come from the plasma side of the house, I have attempted to learn the necessary nuclear engineering to give at least a cursory view of the entire system. Figure 15 of the review article shows a schematic of "The Energy Park", the basic building block for a sustainable, carbon free energy infrastructure, which is economically and environmentally viable and has little of no proliferation risk.

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ARTICLES

ADVANCED REACTORS: PROLIFERATION AND TERRORISM CONCERNS

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INTRODUCTION

The workhorse of the commercial nuclear power fleet in the United States and most other nations is the light-water reactor. Over the last few years there has been renewed interest in reactors that use coolants other than water. Such reactors—often referred to as "advanced" despite the ancient vintage of many of the concepts—include liquid-metal-cooled, gas-cooled, and molten-salt-cooled designs. Articles frequently appear in the popular press lauding the next generation of nuclear power plants and the bold startup companies that hope to bring them to market. Think tanks, lawmakers, and the Energy Department have put forward optimistic visions of the role that non-light water-cooled reactors could play in mitigating climate change and addressing the nuclear waste disposal problem. Some private companies hope to deploy their first units by the late 2020s, and the Energy Department hopes to build its own liquid metal-cooled fast spectrum reactor by 2025.

However, there has been little discussion of the impacts of commercial deployment of these reactors on the risks of nuclear proliferation and terrorism. Many designs would use high-assay low enriched uranium (HALEU). Some would require nuclear weapon-usable materials such as uranium-233 (U-233), plutonium and other actinides. And most advanced reactor fuel cycles involve reprocessing—that is, chemical processing of spent nuclear fuel to extract re-usable nuclear materials. While some fuel cycles are of greater concern than others, all would introduce significant challenges for safeguards and security. For instance, although HALEU is not considered a direct-use nuclear weapon material, it has a higher security classification than lower-enrichment grades of LEU. This has not been a major problem to date because worldwide demand for HALEU has been limited. Detailed analysis is needed of the security implications of building a global infrastructure for production, transport, storage, and processing of large quantities of HALEU. Also, the difficulty of protecting and accurately accounting for the large flows of weapon-usable materials that would be separated by reprocessing plants in these schemes, both at and away from reactor sites, should be assessed. Some issues of concern are discussed below.

HIGH-ASSAY LOW ENRICHED URANIUM (HALEU): SECURITY AND SAFEGUARDS

Many of the advanced reactor designs being discussed today would use HALEU, with enrichments greater than 5% and less than 20% uranium-235 (U-235), instead of the highly enriched uranium (HEU) or mixtures of plutonium and uranium that such designs would have used in the past. HALEU would be necessary to provide sufficient fuel reactivity and allow for extended fuel burnups. Proposed reactors that would use HALEU of varying enrichments include the Oklo fast reactor (2 MWe); the ThorCon thermal molten salt reactor (250 MWe per module); and the X-Energy pebble-bed high temperature gas-cooled reactor (75 MWe per module).

The amount of HALEU that a large power reactor would require is huge compared to current supply and demand. For example, a 4-module, 1000 MWe ThorCon plant would require about 9.5 metric tons (MT) of 19.5%-enriched HALEU for the initial cores, and a supply of 3.8 MT per year.[1] In contrast, current worldwide demand for U.S-origin HALEU is around 1.5 MT per year, and the excess HEU stockpile that the DOE has designated to be blended down to meet that demand will be exhausted by 2040.[2]. Additional ways for the DOE to obtain HEU from existing stockpiles for blending down to HALEU, such as a plan to build a facility at the Idaho National Laboratory to recover HEU from irradiated naval reactor fuel, are speculative at this point. In 2015, the DOE assessed this option would be "very high cost" and "very high risk."[3] Assuming there is only about 30 MT of 19.5%-enriched HALEU equivalent (1.5 MT x 20) remaining, a 1000 MWe ThorCon plant would consume the entire amount in less than six years.

Other proposed advanced reactors would also require tons of HALEU per year. X-Energy, said to have a thermal efficiency of 38%, would use 15.5% enriched uranium at a burnup of 163,000 megawatt-days per metric ton heavy metal (MWd/MTHM), and that a 7-gram pebble would generate 27.4 MW-hours of thermal energy. Thus a 1000 MWe (2632 MWth) X-Energy plant would require 841,500 pebbles containing 5.9 MT of HALEU per year. And although there is little public information about the Oklo 2 MWe design, a similar reactor concept, the Los Alamos "Megapower" reactor, would use 2.6 metric tons of HALEU for a 5-year core lifetime, which works out to 260 metric tons per GWe-year.

Thus the HALEU demand for a reasonably sized fleet of advanced reactors such as ThorCon or X-Energy could easily be two orders of magnitude greater than the current supply rate, exceeding what could be obtained from additional HEU downblending and requiring new production. An industrial-scale HALEU fuel cycle to support conversion, enrichment, fabrication, transportation, waste management, and (hopefully) disposal would need to be built from scratch. And if the U.S. moves forward with commercialization of HALEU-fueled advanced reactors, U.S. companies may seek to export them, and the rest of the world may pursue their own programs. In light of this, it is essential to evaluate the risks of a greatly expanded civil use of this material, both in the U.S. and worldwide.

What are the proliferation and terrorism risks of commerce in HALEU? With regard to the former, there is no formal distinction between high-and low-assay LEU in IAEA safeguards. The IAEA classifies all LEU, including HALEU, as "indirect use material," and the agency's goals for timely detection of diversion are the same as for lower-assay LEU.

Nevertheless, the additional proliferation risk of stockpiling HALEU has been recognized by the international community. Under the November 2013 Joint Plan of Action, Iran committed to voluntarily reduce its inventory of 20% (actually, "up to 20%") enriched LEU to only what was needed for "working stock" for its research reactor, and to temporarily not enrich above 5%; measures that were strengthened in the July 2015 Joint Comprehensive Plan of Action (JCPOA). These agreements have created a new de facto safeguards category for HALEU that acknowledges its potential for reducing the time to acquire a nuclear weapon, at least for a country that possesses uranium enrichment facilities.

And the security sector appreciated the risks of HALEU long before that. The categorization table in INFCIRC/225, the IAEA's recommendations for protecting nuclear materials from terrorist theft, classifies 10 kilograms of U-235 contained in LEU enriched to 10% U-235 or above (sometimes referred to as "intermediate-enriched") as Category II, the second most sensitive security category. In contrast, any quantity of LEU under 10% U-235 enrichment is classified as less sensitive Category III material. This 10% enrichment threshold was present in all revisions of INFCIRC/225 going back to Rev.1 in 1975.

In 1979, the U.S. Nuclear Regulatory Commission (NRC) amended its regulations to impose physical protection requirements on Category II and III material (which it called "special nuclear material of moderate and low strategic significance," respectively). In doing so, it largely adopted the INFCIRC/225/Rev.1 categorization table, and in particular preserved the Category II threshold of 10 kilograms for intermediate-enriched LEU.[1] The NRC's rationale for the amendments was both to enhance "domestic protection of such materials…" and to demonstrate "U.S. willingness to accept international security standards."[2] [4] The NRC pointed out that [5]

> "In regard to … LEU … clandestine enrichment to higher levels may go beyond the capability of subnational terrorists, but it does not go beyond the capability of other governments.

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[1] The NRC did not adopt the INFCIRC/225/Rev. 1 recommendations entirely. While the IAEA recommendations were "designed to minimize the possibilities of theft of SNM of moderate or low strategic significance," the NRC's amendments were "primarily designed to require early detection of theft of SNM of moderate or low strategic significance," a weaker standard [4].

[2] In fact, the IAEA categorization table was likely developed with significant input by experts from the U.S. Atomic Energy Commission (the NRC's predecessor) in the late 1960s. It is not clear why the AEC/NRC did not incorporate the table directly into their regulations instead of doing it indirectly by helping to develop and later adopting an international standard.

> Unless properly safeguarded, low enriched uranium could be stolen on behalf of foreign governments and enriched to explosive useable levels after it is smuggled out of the U.S."

Thus the threat the rule sought to address was a subnational group with state support.

However, the Statement of Considerations for the rule did not explain why it treated HALEU differently depending on whether it contained more or less than 10% U-235. The obvious reason is that fewer separative work units (SWU) would be needed to produce HEU from the more enriched material. According to a U.S. government official, the thinking was that it was "much easier" to use the material with U-235 > 10%, but that was at a time when enrichment was "a bit slower" than today. More elaboration on this point was provided in a 1998 paper by Forsberg:[6]

"Uranium-235 with enrichments between 10 and 20 wt % are not weapons-usable, but could be converted to weapons-usable materials with a relatively small uranium-enrichment plant. The complexity of these enrichment plants is such that this could not be accomplished by a subnational group, but it could be accomplished by many countries. The third category is uranium enriched to <10 wt % U-235 but above natural enrichment (0.71 wt % U-235). To convert this material to weapons-usable material, a substantial uranium-enrichment plant would be required. Such a plant would involve massive resources and would be very difficult to hide."

But how important is this distinction in today's threat environment? The difference in the quantity of SWU needed to produce enough HEU for a weapon doesn't appear that significant. The goal of the NRC's security regulations is to prevent theft of a "formula" quantity of strategic special nuclear material (e.g. HEU or plutonium), or to deter theft of smaller amounts that could be combined to form one formula quantity. Production of one formula quantity of 90% enriched HEU (about 5.5 kilograms) starting from 5% enriched LEU feed would require about three times more SWU than using 19.75% enriched feed, and 1.7 times more than using 10% enriched feed. This may be a significant difference for a gaseous diffusion plant, but it is not necessarily one for a modern gas centrifuge plant.

Nevertheless, the NRC staff maintains that the 10% threshold is still relevant. In the January 2015 final regulatory basis for a proposed rule on "enhanced security for special nuclear material," the staff proposed strengthening security on LEU enriched to 10% or above because it believed that "greater oversight is required," based on risk insights developed since the 9/11 terrorist attacks. One may read into this statement the NRC staff's judgment that the capabilities of subnational groups to enrich uranium have increased—either with state assistance or independently.

But even that assumption doesn't fully explain the 10% threshold. If enrichment by subnational groups is more plausible today, then lower assay grades of LEU would also need greater protection.

One way to look at this is to posit that if terrorists actually were able to develop a "quick and dirty" enrichment capability, they would seek to build the smallest possible centrifuge cascade and thus would want to obtain the most highly enriched feedstock available. (The underlying assumption is that if adversaries had access to a large enough enrichment capacity, their preference would be to use natural uranium feed.) According to Glaser, the smallest practical first-generation cascade would have 60 centrifuges at 2 SWU per year each and a total capacity of 10 SWU per month, for a total of 120 SWU per year.[7]

At 120 SWU/year, adversaries' options for enrichment would be limited. But they could produce one formula quantity of weapons-grade HEU (> 90% U-235) in one year starting with uranium enriched at 15%, the midpoint of the 10-20% range, assuming a 0.5% tails assay (characteristic of early nuclear weapons programs). In contrast, 270 SWU would be required to achieve the same goal with 5% enriched feed. Similarly,120 SWU could be used to produce one formula quantity of 40% enriched HEU from 10% enriched feed, whereas 220 SWU would be needed if 5% enriched feed were used. Therefore, a requirement for additional physical protection for intermediate-enrichment LEU is consistent with its potential for enrichment to a formula quantity of HEU within one year using a minimally capable centrifuge plant.

In addition to requiring additional physical protection measures for intermediate-enriched HALEU, the NRC also imposes more rigorous material control and accounting measures. However, as mentioned above, this is not the case for IAEA safeguards. The fact that the IAEA regards all LEU as

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. Articles are not peer reviewed.*** 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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equivalent with respect to safeguards, yet recommends different security measures for LEU with enrichments below and above 10%, seems to be an inconsistency.

If the production and civil use of HALEU is to be greatly expanded, these inconsistencies need to be resolved. If intermediate-enriched HALEU requires more stringent measures than lower-assay LEU, then it warrants more rigorous safeguards as well. U.S. government agencies and the IAEA should take a hard look at the safeguards implications of a commercial HALEU fuel cycle in view of contemporary adversary capabilities, and adjust their requirements and recommendations accordingly. The IAEA should consider a smaller significant quantity (perhaps 50 kg instead of 75 kg) and a shorter timeliness detection goal (perhaps 6 months instead of one year) for HALEU with U-235 10% or greater. But such radical changes are nearly impossible at the IAEA. Short of that, the IAEA could consider separate tracking of HALEU production and use, similar to its approach for the "alternate nuclear material" neptunium-237, at least until agreement could be reached on more stringent measures. The U.S. could also impose stricter requirements on HALEU material accountancy and control in countries subject to 123 agreements for nuclear cooperation.

Another criterion relevant to proliferation is the quantity of SWU required to generate a unit of electricity at reactors that use HALEU. In general, the fewer SWU needed to support civil nuclear power, the better for nonproliferation. Transitioning to a fuel cycle that requires less enrichment could reduce the need for construction of new enrichment capacity around the world. However, many advanced reactor designs are not optimized for more efficient utilization of enrichment services. For example, a 1000 MWe light-water reactor with a 60-year lifetime would require about 150,000 SWU/GWe-year on average. In comparison, consider the ThorCon plant, which would use an average of 5 MT of 19.5% enriched HALEU per year (taking into account the initial core load and the eight-year lifetime of the reactor). Production of this fuel would use 200,000 SWU/GWe-year on average, or 33% more SWU/GWe-yr than an LWR. And an Oklo-type fast reactor would require a whopping 10 million SWU/GWe-yr. This is going in the wrong direction.

There is one potential application of HALEU in advanced reactors that could be beneficial for nonproliferation: its use as a driver fuel in once-through "breed and burn" reactors, such as the TerraPower "traveling-wave" reactor.[3] In theory, such reactors could use uranium more efficiently in a once-through cycle by increasing the internal conversion of U-238 to Pu-239, and subsequent fission of Pu-239, without the need to reprocess and recycle spent fuel. However, such reactors would need fuels able to achieve very high burnups. Higher-enriched fuels such as HALEU would be needed for high-burnup driver fuel at startup (and until the system attained an equilibrium state where it could operate only on depleted uranium feed). If such systems were possible, they could reduce the quantity of SWU needed per GW-year. For example, TerraPower estimates the lifetime-averaged separative work for its reactor would be 30,000 SWU per GWe-yr, about 20% of that required for an LWR.[8] Unfortunately, major technical obstacles remain, including the development of fuel materials that can safely withstand very high burnups.

HALEU: THE RADIOLOGICAL WEAPON THREAT

Apart from its attractiveness for a nuclear weapons program, HALEU also presents a radiological threat because it could be used to construct a stealthy and potentially devastating radiological emission device (RED). This danger was highlighted by a September 1999 criticality accident at the JCO uranium conversion plant in Tokai-mura, Japan. The accident was caused when workers, circumventing nuclear criticality controls, poured 16.6 kilograms of 18.8% enriched uranyl nitrate solution (containing just over 3 kilograms of U-235) into a precipitation tank which had a batch limit of only 2.4 kilograms of total uranium of that enrichment. The tank, with a diameter of 45 centimeters and a height of 60 centimeters, was surrounded by a cooling jacket through which water was circulated. The error turned the precipitation tank into a critical aqueous solution nuclear reactor, the cooling jacket serving as both a neutron reflector and a heat removal mechanism. After a number of high-power pulses, the system attained a steady state at a power of around 1 kilowatt-thermal and ran for nearly twenty hours before personnel were able to fully drain the cooling jacket and render the reactor subcritical.

The accident exposed three workers in the immediate vicinity of the tank to doses of 3, 10, and 17 Sieverts (Sv). The two most highly exposed workers received lethal doses (e.g. exceeding about 4 Sv) and eventually succumbed to acute radiation syndrome. But the unshielded reactor also generated steady-state neutron and gamma radiation fields that combined were more than ten times background (3 μSv/hr) at 750 meters from the reactor. At 50 meters from the reactor, the neutron dose rate was 10 mSv/hr, and the gamma dose rate about ten times lower. But the brief initial pulse was one thousand times more intense, resulting in a dose rate that must have been on the order of 10 Sv/hr at 50 meters and 3 mSv/hr at 750 meters.

Although this was an unfortunate accident, the concern is that it could be deliberately reproduced by an adversary in possession of a quantity of HALEU on the order of kilograms. The IAEA rightly observed that "from a nuclear engineering point of view, the water-cooled tank system was a very

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[3] .Although TerraPower continues to refer to this reactor as a "traveling-wave reactor," that is a misnomer. The design was changed several years ago to what would be more accurately called a "standing-wave reactor."

simple system."[9] In fact, the solution reactor concept is so simple that it was the basis for the third and fourth nuclear reactors ever built, the 1943 and 1944 "water boilers" at Los Alamos, which used 14%-enriched uranium. With beryllium and graphite reflectors, the critical mass was as low as 565 grams of U-235 (4 kg of total uranium).

And while the off-site radiological consequences of the JCO accident were limited, the reactor itself was far from an optimized system. A higher power steady state could have been achieved with less nuclear material and a greater heat removal rate than the natural circulation in the cooling jacket provided. Historical "water boilers" were designed to operate at powers as high as 50 kW-thermal with only 5 kg of uranium enriched to 12.5%. Such an assembly, placed in a refrigerated truck with gamma shielding, and parked on a city street, might not be detected for days or longer, by which time tens of thousands of people could have been exposed to extremely high radiation levels.

The threat posed by such a scenario should be considered in developing appropriate physical protection measures for the commercial use of HALEU. Given the relatively small quantities of HALEU that could be used to fuel a critical system, it may be warranted to reduce the Category II lower limit of 10 kg U-235 for HALEU with 10% or greater U-235.

ADVANCED REACTORS, REPROCESSING, AND WEAPON-USABLE FUELS

Many advanced reactor designers assert that their systems would be capable of "consuming" spent fuel from light-water reactors and recycling their own nuclear waste. These features have become a major selling point for the public and for many on Capitol Hill. But vendors and their supporters rarely explain what such operations would entail: reprocessing and fabrication of plutonium and other transuranic elements into fresh fuel. They avoid discussing the safety and environmental risks of these processes, not to mention the security risks associated with large-scale plutonium separation and widespread deployment of plutonium-fueled reactors. And even though the approaches needed to adequately safeguard and protect these reactors and their fuel cycles have not even been defined for the most part, there is a major push to deploy advanced reactors within the next decade both in the United States and abroad.

For example, a number of liquid metal-cooled fast reactor developers are pursuing construction of test or demonstration units. In the U.S., Oklo began pre-licensing discussions with the NRC in 2016. Also, the DOE has $35 million in FY 2018 funding to begin studies of the "Versatile Test Reactor," a 300 MWe sodium-cooled fast reactor. And several U.S. vendors are seeking to build plants in Canada, which is becoming a sort of Cayman Islands for off-shoring advanced nuclear plants because of a widespread (but probably unjustified) belief they will be easier to license there. For example, the company Advanced Reactor Concepts recently announced a collaboration with New Brunswick Power to explore "the potential future deployment of the ARC-100," a 100 MWe sodium-cooled fast reactor, "at NB Power's Point Lepreau nuclear plant site and thereafter at other sites in Canada and worldwide."[10]

Although little is publicly known about these three projects, they are all metal-fueled fast reactors modeled after the defunct Experimental Breeder Reactor-II (EBR-II). And all apparently intend to use plutonium and other transuranic-based fuels at some point. Although Oklo initially plans to use HALEU, CEO Jacob DeWitte testified before Congress in July 2017 that

> "…our reactor can actually consume the used fuel from today's reactors as well as the depleted uranium stockpiles around the nation. In fact, fast reactors like ours could power the world for over 500 years with the global inventory of used fuel and depleted uranium. Our reactors can also assist with plutonium disposition by consuming excess cold war era materials and turning them into clean, peaceful energy."

Also, the DOE has chosen a metallic alloy of plutonium and 5% enriched LEU fuel as the preferred baseline for the Versatile Test Reactor.[11] And the ARC-100 would reportedly use HALEU, for its initial core, but after a 20-year cycle would send the spent fuel for pyroprocessing (a type of non-aqueous reprocessing) to extract plutonium and other transuranics for fabrication into fresh fuel.

Why is this a problem? Aside from the proliferation and terrorism risks associated with reprocessing and plutonium fuel fabrication facilities, DeWitte also testified that Oklo hopes to sell its "microreactor" to "remote and rural communities." Similarly sized heat pipe-cooled fast reactors require about 2.5 MT of fuel enriched to about twenty percent; thus each reactor could require several hundred kilograms of plutonium.[12] Who is going to provide the necessary security, and at what cost? And how will the material be safeguarded against diversion? In non-nuclear weapon states, verification of plutonium-fueled reactors widely dispersed throughout remote communities, such as the Arctic, could prove an enormous burden for the IAEA.

One may wonder why so many advanced reactor startups emphasize reprocessing and spent fuel recycling. It may be a legacy of message testing that dates back to the Global Nuclear Energy Partnership (GNEP) era, when the DOE had proposed a global system for supplying fresh fuel and reprocessing spent fuel. In 2006, Bisconti Research was commissioned by Idaho National Laboratory to do focus group testing for GNEP communications.[13] The study found that the top message to emerge from the focus group was "With GNEP, the U.S. joins other nations recycling fuel and will recycle valuable fuel to produce energy and simplify waste management."

But reprocessing and spent fuel recycling are not essential for many types of advanced reactors, including liquid metal-cooled fast reactors, which can operate on HALEU fuel on a once-through cycle. For molten salt reactors, however, on-line processing of the liquid fuel is inescapable. At a minimum, gaseous and noble metal fission products have to be continuously removed. And in order to achieve high burnups, neutron-absorbing fission products would also need to be periodically extracted from the fuel. The difficulties in developing material accounting methods for the required on-site reprocessing plants are obvious and widely appreciated in the technical community.

To illustrate those challenges, consider the Transatomic Power (TAP, which ceased operations very recently) molten fluoride salt reactor. The TAP reactor is a 520 MWe spectral-shift reactor, fueled by LEU. During the first part of its 29-year operating cycle, an intermediate-energy neutron spectrum promotes conversion of U-238 to plutonium. In the second part of the cycle, a thermal spectrum promotes fission of the plutonium that has built up in the core. Consequently, the plutonium content of the molten salt rises steadily to a peak of about 4 MT after 20 years of operation, after which it slowly decreases to about 3 MT at shutdown.[14] In order to achieve a 29-year lifetime, the fuel must be processed to remove neutron-absorbing rare earth fission products on an approximately 50-day cycle, or 7.3 cycles per year. When the core plutonium content is at its peak, the plutonium throughput of the processing system would be about 29 metric tons per year for a 520 MWe reactor. This is an enormous flow of plutonium given such a small reactor. In comparison, the peak throughput of a large commercial reprocessing plant is around 8 MT of plutonium per year, which corresponds to the annual spent fuel discharges from about forty 1000 MWe LWRs.

Because there is so little known about this reactor and the required fuel processing system, not much can be said specifically about it. It is not even known if the process is feasible or even possible. However, it is difficult to see how an effective safeguards approach based on material accountancy could be developed for this reactor. There is little information available about important factors for material accountancy, such as uncertainties in core inventory calculations, separation efficiencies, waste streams, and process holdup (material stuck in the system). In 2014, a review article pointed out that "acquisition of fundamental data for the extraction processes is still needed especially for the actinide-rare earth fission products separation."[15] Subsequently, experimental work on separating uranium and neodymium from molten fluoride salt found only "low" extraction efficiencies, calling into question the current processing approach.[16] Even if a process loss rate of 0.1% per year could be achieved, which would be remarkable, this would correspond to more than one significant quantity of plutonium (8 kilograms) going into waste every year. How will this material be measured?

One approach for safeguarding such facilities would be to greatly reduce reliance on material accountancy and to rely instead on containment and surveillance (C/S) and process monitoring, as has been proposed for fast reactor fuel pyroprocessing plants. But these alternative measures have inherent limitations and are unable to provide the same level of confidence as material accountancy. A shift in philosophy by the IAEA to accept such measures as substitutes for material accountancy would be a step in the wrong direction, ultimately increasing the risk of proliferation. The IAEA should hold its ground and not accept weaker safeguards standards for facilities that may well be unsafeguardable in practice. Also, in addition to its impact on international safeguards, the inability to conduct timely material accountancy would hamper the ability of state authorities to rapidly assess the validity of theft allegations. If someone were to call in a threat, claiming to have diverted enough plutonium for a bomb from a processing facility, it could take weeks or longer to establish whether material was actually missing.

In summary, the threats of nuclear proliferation and nuclear terrorism must be primary considerations in charting the future course of nuclear energy. New nuclear technologies should only be deployed only if they can be effectively safeguarded from nuclear material diversion and protected against theft. To this end, the U.S. should make all advanced reactor and fuel cycle demonstration facilities, such as the Versatile Test Reactor, eligible for IAEA safeguards, and engage the IAEA on developing safeguards during the facility design phase. Congress should also ensure that all demonstration reactors on DOE sites be subject to NRC licensing, so that the NRC can develop methods for oversight of material accounting and physical protection at advanced reactors and fuel cycle facilities.

Development of once-through breed-and-burn reactors that could increase uranium utilization and reduce the need for enrichment would undercut the major rationales for reprocessing and plutonium recycling, helping to further nonproliferation goals. However, such reactors present many technical challenges. At present, the LWR operating on a once-through cycle still appears to be the least risky option for future nuclear power deployment.

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Space-based Missile Defense: Still Unwise

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Congress, in the fiscal year 2019 National Defense Authorization Act, [] has directed the Pentagon to develop a space-based boost phase missile defense system, whether or not the administration's as-yet-unreleased Missile Defense Review endorses the concept. This defense would be regionally-focused, with a proposed live-fire intercept test during fiscal year 2022. No money has yet been appropriated to carry out these plans.

The aim is to build a constellation of defensive weapons in space to intercept long-range missiles in their "boost phase," the first three to five minutes of launch, while their engines are burning. Destroying the missile in boost phase provides an advantage—it catches the missile before it can release decoys and other countermeasures that greatly complicate intercepting during the subsequent midcourse phase, when the missile's warhead is coasting through the vacuum of space.

Boost-phase defense is also an enormous technical challenge. Because launch is short, the defense must be close enough to the launch site to reach the missile quickly. Because North Korea's geography—a relatively compact peninsula—allows for the possibility of hosting defenses on its periphery, proposals for boost phase defenses have included putting interceptors or lasers on ships, [] drones, or airplanes. [] This is the motivation for putting missile defense satellites in low Earth orbits—with altitudes of a few hundred kilometers—that periodically pass over the missile's launch site.

The concept of a space-based missile defense has a long history. While the Reagan-era concepts were abandoned as technically unworkable and too expensive, proponents have continued to advocate for space-based missile defense, most recently a constellation of orbiting kinetic interceptors or lasers.

The Pentagon itself has not asked for money for such a program since the late 2000s and Pentagon officials have repeatedly voiced doubt that it would be useful or cost-effective. The Pentagon Vice Admiral James Syring, then-director of the Missile Defense Agency, said as much when he testified before the House Armed Services Committee in 2016. [] "I have serious concerns about the technical feasibility of interceptors in space," he said, "and I have serious concerns about the long-term affordability of a program like that."

This judgement is in line with the best publicly available technical advice. In 2005, the American Physical Society conducted an in-depth study of boost phase missile defense and concluded that space based missile defense would be extremely costly. [] In its 2012 study, the National Academy of Sciences and Engineering drew on this work and agreed, concluding that a space-based boost-phase missile defense would cost 10 times more than any terrestrial alternative, and a system providing an austere capability to defend against a few North Korean missiles, a constellation of 600 interceptors costing on order of $300 billion would be required. []

While such a system would rank among the most expensive military projects ever attempted, the most serious issue isn't the cost—it's the fragility. The system would be vulnerable to being overwhelmed by the salvo launch of several missiles. Doubling the number of missiles that the system could deal with would require doubling the size of the system. []

Since the interceptors orbit at an altitude of a few hundred kilometers, they are also vulnerable to anti-satellite weapons launched from the ground on short- or medium-range missiles as well as to space-based anti-satellite weapons. Adversaries could use these weapons to create gaps in the defense, rendering it ineffective.

That a space-based missile defense system would be unwise from a military and economic point of view is clearly the case for a fully deployed defense, but it holds true even for a small number of orbiting "testbed" interceptors, which would still have significant security costs. While a small number of boost-phase interceptors would not provide any useful defense against missiles, they could have significant inherent anti-satellite capabilities.

The space-based missile defense interceptors could not only reach satellites in low-earth orbit, they could reach valuable military and commercial satellites in mid-earth and in geosynchronous orbits. Most schemes for space-based missile defense require a burnout-velocity for the interceptors of 4-6 km/s. The interceptors will already be in low-earth orbit, possessing a speed on order of 7 km/s. Using a combined speed of 11-13 km/s, space-based boost phase interceptors could carry a kill vehicle to geosynchronous orbits in around an hour.

Because of the expense and the operational challenges, deployment of a fully-realized space-based missile defense constellation is unlikely. However, it is entirely more plausible that the test bed called for in the defense bill could proceed, and a few interceptors would be developed and place in orbit under the guise of research and development. Although this would be small in scope, it would be big in effect.

Putting prototype interceptors in space would surely be viewed by adversaries and allies alike as putting the first dedicated space weapons in orbit. It would likely encourage development by others of anti-satellite weapons to challenge these systems or of similar space-based technologies. Of course, one cannot know for certain what the actions and counter actions would be. But the likely outcomes—heightened tensions, an arms race, risk of miscalculation and misperception leading to a conflict—all decrease security with little in return. Pursuing space-based missile defense continues to be costly and deeply unwise.

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Peer Review: It has a Past; Does It Have a Future?

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I have always thought of "peer review" as an enduring foundation for all of "science". But a recent article in the June 23, 2018 issue of *The Economist,* titled "Publish and Don't Be Denied: Some Science Journals that claim to peer review papers do not do so" has left me somewhat doubtful as to its eventual endurance.

As a physics graduate student and young researcher, I was only familiar with APS Journals. Through them, and via hard experience, I learned what "peer review" meant. It was the means to guarantee that only competent – not necessarily excellent – papers were published to enter the public domain of "real science". Later on, I learned of the existence of some non-APS journals, non-American and/or commercially published research and review journals, which I also presumed to be peer reviewed. There were comparatively few physics journals in those days, all supported by subscriptions that were affordable to libraries and individual physicists. But publishing costs have gone up, and the demand for "open access" to journal articles has spread and been widely accepted. With the demise of subscription support, alternate means of financing publication costs must be found, and that alternative is usually "page charges" – "pay us, per page, and we'll publish your paper" – perhaps without the road block and time delay of peer review.

During my professional lifetime there has been an explosion in the number of active research scientists and in the number of – supposedly – research journals. The path to career advancement and security is the publication of research papers: the more, the merrier. There seems to be a growing number of journals that will further individual careers by accepting page charges rather than demanding the expense and the delay of peer review. And fewer institutions, reviewing their researchers for support and/or advancement, seem to be concerned within which type of journal the pertinent research has appeared. (Often the review is done by "administrators" rather than fellow researchers. *The Economist* article also describes several "experiments" in which "fake" articles are included in the vita under review.)

Several scholars, cited in this *Economist* paper, have compiled "whitelists" – journals that significantly rely on peer review – and "blacklists" – those that do not. One blacklist contains 12,000 journals. One estimate in this *Economist* article is that the number of articles published in question-able journals has risen from 53,000 per year in 2010 to more than 400,000 today. An estimated 6% of academic papers by American researchers are published in "non-white" journals.

The rise in the number of such articles and the size of the "blacklist" indicates that there "is money to be made" from page charges – for both "white" and "black" journals. The growing number of the latter includes those who adopt appearance similar to the more respected ones and/or include the names of respected scientists on their editorial boards, often without the knowledge or consent of the named individuals. The growing demand for ever-larger academic vita, the shrinking of library budgets, and the insistence of governmental funding bodies for open access makes it unlikely that we'll soon go back to a subscription-based universal peer reviewed scientific publishing system.

One possible alternative, currently used by parts of the world physics community, is open-web publishing. Anyone can submit anything – dross or gold – to those lists; let the reader search for value. The problem with this approach is that each reader has to do his/her own search in ignorance of the effort put in by other readers. If there were a means for those other readers to enter their comments in the same list location, this would be a form of "peer review" – open or closed, depending upon whether the reviewer identification was included. Of course, if the initial article submitter is offered a chance to respond to these "peer" comments, the result would be a "discussion board" or blog which might grow indefinitely. So, there has to be a role for an ultimate editor/"peer reviewer" – and who is to pay for that?

REVIEWS

True Genius: The Life and Work of Richard Garwin, the most influential scientist you never heard of.

By Joel N. Shurkin (Prometheus Books, 2017), 308 pages, ISBN 9781633882232, $25 hardcover.

Although many Forum on Physics and Society members have heard of Richard Garwin, for others it is probably fair to say that Joel Shurkin is correct in describing him as "the most influential scientist you never heard of." Shurkin writes that, according to legend, Garwin was described by his thesis advisor Enrico Fermi as the "first real genius he had ever met". With this introduction to Garwin along with what little I know about him I looked forward to learning more about this remarkable man but unfortunately Shurkin writes very little about Garwin himself. Most of the book describes Garwin's work. We learn hardly anything about who he is, how he worked, and what methods, techniques, or unusual ways of thinking he applied to his work that set him apart from so many others doing similar things. Garwin's relative anonymity seems to have stemmed from the secret nature of his most influential work, his professional position, and the man himself. Garwin spent most of his professional life working for IBM where his contract stipulated that he could spend one-third of his time working for the government.

This book deals mostly with this one-third of Garwin's work as a consultant primarily in defense related areas and occasionally elsewhere, but it also describes some of the work he did for IBM and in physics research. Garwin's work in physics includes the parity experiment done in cooperation with Leon Lederman, and consulting with Lederman's group at CERN in Geneva. Regarding his work at IBM there are relatively brief descriptions of prescient and inventive proposals for devices ranging from the laser printer which after some hesitation IBM built, to others like the touch screen and a heads up cockpit display that were too far ahead of their time and consequently were only developed decades after Garwin proposed them.

Garwin's defense work occupies the bulk of the book. His first major defense project was at Los Alamos where he designed a working H-bomb device based on the principles proposed by Teller and Ulam. Most of his subsequent defense work was mainly as consultant and advisor to government agencies and presidents. He was a long standing member of the JASON consulting group and President's Science Advisory Committee. In these capacities he worked on many things including designs of technological barriers across the Ho Chi Minh Trail during the Vietnam war, arms control treaties, intercontinental ballistic missile systems, and anti-ballistic missile systems.

In addition to this defense work, Garwin was involved in an advanced design for an air traffic control system and the proposed but never built Super Sonic Transport airliner. He also proposed in 1968 a digital patient information system hooked up to a large and fully networked database that is very similar to what is only now being implemented on a large scale in hospitals and U.S. doctors' offices. Regrettably, I found enough technical and historical errors in the description of Garwin's work to cast doubt on the overall accuracy of the author's accounts of some of these events.

Perhaps the book's most telling insight into Garwin's persona is summed up by what Shurkin describes as a "Garwin joke" which roughly goes as follows: Somehow Garwin and two other men are arrested during the French Revolution and sentenced to the guillotine. The first two men are spared because the guillotine malfunctions when the blade stops one inch above their necks. When Garwin is placed in the device he looks up at the machine and says "I think I know what your problem is."

This sums up the book's description of Garwin's dispassionate, focused, and usually brilliant approach to technological problems and why he was such a sought-after member of the many government panels he served on. His intellect was respected by all and his amoral approach to the consequences of the weapons he worked on and the policies he critiqued made him a particularly trustworthy colleague. Shurkin describes Garwin as gruff but with a sense of humor and relates that William Perry, a former Secretary of Defense, said that Garwin could be "an acquired taste. I liked him a lot. He is very smart and sometimes impatient with anyone not quite as smart as him." Garwin is described as being famous in Washington for tearing apart admirals and humiliating generals.

That is about all that one can find in this book, a book which is neither a personal nor a scientific biography but more a brief history of the many projects that Garwin was involved in. There is much more to be written about who Garwin really is.

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Silencing the Bomb

Lynn R. Sykes, Columbia University Press, New York, 283 pp., $35 (cloth), ISBN 9780231182485.

Almost from the first use of nuclear weapons in 1945 there have been attempts to limit them. One approach has been to limit the testing of these weapons in hopes that this would eliminate or, at least slow down, the development of new nuclear weapons. This book presents a detailed history of the attempts to limit testing. The author, Lynn Sykes, is a seismologist who has spent some fifty years working on limiting nuclear testing, which puts him in an excellent position to discuss it. He describes the arguments and issues involved in setting up the various test ban treaties.

The first approach was to limit testing in the atmosphere. In addition to its use in developing new, more destructive, nuclear weapons, testing in the atmosphere produced significant amounts of radioactive strontium 90. Sr 90 eventually got into the food chain where, because of its chemical similarity to calcium, it ended up in human bones and teeth around the world in the 1950s. Discussions between the United States and the Soviet Union led to the Limited Test Ban Treaty (LTBT) in 1963. This treaty banned testing in the atmosphere, in outer space, and under water. However it did not ban testing underground.

The reason that underground testing was not included in the LTBT was the difficulty of verification. At the time the only means of detecting underground explosions was by seismic waves. The US feared that, unless there were seismographs directly on Soviet territory the USSR could cheat. The USSR on the other hand feared that US monitoring posts would just be an excuse for spying. These fears did not apply to tests in the atmosphere or under water. Atmospheric tests can be detected from the generation of infrasound, very low frequency sound waves. Acoustic waves in the oceans allow the detection of underwater explosions. Both types of waves can be detected at great distances and do not require monitoring posts on the other's territory. Sykes also mentions instruments for detecting explosions in outer space but gives no details.

Further consideration of underground testing raised several important questions. Could seismic waves be used to detect nuclear explosions and distinguish them from earthquakes? Is there a lower limit on the size of blasts that can be detected? And would it be possible to disguise a blast by exploding it in a large enough hole? Negotiations based on these considerations led to the Threshold Test Ban Treaty (TTBT) of 1974. This treaty limited underground nuclear tests to yields with an upper limit of 150 kilotons. At the urging of the Soviets the limit applied only to the testing of nuclear weapons and not to peaceful nuclear explosions (PNEs). PNEs were used by both the US and USSR to create large cavities in salt for storage, to break rock for petroleum recovery, and as energy sources for seismological studies.

Again the TTBT raised a number of problems. Were the Soviets cheating? They did try to hide one large explosion but were only partly successful. One cannot distinguish between a weapons test and a peaceful nuclear explosion. India, at least, did claim that its first weapons test was a PNE. This led to the Peaceful Nuclear Explosion Treaty of 1976, which stated that any explosion at a declared weapons test site would be considered a weapons test. Any explosion outside these sites would be considered peaceful.

What is the relation between the size of the seismic disturbance and the size of the explosion that produced the seismic waves? The seismic disturbance depends not only on the size of the explosion but also on the nature of the ground surrounding the explosion. This led to some overestimations of the size of Soviet explosions.

In the years since the TTBT, detection of underground explosions has greatly improved. The seismic signal of a nuclear explosion can be distinguished from an earthquake and the location of the source can be determined. If the source is sufficiently far underground it cannot be a nuclear explosion. Nuclear explosions produce small quantities of radioactive xenon which can be detected at great distances from atmospheric explosion and from some underground explosions. Furthermore, satellite imaging can show displacements of the ground caused by nuclear explosions or earthquakes.

These improvements in detection led to the Comprehensive Test Ban Treaty, which banned all nuclear tests in the atmosphere, underwater, underground, and in space. The treaty was signed in 1996 by over one hundred countries. The treaty requires all states possessing nuclear weapons or reactors to ratify it before it can go into effect. As of 2017, 183 nations including several nuclear nations have ratified the treaty. However, several nuclear nations including the United States have not yet ratified it.

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