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PHYSICS & SOCIETY

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Note from the Editor

Welcome to the April issue of the Forum newsletter.

Physics and Society is more than arms control and energy production. Following up on the plan to expand the topics covered in the Newsletter we have in this issue several different things. One is an article by Agnes Mócsy on Physics and Art. Agnes holds a PhD in theoretical Nuclear Physics and is a Professor of Math and Science at the Pratt Institute, a well-known Art and Design college. Her perspective on the relation between art and science is truly original, and the APS has recently recognized her by making her a Fellow. We have also a thought-provoking article by Robert Austin on physicists and the war on cancer. This is followed by an article on recycling the batteries we all use on our phones and laptops.

In the News section, we have perspectives from our incoming and outgoing Chairs.

Please continue to send articles and suggestions for articles. This newsletter is to a large extent reader driven. We are very open as to topics and welcome controversy, as I explained in the Editor's note in the October issue at https://www.aps.org/units/fps/newsletters/201610/editor.cfm for details.

Oriol

Oriol T. Valls, a Condensed Matter Theorist at the University of Minnesota, is the P&S newsletter editor.

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IN THIS ISSUE

Letter to the Editor

In the January Newsletter, Parmentola and Kessel (hereinafter called P&K) replied to my article [1] that pointed out seven shared drawbacks of fission and fusion reactors with a manifesto on the need for nuclear energy to save civilization [2]. Nevertheless, they concede that both classes of nuclear reactors do share the problems of radiation damage, radioactive waste disposal, remote handling and tritium release, but purport to show that these drawbacks can be mitigated or eliminated.

On the other hand, P&K deny that the additional drawbacks of nuclear proliferation, water demands and overwhelming operational costs will apply to fusion reactors. The following observations emphatically re-affirm the relevance of these problems for fusion systems.

Nuclear Proliferation. It's a relatively simple matter to produce fissile material (Pu-239 or U-233) in a fusion device, while extraordinarily difficult to generate net electricity. In fact Pu-239 could be produced even today, albeit in tiny amounts, in the JET assembly at Culham operating in deuterium simply by placing natural or depleted uranium oxide at any location inside the bore of the magnet coils or between the coils. Slower neutrons will be those most readily soaked up by U-238.

P&K's Ref. 9 and related publications emphasize the high weapons quality of the Pu-239 that can be produced in fusion reactors, and call for elaborate safeguards. Implementing safeguards to prevent plutonium production (or tritium diversion) may be feasible, but that is surely a drawback shared with fission reactors.

Coolant Demands. Constraints on water usage will increasingly curtail the deployment of *any* large thermoelectric power plant. ITER is likely to be the only fusion facility even remotely resembling a reactor for the next thirty years, and ITER will use only water as the primary coolant. If successful, water will probably be the primary coolant in subsequent fusion facilities as well as the fluid for the secondary coolant loop, just as water has been used almost exclusively in commercial fission reactors for the last sixty years.

Despite the endless succession of "Advanced Fission Reactor Initiatives" (P&K's headline) that incorporate alternative coolants, *all commercial fission* reactors under construction worldwide continue to be cooled by water. This sobering circumstance indicates that water cooling of fusion reactors cannot be readily replaced by gas or liquid metal or molten salt.

Outsized Operating Costs. At least 1,000 mostly skilled personnel (over four shifts) will comprise much of the operating cost. Another significant expense as exemplified by the 100 MWe to be consumed *continuously* on the ITER site [3] is the background power drain by essential auxiliary systems — helium cryostats, water pumping, vacuum pumping, tritium processing, building HVAC, etc. This non-interruptible power consumption has nothing to do with the reactor's recirculating power during operation, the subject addressed by P&K, and must be purchased from the regional electric grid during planned and unplanned outages.

For inertial confinement systems, the manufacture of millions of target fuel capsules every year will be a huge ongoing expense. And all types of nuclear plants must fund the periodic disposal of radioactive wastes as well as end-of-life decommissioning.

It is inconceivable that the total operating cost of a fusion reactor will be less than that of a fission reactor, and therefore the capital cost of a viable fusion reactor must be close to zero (or heavily subsidized) in localities where the operating costs alone of fission reactors result in a non-competitive cost of electricity.

[1] *D. L. Jassby,* APS Physics & Society*, Vol. 45, No. 4 (Oct. 2016), pp 5-6.*

[2] *J. A. Parmentola and C. E. Kessel,* APS Physics & Society*, Vol. 46, No. 1 (Jan. 2017), pp 9-12.*

[3] *J. C. Gascon, et al., "Design and Key Features for the ITER Electrical Power Distribution,"* Fusion Science & Tech. *Vol. 61, Jan. 2012, p. 47-51.*

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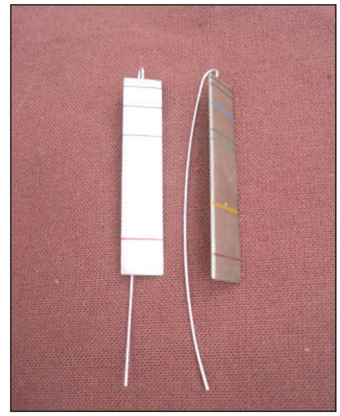
Science as a Muse for Art and Design

Ágnes Mócsy

What benefits can scientists gain from engaging with the arts and artists? What benefits can artists get from engaging with science and scientists? What benefits can society gain from either of these? As a theoretical nuclear physicist who chose a career at an art and design school over a career exclusively focused on research, I have spent the past decade finding answers to these questions. As a professor teaching physics and astronomy at an art and design institute, I have relished the opportunity to be that matchmaker; a matchmaker for my own diverse interests beyond physics, and a matchmaker to make people fall in love with subjects they didn't know they were inclined to fall in love with. Here I will present a selection of the works of my students who have used sculpture, painting, product design, graphic design, film, animated shorts, poetry, and fashion to communicate deeper aspects of science and to tell physics stories through the medium they are most comfortable with; pieces which can tell stories to wider audiences. I believe physics is accessible if we make it accessible. I believe we can bring science and our discoveries to life through designers and artists. I believe we can unveil a deeper connection between art and science. In doing that, we can reach people who otherwise would potentially be uninterested. Let me start with an art form that is probably least often associated with physics.

Physics and fashion don't often get mentioned in the same sentence. But fashion is more than just what to wear. It is a visual language. Just like music and literature, it is a form of expression and one that many feel passionate about. It is also an art form we all participate in. As such, it can have an impact, cause a stir, raise questions, start conversations, and reach across boundaries. Just like curiosity is one of our driving human traits, an internal force that eventually drove us to the process of evidence-based reasoning we call science, fashion is also a very fundamental form of expression intrinsic to who we are. So what can physics get from fashion and vice versa. Can we as physicists participate in the creation of fashion? Can we give fashion a new source of inspiration, can physics and science be the muse? Can we use this medium to tell a science story?



SPECTROSCOPY EARRINGS by Ashley Landon
The earrings depict the emissions spectra of Hydrogen and Helium, the two most abundant primordial elements in the universe. The emission spectra show the frequencies of electromagnetic radiation emitted by an atom transitioning from a higher energy state to a lower one. It's the fingerprint of an element. The earrings were made with silver and inlays of color resin.

Here in NYC I see many wearing leggings made with the beautiful images taken by the Hubble Space Telescope. Can we do more than taking beautiful astronomy images and putting them on clothes? It is easy to put a beautiful image on a dress but does that tell us any more about astronomy than putting a picture of a flower on a t-shirt tells us about botany? Also not all of the inspiring and amazing aspects of science are so visual. The beauty is not always so easy to see. Like in the case of my own research on the earliest moments after the birth of our universe where we create a hot state of matter, the quark-gluon plasma, from which strong interactions carve out more familiar particles like protons and neutrons. Here I show examples of works that make the invisible visible and unveil a deeper connection between fashion and physics; at the same time exposing the scientific process to a wider audience.

To learn more about the author and her activities please visit www.agnesmocsy.com

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

"SHIFT' DRESS *by Ruby Gertz*

In fashion a shift dress is a sleeveless dress that hangs loosely from the shoulders and does not cinch at the waist. This wearable astronomy "shift" dress plays with words by illustrating the blue-shift and red-shift of light; light from an object becomes bluer or redder depending on whether it's approaching or receding. As the model walks away, the dress is redder and as the model approaches, the dress is bluer.

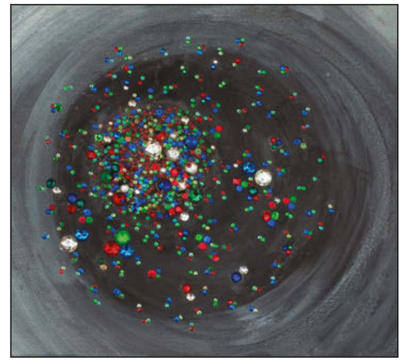
COSMOS CREATION COLLECTION *by Dalitza Babilonia*

This collection is inspired by the different stages of our Universe's evolution, starting 13.82 billion years ago with the Big Bang, passing through the formation of hydrogen and helium, the dark ages, star formation and galaxy formation.

STELLAR FORMATION *by Lauren Moseley*

This evening wear collection depicts the stages of star formation. The looks from left to right represent the following stages: giant molecular cloud, emission nebulas, molecular cloud collapse, individuation of protostars, the beginning of thermonuclear fusion, the T-Tauri stage, and the main sequence.

QUARK-GLUON PLASMA ENTERING HADRONIZATION - FROM THE GLAMOROUS GLUONS SERIES *by Sarah Szabo*



This piece is part of a collection displayed at Brookhaven National Laboratory where one of the last atom smashers in the world collides atomic nuclei to study the behavior of quarks and gluons, the fundamental building blocks at the center of who we are, and quark gluon plasma, the matter that existed in the infant universe at one microsecond after the big bang. Canvas on panel, acrylic, oil, glitter, acrylic medium, decorative metal studs, minuscule rhinestones used to illustrate the collision of nuclei recreating the quark-gluon plasma, which is a soup of quarks and gluons condensing into composite particles, such as protons. Higher mass quarks are represented by larger sequins. They are created less frequently and often found in close proximity, in areas of higher energy density.

GALAXY BLOSSOM *by Ji Hyun Chong*

Using the Hubble Space Telescope, astronomers measured the motion of the Andromeda galaxy, the nearest galaxy to our Milky Way galaxy. Both galaxies contain supermassive black holes at their center surrounded by billions of stars making up spiral arms. Andromeda is approaching the Milky Way at a speed of 300 kilometers every second. In four billion years, Andromeda and the Milky Way will collide and the two spiral galaxies will merge to form a new elliptical galaxy. This project was inspired by a computer simulation of the collision showing that the two supermassive black holes will collide with each other accompanied by a flash of light. This stand lamp portrays the collision. The galaxies are represented by white oak and mahogany veneers mounted on cylindrical wooden center pieces. The center pieces represent the supermassive black holes while the strips of veneer represent the spiral arms. The Andromeda galaxy is made to resemble a Fibonacci spiral to reflect the way Andromeda appears to warp as it collides with the Milky Way.

INVISIBLE FORCES by Celeste Tsang

So many of the forces that govern the physical universe are invisible forces; unseen by the naked eye. This sculpture makes visible the invisible forces of gravity and magnetism through tension. The forces of gravity and magnetism are visually seen in one instance by magnetic repulsion, and in the tension of the threads that keep the magnets from achieving their desired positions. The one magnet's seemingly gravity defying appearance means that, with the magnets' close proximity with each other, the force of attraction between the two magnets is stronger than that of the gravitational force enacting on the magnet suspended in air, stronger than 9.8 m/s^2*. The metal filings serve as a way to visually think about the magnetic domains, the clusters of atoms that align according to their polarity, that exist in magnets and a piece of metal under the influence of a magnetic force.*

WHAT IF YOU COULD FEEL THE SURFACE OF THE MOON AT YOUR DINNER TABLE? *by Anjali Chandrashekar*

Luna is a collection of ceramic lunar plates with a real representation of its surface and different phases. The project is aimed at creating a tactile and interactive dining experience by bringing some celestial/lunar understanding into homes. It also serves as a great piece for a dinner table conversation. This unique art+science intersection was brought to life using different methods. LIDAR is a remote sensing technology that measures distance by illuminating a target with a laser and analyzing the reflected light. With accurate LIDAR images, the surface was then height mapped to model the craters onto the plates, as is on the lunar surface. The mold was made possible by 3D printing of a model of the plate while maintaining accuracy and definition. The plates were then cast in ceramic to create a cross sensory experience while dining.

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Final Report: The Princeton Physical Sciences Oncology Center
Complex Ecologies for Explosive Evolution of Interacting Cancer Cell Populations

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1. Summary

The Princeton Physical Sciences Oncology Center failed as a Center but succeeded in developing several new ideas and technologies we think in the coming years will be recognized as fundamental novel and important ideas which were not given a chance to grow. We developed a novel micro-engineered microfluidic cell culture device that resembles the in vivo landscapes of stress heterogeneity in a tumor. With this "evolution accelerator" we were able to recapitulate the adaptive cellular response to a heterogeneous microenvironment as well as investigate interactions amongst prostate cancer of cells in this tumor-like community. The technology not only can be used to investigate various fundamental biological questions from an ecological point of view by analyzing the population dynamics of multiple cell types in the microenvironment, but also has a potential to work as a platform for preclinical drug development and assays of likely performance.

2. Physicists Tilting at Windmills with Expected Results!

The Princeton Physical Sciences Oncology Center (PPSOC) was one of the most heavily "physics centric" of the 12 Physical Sciences Oncology Centers (PSOCs) funded by the National Cancer Institute. Unlike many of the other Centers, it spanned the United States, with members at Princeton University, Johns Hopkins Medical Institute, University of California San Francisco, University of California Santa Cruz, and the Salk Institute. It represented a mixture of physicists, electrical engineers, oncologists and biochemists. It was made de novo, that is, none of the branches had ever worked together, the physicists and engineers knew nothing about cancer except it seemed to be killing members of their families at enormous cost quite relentlessly. So, it represented what was the initial intent of the PSOC effort done with great energy and courage by Ann Barker, and led by Larry Nagahara and Jerry Lee.

The PPSOC from the start was deliberately high risk and high reward: the mission was to rethink cancer as an intrinsically evolutionary phenomena, not a disease in the normal sense of the word as an invasion by some foreign entity to fought and destroyed, but rather primarily a condition of inappropriate growth of the body's own cells, including invasion of tissues with the body remote from the local lesion: metastasis. But not a disease. The approach driven by the physics arm of the PPSOC was to stress four main aspects of this condition: (1) The importance of the local ecology within which the cancer cells are growing; (2) the importance of a stress landscape within the ecology which drives part of the heterogeneity of the cancer tumor; (3) The importance of the role of the number $N\iota$ of individuals within a local population within the overall ecology; (4) the importance of understanding interactions $ki\ jNiNj$ between different subpopulations with the overall ecology, which brought in aspects of game theory.

Why did we fail? Probably the hardest part was bridging the enormous cultural, scientific and ideological chasms that separated the different parts of the Center. It is one thing to talk about multidiscipline work, quite another to do it at an equal footing without one discipline becoming subservient to the other. In the case of the PPSOC it was extremely difficult for the physicists to change the path and direction of the already powerful and directed oncology arms of the Center, especially when the oncology arms did not exactly get along with each other, which became very clear at the start. Even between the physicists and engineers there was an inner tension: engineers tend to want to build things using already developed technologies which are understood if not yet mature, while physicists tend to want to be the creators of new ideas and concepts which MIGHT become useful technologies down the road, but not right now.

A consequence of this split was that the Center, while there were at least weekly SKYPE meetings between the branches and at least bi-monthly trips to the various branches, at times resembled a cancer-based United Way, where funds were sent from the Princeton hub to the branches, and the branches used these funds to continue their own previously established work with no real change in their direction. This is not really a criticism but rather a statement of fact about how hard it is to change the direction of an already strong group, especially if the changes come from a branch which has no expertise in the field, but perhaps foolishly thinks it knows a better way to attack the problem of cancer resistance.

Another aspect of the problems the PPSOC faced was the fundamentally different way that physicists and oncologists carry out research. Physicists tend to study the simplest system they can that illustrates a fundamental property they are trying to understand, while oncologists are forced to study an extremely complex system which changes by the minute and varies greatly from sample to sample. Also, there is in oncology enormous financial aspect to the consequences of the research. The combination of these two factors results in the perhaps not well known fact that of 53 "landmark" papers in oncology only 6 were found reproducible even with co-operation of the original authors [1]. In the PPSOC the poor reproducibility of the oncology literature bit us: one of the principles in the Center had to withdraw after the company he founded could not reproduce his own data, and later the seven core papers were retracted. Although this happens in physics too [2], it is much more common in oncology and you have to be prepared for the huge uncertainties, the lack of reproducible data, and the premature drive to the clinic and Big Pharma.

It was tough sledding, but I don't want to project the impression that all was darkness. All the branches of the PPSOC worked very hard to overcome the chasms that separated us, and while ultimately there was no real cohesion there were some real achievements that I believe in about ten years will lead to major new ways we view the origins and progression of cancer. It simply takes a long time to change the course of experimental science, particularly in biomedicine. Too bad so much is actually at stake as the ship plows on ahead full speed into the icebergs.

3. Progress after the fall

If you believe in what you are doing you don't quit. "Illegitimi non carborundum" Since we have a belief that what this Center started was too good to be to "carborundum'd" by peer review, which is of course basically inevitable, we have gone underground to keep alive the Dream, but we now carefully avoiding spinning windmills in the dark, and avoiding the grinding teeth of peer review as much as possible.

We had a strong feeling about physics, ecology and cancer when we began our effort in 2010. We believed that there is a deep connection between ecology and the physics of living systems. John Dunne wrote evocatively in 1623 in his *Devotions Upon Emergent Occasions*: "No man is an Iland, intire of it selfe; every man is a peece of the Continent, a part of the maine".While Dunne probably had a different use of the word "Emergent" than modern physicists such as Phil Anderson use, we take those words seriously:"emergence" for us means the revelation of unexpected and not reductively predictable collective behaviors of biological agents as they exist as communities in complex ecologies. We also take seriously the later words of Charles Darwin, who famously noted the complexity of life in the "tangled bank, clothed with many plants of many kinds, with birds singing on the bushes, with various insects flitting about, and with worms crawling through the damp earth." Life exists in this tangled bank and in an entangled state, the question is can we deal with that complexity quantitatively?

We expected that if we can build sufficiently complex ecologies even for supposedly "simple" organisms such as bacteria, or certainly as complex as cells in human tissue, emergent and quantitative principles of complexity will be made clear. Rather than passively observing the "tangled bank" of the classical ecologist we construct using the tools of the semiconductor industry micro-fabricated environments where we can control the fitness landscape for communities of biological agents, while still allowing for rich complexity and self-sculpting of the landscape by multi-component organisms at high densities.

Cancer develops within a large ecology, the human body. Within that large ecology, tissue based cancers progress in a complex local ecology which recapitulates Darwinian natural selection amongst different cell types, both cancer cells and non-cancer cells, in a confined volume. The complex stress landscape within which a confined cancer population develops applies spatial and time dependent selective pressures which present spatially varying opportunities for genetic and epigenetic transmission to daughter cells. If the daughter cells are cancer cells and have higher fitness under stress than the mother, the cancer progresses. While animal models can to a certain degree reproduce this ecology that drives cancer progression, better ex vivo ecology models are needed for quantitative studies of evolution under high-stress conditions both to predict the progression of cancer and test the efficacy of drugs under high stress and cellular heterogeneity. On a time scale of weeks we can now demonstrate what normally takes months or years of evolution under metabolic stress. Figure 1 shows the competing growth of prostate cancer cells (red: PC3 epithelial and green: PC3 EMT) cells over a period of two weeks in a chemotherapy gradient (docetaxel). By tracking the behaviors of multiple cell types in the device, including the proliferation rate, population dynamics, cell motility, biosensor activity and the composition of metabolic waste, the technology we have developed could potentially work as a tool to investigate various fundamental biological questions from an ecological point of view, as well as a platform for pre-clinical drug development, or even pre-clinical invitro experiments that allow personalized therapy selection in cancers.

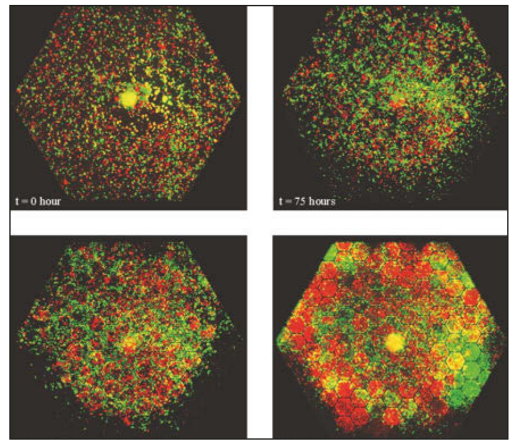

Figure 1: The growth of competing cancer cells in a complex ecology in a drug gradient.

4. Conclusion

Our attempt to renew our Center was met with extreme vetting: our accomplishments were deemed not worthy of being discussed amongst the wise and learned panel cognoscenti. I guess I should not have been surprised. Sitting in on another NIH Panel after the fall, it was pointed out by a reviewer that a proposal which posited that evolution can predict the course of a cancer must surely be wrong. Why? Because suppose that patient steps into traffic and is killed by a car: well, evolution didn't predict that did it? This line of reasoning seemed to meet with sage nods of approval. You can see how hopeless it can be. There is a Chinese saying: Don't go to the front gate of the Kung Fu Master Bodhidharma to show off your Kung Fu skills. Perhaps we did that and were punished, but the oncologists did not all seem like Kung Fu masters. We really did try to change things in the cancer community using ideas from physics. I think we did come up with new ideas, but the results of that work lie in the future, and I am trying to make that day happen. One lesson, however has been that there is some truth to the adage that NIH stands for Not Invented Here.

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[2] *Reich, E.* Plastic Fantastic *(Macmillian, 2009).*

The Future of Automotive Lithium-Ion Battery Recycling: Charting a Sustainable Course

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Argonne National Laboratory

INTRODUCTION

Recycling, *per se*, is not inherently good or bad *(1)*. For materials like glass *(2)*, the benefits are dubious and depend on factors like the shipping distance. There has also been some debate on the benefits of recycling primary alkaline batteries given the abundant and non-toxic nature of the components *(3)*. For automotive batteries, however, the environmental benefits are clear, although they vary with battery type and recycling method. There are also potential economic benefits. If usable materials can be recovered, less raw material needs to be extracted from the limited supplies in the ground. Further, domestic recycling reduces the the raw materials imported from abroad, improving our balance of payments. In addition, significant environmental benefits can be obtained by recycling elements obtained from mining and processing ores (e.g., SO_x emissions from smelting of sulfide ores to yield copper, nickel, and cobalt) *(4) since the environmental effects of recycling are* generally smaller than those from primary production. There are, of course, exceptions, such as recovering lithium from pyrometallurgical process slag.

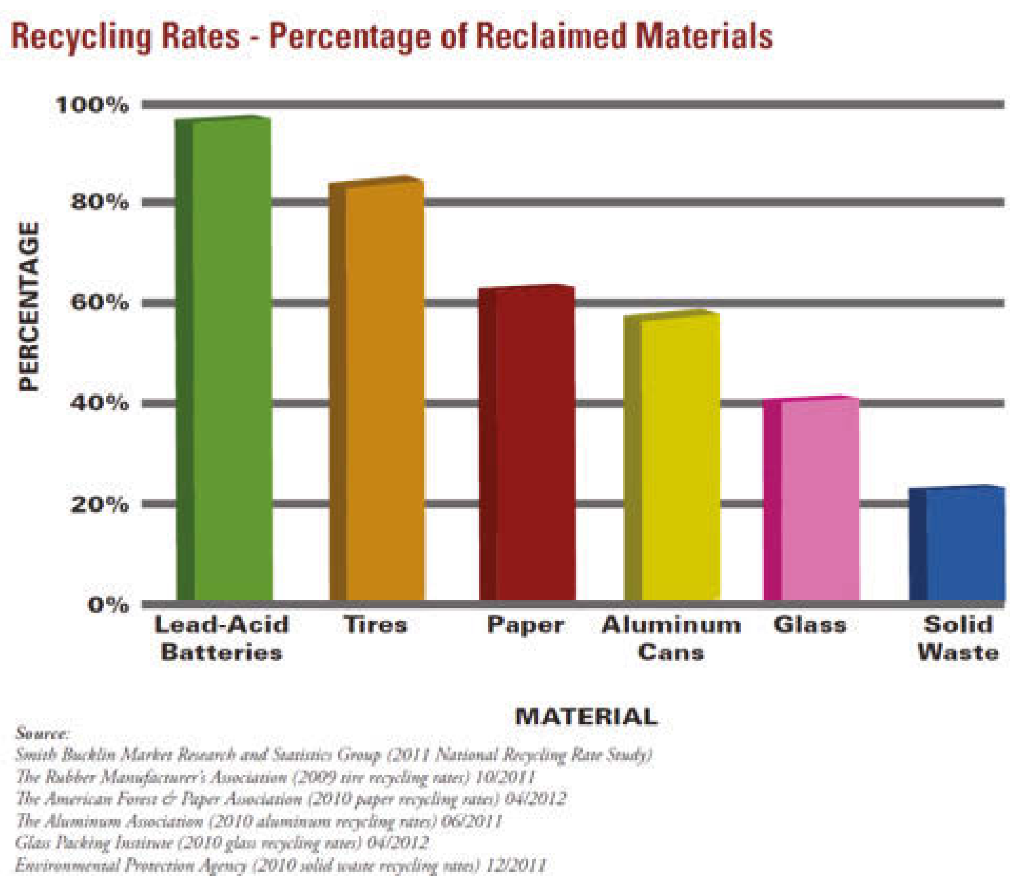

FIGURE 1: Batteries are the most recycled consumer product. (Courtesy of Battery Council International)

Recycling of materials also avoids processing costs for waste treatment. In addition, some spent batteries *(5)* are classified as hazardous waste, which increases transportation, treatment, and disposal costs, and requires additional effort to achieve regulatory compliance.

Lithium-ion batteries are starting to be used in significant quantities for automotive propulsion. Because these batteries are expected to last the life of the vehicle and may subsequently be used for utility energy storage, they will not be ending their useful lives in large numbers for on the order of 10 years. What steps can be taken to ensure that these spent Li-ion batteries are recycled at the end of their useful life. In an ideal system, these batteries would be sent for responsible recycling and not exported to Third World countries with less stringent environmental, health, and safety regulations. Methods are needed for safe and economical transport and processing of the spent batteries, as well as environmentally sound recycling practices. In addition, the recycled product needs to be of sufficient quality to find a market. Fortunately, recycling system for lead-acid and Nickel-Metal Hydride batteries are already in place and can provide lessons that can be applied to recycling Lithium-ion batteries .

LEAD-ACID BATTERY EXAMPLE

Lead-acid batteries are recycled more than any other major consumer product, Figure 1. In the US, about 98% of lead-acid (Pb-acid) batteries are recycled *(6)*. Lead-acid battery recycling is also working well in Europe and Japan. In countries like China, significant changes have recently been made to improve the recycling practices *(7)*. To date, the model shown in Figure 2 has worked admirably for lead-acid battery recycling. Would some variation of this model work as well for other battery types?

COMPARISON OF AUTOMOTIVE BATTERY TYPES

Before examining that question, it is useful to first compare the physical and chemical structures of different types of automotive batteries; namely, the lead-acid batteries used for starting-lighting-ignition (SLI) commonly found under the hood of most cars, nickel-metal-hydride (Ni-MH) batteries used in hybrid vehicles, and Li-ion batteries used in plug-in and some hybrid vehicles. The latter two battery types are used primarily for propulsion and heating, ventilation, and air conditioning (HVAC).

Conceptually and structurally, these battery types are similar but chemically quite different. Each consists of electrode (cathode and anode) active materials on grids or foils that serve as the current collectors, with an electrolyte that carries charge between the electrodes. These components are

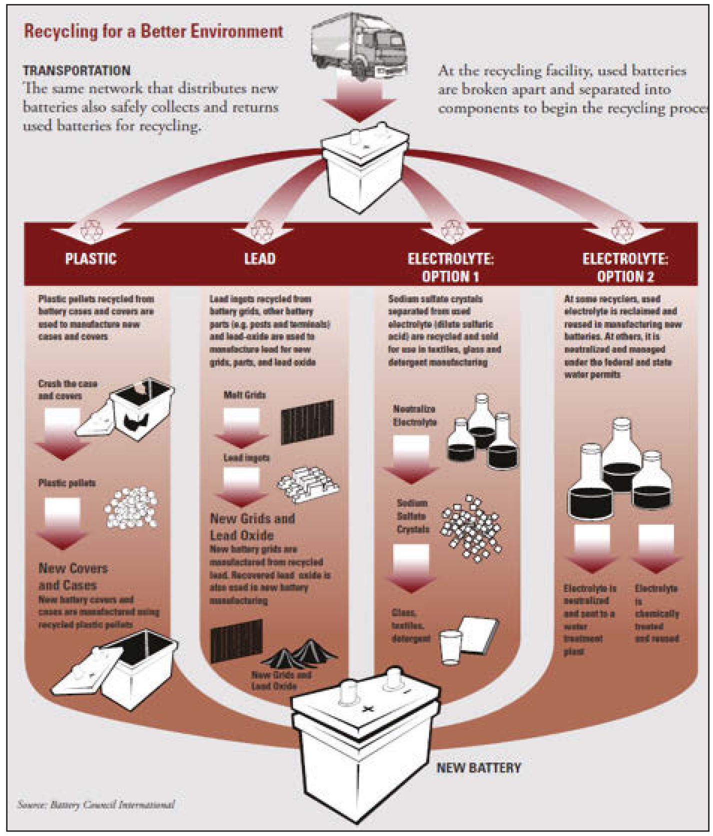

FIGURE 2: Simple processes are used to recycle lead-acid batteries. (Courtesy of Battery Council International)

TABLE 1 Comparison of cell materials

Cell component/battery type	Pb-acid	Ni-MH	Li-ion
Cathode	PbO_2	$Ni(OH)_2$	$LiMO_2$
Cathode plate/foil	Pb	Ni foam	Al
Anode	Pb	MH (AB_5)	graphite
Anode plate/foil	Pb	Ni-plated steel	Cu
Electrolyte	H_2SO_4	KOH	Organic solvent + $LiPF_6$
Separator	PE or PVC w/silica	polyolefin	PE/PP
Cell case	PP	Stainless steel	Varies (metal or laminate)

PE = polyethylene; PVC = polyvinyl chloride; PP = polypropylene housed in an enclosure. The compositions of these components differ greatly among the battery types, Table 1.

The more diverse the battery materials, the more complex the recycling. For Pb-acid batteries, all of the internal components contain lead, which makes up about 60% of the battery mass. Except for electrical connectors, which can be removed when the cells are opened, no other metal is present. As a result, no separation processes are required. Because nickel dominates the Ni-MH battery, it can be the focus of recycling. In addition, the nickel and steel alloys that results from current recycling processes are a valuable input to stainless steel manufacturing, making recycling of these batteries economical today. The many different materials in a typical Li-ion battery complicate recycling.

Lead-Acid Battery Recycling

Disposal of Pb-acid batteries is illegal in most states and many states, as an incentive for consumers to return their batteries, require a monetary deposit. Most Pb-acid batteries are collected when new ones are purchased (the dealers are required to accept them and are paid for their trouble). Additionally, as required by law, batteries are stripped from vehicles that have gone out of service and are about to be shredded. Regulations concerning transportation and processing of batteries are in place and widely known.

Lead-acid battery are recycled by a simple process, Figure 2. First, the battery case is broken open and the sulfuric acid electrolyte is drained out and collected. The plates and connectors, Figure 3, can be removed from the case at this point and recovered whole. Alternatively, the drained battery can be sent to a hammer-mill for size reduction, and the plastic and lead separated by a simple sink-float device. The recovered lead is re-smelted and purified to make new battery components, which avoids the sulfur emissions from primary lead production with the lead emissions from secondary smelting being tightly regulated by the Environmental Protection Agency *(8)*.

FIGURE 3: Lead-acid battery cases and plates after separation.

The plastic is melted and molded into new cases. The acid can be neutralized or processed to sulfate salts for various uses, such as the manufacture of soap.

The recycling operation is profitable because recycled lead (taken back to its elemental form and purified) is known to be of high quality and there is little incentive to export to places with less stringent regulations, although some batteries do find their way to Mexico *(9)*. Some battery manufacturers prefer new over recycled lead.

A key reason for the success of lead-acid battery recycling is that essentially all of the manufacturers use the same raw materials: lead, lead oxide, and sulfuric acid in a polypropylene case. Because the battery design is similar for the manufacturers, automated technology can be used for battery disassembly. Further, lead-acid recycling works well because it is profitable, it is illegal to dispose of the batteries without recycling, the battery chemistry does not require segregation, and the recycling process is simple.

Nickel-Metal Hydride Battery Recycling

Large-format Ni-MH batteries have been used in hybrid vehicles for long enough that some now require disposition by either reuse or recycling and a recycling system is already in place because consumer batteries from smaller devices, such as power tools, have been recycled commercially for many years, Figure 4. However, not all of the battery materials are recovered as high-value products. The nickel and iron are recovered by rotary hearth and electric-arc furnaces as ferronickel to feed stainless steel production. Because this is a high-value product with a huge market, there is no need to separate the nickel from the iron. However, this technique loses rare earths in the metal hydride to the slag, which is used as roadbed aggregate in place of gravel *(10)*. The increasing demand for rare earths in batteries, motors, and other components of vehicles and wind turbines, coupled with China's policies to restrict exports so that they meet their own demand, has provided a significant economic incentive to recover these metals during recycling.

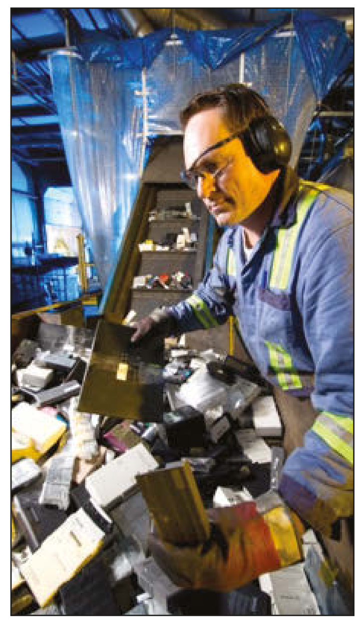

FIGURE 4: Hand-sorting of Ni-MH consumer batteries (Courtesy of Kinsbursky Brothers, Inc.)

Nickel-metal hydride batteries have a similar chemistry (AB_5), although the exact mix of rare earth elements may vary slightly and pack configurations differ. For that reason, differentiation among Ni-MH batteries is not needed. Several companies have announced programs to recover the rare earths from Ni-MH batteries. Umicore, in Belgium, recovers nickel and has an agreement with Solvay (formerly Rhodia) to recover rare earths from slag and *(11)*. Retriev Technologies (formerly Toxco) has a plant under construction in Ohio, partially funded by Recovery Act funds received in 2009, and plans to recover rare earths when its first processing line is completed. Honda has an agreement with Japan Metals and Chemicals *(12)* to recycle its Ni-MH batteries. In Australia, Toyota offers a $100 rebate when a Prius battery pack is returned, and a discount on a replacement *(13)*. In sum, Ni-MH batteries seem to be on track for successful recycling.

Lithium-Ion Battery Recycling

Several factors contribute to making Li-ion battery recycling more complicated than Pb-acid or Ni-MH recycling. First, as shown in Table 1, Li-ion batteries have a wider variety of materials in each cell. The active materials are in the form of powder, coated onto metal foil, and these different materials must be separated from each other during recycling. Within the cells, the chemical compositions of the active materials, especially the cathode, vary with manufacturer and battery function, are changing, and may never standardize. The most common cathode material for the batteries in consumer electronics is $LiCoO_2$ (LCO), but various combinations of Ni, Mn, and Al can replace some or all of the cobalt to optimize performance while lowering raw material cost, which is key for automotive batteries. Another promising cathode material is $LiFePO_4$ (LFP). Most manufacturers use some form of graphite for the anode, but silicon is also used and other materials/mixtures are being studied. Lead-acid batteries have a relatively small number of large lead plates packed together in a single plastic case, while a Li-ion pack is likely to have 100 or more individual cells (~5000 for a Tesla electric vehicle), which are connected into modules and assembled into a pack with control circuitry and thermal management systems attached to each cell, Figure 5. These components could possibly be recovered intact or may contain valuable materials that could provide some economic incentive for recycling.

FIGURE 5: Lead-acid battery and Li-ion pack

Lead-acid batteries are small and easily removed from their location under the hood, while the larger, more complex Li-ion packs vary in shape and location in the vehicle. As a result, removal may be more difficult. However, if removal takes a professional, fewer people need to be trained on proper handling and separation. Further, if Li-ion batteries last for the life of the vehicle, they will all end up in scrapyards or at auto dealers, which are both sufficiently large enterprises to facilitate collection. Vehicle batteries being subsequently used for stationary energy storage could also be collected from utilities after this second use.

At present, there are no regulations regarding recycling of large-format Li-ion batteries. This condition might be thought to be good for recyclers, who would face no restrictions in process design. However, they face the possibility that restrictive regulations could later be imposed. Therefore, processes must be designed to be compliant with anticipated regulations. In addition, the technology is still evolving and recycling processes designed for a specific design or chemistry could become irrelevant.

Automotive Li-ion batteries have only been in commercial use for about 5 years, and it will take some time until they are used in large volumes. Further, their long product life (ideally, the life of the car), means that not nearly enough batteries have reached the end of their lives to support large-scale recycling plants. However, consumer lithium batteries and processing scrap are available and could supply feedstock for a fledgling recycling industry for automotive Li-ion batteries. Several recycling methods have been proposed, each with its advantages and disadvantages, as discussed below and described in Ref. 14.

Pyrometallurgical Recycling (Smelting)

After dismantling the lithium-ion batteries to the module level, they are fed to a high-temperature shaft furnace with a slag-forming agent that typically includes limestone, sand, and slag. The electrolyte and plastics burn to supply some of the energy for the smelting, and valuable metals are reduced to an alloy of copper, cobalt, nickel, and iron, which are then recovered by leaching. The resulting slag contains lithium, aluminum, silicon, calcium, iron, and any manganese that was present in the cathode material. Recycling aluminum or lithium from the slag is not economical or energy efficient and gas cleanup steps are necessary to avoid the release of potentially toxic by-products. This process is operating commercially and is economical for batteries with cathode materials containing cobalt and nickel but not for newer designs with manganese spinel or LFP cathodes, Table 2.

TABLE 2: Recovery of cathode material maximizes product value

Cathode	Price of Constituents ($/lb)	Price of Cathode ($/lb)
$LiCoO_2$	8.30	12-16
$LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$	4.90	10-13
$LiMnO_2$	1.70	4.50
$LiFePO_4$	0.70	9

Intermediate Recycling Process

In this process, commercially used in Canada, batteries undergo size reduction in a hammer-mill and a shaker table separates mixed plastics and metals. Filtering of the aqueous stream leaving the hammer-mill yields mixed metal oxides, carbon and a liquid stream which is dewatered to some extent. It is then mixed with soda ash to precipitate Li_2CO_3, which is subsequently filtered from the solution and sold. The metals (including the Al) can be separated and sent for recycling. However, as with pyrometallurgical recycling, the process is only economical if cobalt and/or nickel are contained in the cathode.

Direct Recycling

This bench-scale physical process, which has been demonstrated for several cathode materials, recovers battery materials for reinsertion into the battery supply chain with little or no additional processing. Breached discharged cells are placed in a container to which CO_2 is added, and the temperature and pressure are raised to bring CO_2 above its critical point. The supercritical carbon dioxide extracts the electrolyte (ethyl methyl carbonate, diethyl carbonate, and $LiPF_6$) from the cells and is removed. The electrolyte separates from the gaseous CO_2 and, after further processing, can be recycled for use in batteries. The cells, devoid of electrolyte, undergo pulverization or other size-reduction steps, possibly in the absence of water or oxygen to avoid contamination of materials. Subsequently, the cell components are separated through techniques that exploit differences in electronic conductivity, density, or other properties. Cathode materials may need to undergo re-lithiation prior to reuse in batteries.

This process has the advantage that almost all battery components, including aluminum but excluding separators, are recovered and can be reused after further processing. Most important, the cathode materials constitute a potentially valuable product from direct recycling, regardless of cathode type. There is some question, however, on whether the recovered material will perform as well as virgin material, which could have implications for battery power and lifetime. As such, manufacturers may be reluctant to purchase recycled compounds. Manufacturers of products with tight quality standards have historically been reluctant to purchase recycled materials because of performance concerns *(15)*. Product quality will depend on having a known, uniform input stream; mixing cathode materials is likely to reduce the recycled product value.

Discussion

Several factors could help promote Li-ion battery recycling. Packs are large and recognizable. They will be removed from end-of-life vehicles if there is an economic incentive or a regulatory imperative. They will be labeled to enable identification for proper routing. The recovered batteries could be returned to the original manufacturers. However, while these manufacturers would know what the batteries are composed of, they might not want to be in the recycling business and they would be required to process recycled compounds that could be obsolete 10 years or more after initial production.

Several developments would facilitate making Li-ion battery recycling economically viable:

- Separation technology that enables processing different chemistries, recycling processes for each cell chemistry, or technology that produces valuable products from a mixed stream;
- Methods for separation of cathode materials after initial processing;
- Greater recycling process flexibility or standardization of battery materials and designs; and
- Assurance that regulations will not impede recycling.

Initial battery manufacturers can promote eventual recycling using design for recycling, including the following steps: inclusion of labels or other distinguishing features, use of a minimum number of different materials, standardization of formats and materials, avoidance of toxic materials (cadmium, arsenic, mercury, halogens, etc.), and designs that allow easy separation of parts, including a separable cooling system, reversible joining (i.e. nuts and bolts instead of welds), and avoidance of potting compounds to hold cells in place. Of course, these design changes cannot be made at the cost of any reduction in performance or safety during the battery's useful life. A committee of the U.S. Advanced Battery Consortium (USABC) is working on design-for-recycling guidelines for U.S. auto manufacturers *(16)*.

Work is underway to address all of the roadblocks to Li-ion battery recycling within the 10 years or so before large numbers of large-format automotive batteries are ready for final disposition.

A PROBLEM IN THE MODEL RECYCLING SYSTEM

Recent events where Li-ion batteries have been included the lead-acid battery input stream at secondary lead smelters have resulted in fires and explosions *(17)* and have identified issues with the system on which future Li-ion recycling can be modeled. This contamination of the input stream may be the result of honest mistakes due to the fact that many current Li-ion batteries are indistinguishable from lead-acid batteries. It may also be a consequence of recyclers paying for their desired input material (Pb-acid batteries) and charging for disposition of other less-desired input material, resulting in contamination to avoid these fees. Regardless of the reason, such events pose a serious danger and must be prevented. In practice, however, it is difficult to detect due to the similar structure of the batteries and that batteries are often delivered to recyclers in huge loads (over 3,000/hour– up to 70,000/day). This problem could be reduced if there were a profitable outlet for the recycling of Li-ion batteries or if all Li-ion batteries could be recycled to high-value products, Table 2. At the present time, however, Li-ion manufacturers are moving toward cheaper materials, which exacerbates the problem. Any model system for battery recycling will need to avoid cross-contamination. This issue is being addressed in the U.S. by the Society of Automotive Engineers and in Europe by EUROBAT. Both groups have active working groups attempting to better define and find solutions to the problems of cross-contamination of battery types in recycling streams *(18,19)*.

While segregation systems for large-format batteries are needed, the optimum separation point in the recycling chain is unclear, and rescreening might still be necessary before final processing. The screening could be based on density differences (Li-ion batteries are likely much lighter than Pb-acid batteries) but careful separation is likely to increase recycling costs, which would likely be borne by consumers. Separation could be facilitated if manufacturers labeled battery components by means of bar codes, RFID chips, or delegated paint color or type (*e.g.* visible under black light). It would also be helpful to have clear incentives for good recycling practices and penalties for poor practices.

VISION OF IDEAL FUTURE SYSTEM

Ideally, the search for the best battery chemistries and designs will result in a few designs that satisfy everyone's requirements, and the batteries of a given type would be made as uniform as possible. Further, those that could be recycled together would have at least one distinguishable, common feature. Conversely, different battery types would look different and have a least one feature that differentiates them from batteries to be recycled in a different way. This would require that batteries be designed with recycling in mind. There would need to be an easy way to route these spent batteries to the appropriate recycling facilities in a safe and legal manner at the conclusion of their useful lives and regulations that assure safe transport and handling while discouraging cross-contamination would need to be in place. Sorting/routing could be immediate, via a transfer station, or take place within a unified recycling facility. Separate streams would be processed to produce valuable, high-purity materials that could be reused in batteries or other high-valued products. An alternative to separate processing would require process development to enable production of a valuable product from a mixed stream (or product separation into valuable streams). In either case, strict industry standards would be needed to ensure that recycled products meet the same high quality standards as virgin materials to facilitate their reuse.

Accomplishment of this future vision before large numbers of automotive propulsion batteries have reached the end of their useful lives requires research and planning to continue over the next 10 years or so. It is a daunting task, but it can be accomplished if there is a broad commitment from industry and government.

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FORUM NEWS

Forum on Physics and Society Leadership Focus: from the New FPS Chair

I am delighted to be serving as chair of FPS during the coming year. There has been much discussion among your elected FPS officers about the role of the Forum and what can be done to increase its visibility, its relevance to the membership and its attractiveness to younger physicists. I request that you provide your ideas on this, or any other topics that you think the Forum should be working on, or things that we should be doing. I would like to suggest some possibilities.

1. Initiate small working groups that study key topics that would produce "white papers" that would be published in the appropriate APS newsletter. We could enhance the attractiveness to younger physicists by offering modest stipends to defray potential costs for their participation, (for example, a trip to meeting to organize the work, and one to present the findings), with the certainty of getting some form of publication that would enhance their resumes. These topics could include:
   A. Specific ideas on improving diversity in physics;
   B. The impact of new technologies on the role of nuclear weapons in U.S. strategic planning;
   C. The societal impact of basic scientific research;
   D. The emergence of new energy technologies and their potential impacts on the energy generation mix in the U.S.;
   E. The potential impact of artificial intelligence on society;
   F. What we know about sea level rise and possible mitigating actions;
   G. Physics and Health - the role of physics in the mitigation of pandemics.

2. Workshops, or "summer schools" on specific topics, such as arms control, energy efficiency, climate change, science and technology policy, and science and diplomacy.

3. Enhanced programming at the APS annual meetings.

It seems like a lot, but there is already some of this going on in the FPS. My idea is to capture the interests of our membership and to build much greater collaboration with other units in the APS. Many of the suggested topics are cross-cutting, as they should be, and would benefit from active participation beyond FPS.

As mentioned above, your ideas are most welcome. With your support, I anticipate a very productive, and active, year for the Forum.

Allen L. Sessoms,
allensessoms@gmail.com

Activities of the Forum on Physics and Society 2016

Ruth Howes, Past Chair of Forum on Physics and Society, 2018; Chair, 2017

The first activity of FPS, in the spring and summer of 2015, was to identify a new editor for the Newsletter of the Forum on Physics and Society. Andrew Zwicker, our longtime editor, was elected to the New Jersey State Legislature. We congratulate him although we will miss him. A search committee (PushpaBhat, FPS Council Representative; Cameron Reed, Editor of the FHP Newsletter; and Laura Berzak Hopkins, associate editor of the FPS Newsletter, and Ruth Howes) selected Oriol Valls, a professor of physics at the University of Minnesota and a well-published physicist specializing in superconducting systems, for the position. To date, Dr. Valls has solidly fulfilled his promise as editor.

Next Ruth Howes and Bev Hartline conducted a survey of all FPS members to determine the areas and activities which interested the membership. The survey had a response rate of a little over 10% and provided many of the ideas included in our plans for the future of FPS. If you would like to see details, the results of the survey were published in the October edition of the FPS Newsletter.

The fact that the April Meeting of the APS was held in January meant that FPS had to hold elections in December. Gratitude is due to the Nominating Committee (Frank Von Hippel. Warren Buck, John Harte and Ruth Howes) for locating an excellent slate of candidates and to Tony Fainberg, Secretary/Treasurer of FPS, for conducting the early election in a timely manner.

The major effort of FPS this year has been outreach to other forums, topical groups, and divisions of APS as possible. Allen Sessoms has done a terrific job as program chair. One of the more important links has been to the APS Office of Public Affairs, culminating in a report to members by Francis Slakey, Interim Director of the Office, concerning the financial plans of the Current Administration and a talk by Mike Lubell, former Director of the Office, on the best way for APS to respond to the new administration.

Finally I have started a small, all volunteer study to look at the importance of basic research to the development of new and important technologies. The time scales involved are long, on the order of 10-15 years so it is not a trivial problem. The idea is not only to develop case studies of technologies, but also to produce a method for doing such studies that can be adopted by physicists working on science advocacy in Congressional Districts around the country whatever their specialties in physics. FIAP has helped lay the groundwork for the study which is still in its early stages. If you have ideas or are interested in participating, please contact me at rhowes@bsu.edu.

Continued Project: The FPS Bylaws need revision. I will work with Ken Cole at APS to prepare a draft that is consistent with our current practices; lets elected officers take positions on January 15 (as approved by the Executive Committee and avoids confusion as APS plans to move the April Meeting at least once more in 2019); and is consistent with the new APS governance policy.

rhowes@bsu.edu

Media Editor Wanted

This Newsletter has an opening for a Media Editor. The duties of the position are quite open, but in general the Media editor is expected to increase the electronic and social media presence of the Forum and its newsletter. This is to be done in cooperation with the Editor and with the people in charge of media at the APS. If you think you might be interested in volunteering with this, please contact the Editor at otvalls@umn.edu

Have you come across a good book that we should review?

Our Forum is interested in nuclear weapons, other war/peace issues, the environment, energy resources, science policy, uses and misuses of science, and other physics-and-society issues. Please contact our book reviews editor with your suggestions of books we should review: Art Hobson, ahobson@uark.edu.

Major FPS Committees 2017-18

Contact information for chairs of major FPS committees for 2018.

Please submit suggestions for programs or names for nomination to the FPS Executive Committee, Fellowship or Awards to these chairs.

Awards Committee: Arian Pregenzer (apregenzer@gmail.com)

Fellowship Committee: Joel Primack (joel@physics.ucsc.edu)

Nominating Committee: Allen Sessoms (allenlsessoms@gmail.com)

Program Committee: Beverley Hartline (bhartline@mtech.edu)

REVIEWS

The U.S. Government & Renewable Energy: A Winding Road

by Allan R. Hoffman, Pan Stanford Series on Renewable Energy, Volume 7; Pan Stanford Pub. Ltd., Singapore, 134 pages, ISBN 978-981-4745-84-0.

This book recounts the work of Dr. Allan Hoffman, who first took an interest in energy issues as a young assistant professor of physics at the University of Massachusetts, Amherst, with a Ph.D. in low temperature solid state physics from Brown University. He joined a faculty lunch discussion group on nuclear energy and quickly became a popular speaker who presented a technical case against nuclear power. Hoffman then served as the APS representative in the second class of Congressional Fellows in 1974. He accepted a position on the Science Subcommittee of the Senate Commerce Committee as the only scientist on the committee's staff. Hoffman describes his struggles to learn the ins and outs of our political system, a learning curve up which all Congressional Fellows scramble.

In 1976, Hoffman was asked to prepare a comment for the Carter transition team on energy issues while still serving on the commerce committee staff. This assignment brought opportunities for him in the Executive Branch, and he accepted a political appointment as head of the Department of Energy (DOE) Office of Advanced Energy Systems in 1978. DOE had just been established in response to the OPEC oil embargo of 1974. Hoffman was immediately asked to lead a multi-agency study, "A Domestic Policy Review of Solar Energy" where the term "solar energy" encompassed the full range of renewable energy technologies. Hoffman not only dealt with the myriad practical problems of quickly getting the huge project underway but also insisted on public input to the study which was completed at the end of 1978 and published early in 1979.

As Carter prepared to leave the White House, funding for renewable energy programs lost out to funding development efforts for biological synfuels. Hoffman resigned from DOE and moved to the Energy Productivity Center of the Mellon Institute. The Reagan administration focused on nuclear energy and fossil fuels, and the national effort on renewable energy technologies survived barely thanks to a few dedicated DOE program managers. In 1982, Hoffman joined the Office of Technology Assessment as an energy consultant and then, a few months later, he joined the National Academy of Sciences/National Research Council as Executive Director of the Committee on Science Engineering and Public Policy COSEPUP. He directed high profile policy studies and briefed the Science Advisor to the President on a variety of R&D issues. Unfortunately, his duties did not include studies on energy issues.

In 1991, Hoffman accepted a position as Associate Deputy Assistant Secretary in the DOE Office of Utility Technologies. He was able to stay in the Office of Utility Technologies as deputy to the political appointee for Deputy Assistant Secretary. His boss was interested in renewable energy programs so Hoffman worked well with him in establishing a number of efforts at DOE which are described in this book providing the reader with a wide-ranging, very broad introduction to renewable energy technologies under development. Hoffman eventually became involved in Israeli/Palestinian negotiations and quickly became an expert on the interface between potable water and energy. He also played a leadership role in the showcasing of renewable energy at the 1996 Olympics in Atlanta, a tradition followed by subsequent Olympics. He became involved in DOE's co-operative programs with other countries including Germany, Korea, Japan, China and the European Union. These programs supported international R&D on renewable energy. With the advent of the Bush-Cheney administration, Republican political appointees took over leadership of the DOE. They had little interest in renewable energy. Hoffman accepted a two-year detail as Senior Advisor to Winrock International's Clean Energy Group to work on water/energy issues. Back at DOE in 2003, he assumed a position in the Office of Policy and Budget of the Office of Energy Efficiency and Renewable Energy (EERE) of DOE. His position was that of an elder statesman who could be called upon to undertake special projects. He also had considerable control over his own schedule and budget. Although he was 70 years old, Hoffman stayed at the DOE to take advantage of the Obama administration's interest in renewable energy technologies. He was assigned to support the inexperienced head of the offshore wind energy program. Once again he found himself on a steep learning curve about a new technology. He retired at the end of 2012.

The book concludes with a summary of the renewable energy situation today and an optimistic look at its future.

In addition to providing a summary of programs in renewable energy in the U.S. and internationally, this book presents very accessible summaries of the technologies under development in the field. Perhaps more importantly, this thin volume provides a rare look at the role a scientist can play in developing programs in R&D, including the challenges and frustrations of working for the federal government. It should be of particular value to physics students considering careers in government agencies since it highlights both the available rewards and the numerous challenges. Hoffman writes with unusual honesty and presents an unvarnished and unique view of the work that a dedicated physicist can do in developing programs and promoting research on new and needed technologies. I strongly recommend it to all physicists and especially to those interested in influencing policy in support of new technologies and younger people interested in applying their physics training to making national policy.

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Almighty: Courage, Resistance, and Existential Peril in the Nuclear Age

by Dan Zak. Blue Rider Press, hardcover, $27, 416 pp., ISBN 9780399173752.

In this important and carefully researched book's acknowledgements, the author advises: "I am not an historian, physicist, lawyer, diplomat, activist, or beat reporter, so I've depended on people who are."

The point of departure and continuing theme for this work, which in the end requires all the disciplines mentioned and perhaps some others, started at about 2 a.m. on 28 July 2000. Three activists, each with a prior history of non-violent public political demonstration against the use or manufacture of nuclear weapons, broke into the presumably securely-guarded Y-12 National Security Complex in Oak Ridge, Tennessee. The facility was believed to be so immune against invasion some workers jokingly called the facility the Fort Knox of uranium. The three who invaded the "impenetrable" facility included two middle-aged men, both army veterans–Vietnam vet Michael Walli, 53, and housepainter Greg Boertje-obed, 57--and an 82-year-old nun, Sister Megan Rice. They were armed with bolt cutters and three hammers to break the chain-link fence surrounding the property. In addition they carried banners with biblical messages and containers of human blood with which they later marked the Y-12 building. They were confronted by an armed guard in a vehicle to whom the nun bowed and spoke first: "Will you listen to our message?" The surprised guard ordered them to stop and asked "How did you get in here?" Calling from the vehicle, he was soon reinforced by another officer who drew his revolver. The first officer's failure to draw his weapon and act forcefully later resulted in his firing from his position. This caused him and his family a great deal of pain, which the author addresses in detail.

Five hours elapsed before the activists were handcuffed and removed to the county jail. Sister Megan phoned a supporter: "We did everything we wanted to do. It's a miracle." The government authorities at Oak Ridge characterized the matter somewhat differently as "a catastrophe."

At the subsequent trial, the three activists were charged with a multiplicity of felonies including sabotage and destruction of government property. Quickly convicted, the male defendants were given prison terms of just over five years. Sister Megan Rice faced the judge and said: "Please have no leniency with me. To remain in prison for the rest of my life would be the greatest honor you could give me. Thank you. I hope it will happen."

Of course, the judge who seemed relatively compassionate said to the defendant: "Sister Rice, I know you want a life sentence and I just can't accommodate that request. Not only am I confident that you will live long past any sentence I give you, but I am sure that you will continue to use that brilliant mind you have. I only hope you'll rise to effectuate changes in Washington rather than crimes in Tennessee." He gave Sister Rice a sentence of two years and eleven months.

Addressing all the defendants, he had a somewhat surprising comment: "I wish you the best of luck and I appreciate your good work, and I hope you will continue them." Almost two years later, May 22, 2015, the judge ordered the immediate release of the prisoners after an appeals court overturned their conviction by a vote of two to one.

In a later interview, Zak was asked what prompted him to write *Almighty*. He answered: "I was educated in grade school by Catholic sisters; that had something to do with it."

To another question, he was asked what was the most surprising thing that you encountered in your research. He answered: "The money! Since 1940 we have spent ten trillion dollars on the weapons; the only thing we spent more on during that time is non-nuclear defense and Social Security. So you can argue that nuclear weapons have been our third highest priority, ahead of infrastructure, agriculture and on and on."

Zak's book is remarkably comprehensive, starting from physics experiments in Columbia University in the 1940's, running through all aspects of the Manhattan Project, weapons tests in Nevada, further weapons tests in the Marshall Islands, and a full-scale inventory of assembled nuclear weapons in Amarillo, Texas. He discusses the disastrous consequences of nuclear weapons detonations through conflict or accident.

The United States maintains a large atomic and thermonuclear weapons inventory comprising three components. The first are air force planes loaded with gravity bombs. So far, these are the only nuclear weapons used in war with devastation to Hiroshima from a uranium-235 bomb dropped on 6 August 1945, and to Nagasaki from a plutonium-239 bomb dropped on 9 August 1945. The second are ballistic missiles in underground silos throughout the country. They can target anywhere in the world in thirty minutes or less. Unlike the bombers, which can be recalled, once launched the missiles cannot be recalled. The third element in the triad are submarines with nuclear missiles. The bombs launched from the submarines can be targeted against an attack by an enemy and would survive a first strike or a counter-attack.

The following observation by Admiral William Gortney, North American Aerospace Defense Commander, at a conference with students in 2015, might be reassuring or horrific or both: "I don't see us being nuclear-free in my lifetime or in yours."

Two recent publications requiring attention and action by the scientific community and the public should be added to the very extensive bibliography furnished in this book: First, *The Big Science of Stockpile Stewardship*, by Victor H. Reis, Robert J. Hanrahan, and W. Kirk Levedahl, *Physics Today*, Vol. 69, August 2016, pp. 46-53. In the quarter century since the US last exploded a nuclear weapon, an extensive research enterprise has maintained the resources and know-how needed to preserve confidence in the country's stockpile. Second, an article by David E. Sanger and William J. Broad in the *New York Times*, 6 September 2016, with the headline "Obama Unlikely to Vow No First Use of Nuclear Weapons."

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