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Editor's Comments

With this edition *P&S* begins its 40th year of publication. While assembling an index for the newsletter a few months ago I had occasion to look at all back issues from 1973 to the present and so reflect on the evolution of topics over these four decades. Some, such as employment and human rights, have waxed and waned in activity but have been relatively quiet over the past while. Discussions of the troubled state of American science education have remained depressingly steady. Other issues inspired periods of intense debate before largely vanishing in view of changing times and altered national priorities (space-based weapons, missile defense). All aspects of the science of energy production and distribution, energy policy, and the environment are perennial players, as is anything involving the adjective "nuclear" – witness the present edition. And then there those topics that were but distant clouds on the horizon for most physicists 20 years ago but which have come charging to the fore; climate change is the obvious one. Years hence another editor will reflect on a more extensive index and it will be interesting to see if and how current issues have been resolved and what new ones arose in the meantime. I will not attempt to speculate on what those issues might be, but I am confident that given the outstanding expertise, thoughtfulness, and dedication of the science-and-society community the quality of *P&S* will remain first-rate.

Our two feature articles for this edition concern some of the issues regarding nuclear power. In an article adapted from a story published in *Nature*, Declan Butler describes the French approach to storing nuclear waste. Robert Hargraves and Ralph Moir examine the prospects for liquid-fueled reactors, in particular the Liquid Fluoride Thorium Reactor (LFTR), a type of breeder reactor that can be used to burn stocks of highly-enriched uranium, U-233, or plutonium and which is more proliferation-resistant than conventional pressurized water reactors. These articles are timely in view of a recent MIT study on the future of the nuclear fuel cycle, which can be found at http://web.mit.edu/mitei/docs/spotlights/nuclear-fuel-cycle.pdf.

News of the Forum includes summaries of this year's Burton Award and Leo Szilard Lectureship Awards, announcement of new APS Fellows elected through Forum nomination, an update on the Physics of Sustainable Energy Conference to be held at Berkeley in March, and a brief summary of Forum-sponsored sessions to be held at the APS March Meeting in Dallas. Reviewers take a look at books on reinventing the automobile, the long-term consequences of CO_2 emissions, and scientific fraud.

On behalf of the Forum and the Editorial Board I have the honor of thanking the physics community for its support over the past four decades. Your contributions and feedback (kudos and criticisms alike) make this fine publication what it is.

—Cameron Reed

EDITOR'S COMMENTS

FORUM NEWS

LETTERS

ARTICLES

REVIEWS

FORUM NEWS

2011 Forum Award Recipients Announced

Recipients of the Forum's Joseph A. Burton and Leo Szilard Lectureship Awards for 2011 have been announced. The Burton Award is given to recognize outstanding contributions to the public understanding or resolution of issues involving the interface of physics and society. The recipient for 2011 is **M. Granger Morgan**, Head of the Department of Engineering and Public Policy at Carnegie Mellon University *"For his public service and major contributions in the field of risk analysis and its application leading to increased public understanding of issues at the interface of physics and society."* The Leo Szilard Lectureship Award is given to recognize outstanding accomplishments by physicists in promoting the use of physics for the benefit of society in such areas as the environment, arms control, and science policy. The 2011 recipient is **John F. Ahearne** (Sigma Xi) *"For nearly four decades of selfless dedication to the nation, and for providing a voice of reason in advising on the use of physics for the benefit of society in areas as diverse as nuclear energy, arms control, risk communication, biological safety and ethics in science and engineering." P&S* extends hearty congratulations to Drs. Morgan and Ahearne on their well-deserved recognitions, and extends thanks to the members of the selection committee for their careful work: Donald Prosnitz (Chair), James L. Bonomo, Anthony Fainberg, and Rich Muller.

The deadline for nominations for the 2012 Burton and Szilard Awards is July 15, 2011. Information on Forum prizes and awards is at www.aps.org/units/fps/awards/index.cfm.

New Fellows Elected through the Forum

We are pleased to report that four members of the APS were elected to Fellowship at the November Council meeting through FPS nomination: **Neil De Grasse Tyson** (American Museum of Natural History), for his leadership as an educator who has excited millions of people about astrophysics and science, and for his service to the U.S. on commissions on NASA, space exploration, and the aerospace industry; **James Fuller** (University of Washington) in recognition of his pivotal contributions to international arms control, nuclear disarmament, and proliferation prevention and for his leadership in educational outreach; **Richard Rowberg** (National Academy of Sciences), for many contributions to the incorporation of technical insight into government decisions through his many advisory roles to the Congress on science and technology policy; and **Andrew Zwicker** (Princeton Plasma Physics Laboratory) for his outstanding service to Physics and Society issues and his excellent leadership on innovative education research and education outreach. Thanks are also due members of the Fellowship Committee for their good work: Pushpa Bhat (chair), Charles Ferguson, Siegfried Hecker, Usha Varshney, and Pete Zimmerman.

FPS Election Results

Results of Forum elections were announced just as P&S was going to press. Congratulations to Valerie Thomas (Vice Chair) and Pierce Corden and Norman Gelfand (Members At-Large).

APS Congressional Science Fellowships

Applications for APS Congressional Science Fellowships are due January 15, 2011. Details: aps.org/policy/fellowships/congressional.cfm. Congressional Fellowships are an opportunity for physicists who want to apply their knowledge and skills beyond the lab bench to the conduct of national policy. Fellows serve a one-year term working in the office of a Member of Congress or for a congressional committee. The fellowship term is for one year, usually running September through August. Benefits include a stipend of $70,000 per year, a relocation allowance, an allowance for in-service travel for professional development and reimbursement for health insurance up to a specified maximum.

FPS to Host Sessions at APS March Meeting

The annual March meeting of the APS will be held at the Dallas Convention Center from March 21-25, 2011. FPS is hosting two sessions by itself plus one jointly with the Forum on Education. The tentative titles of presentations are given here; times and locations were not available at press time.

The Physics, Technology, and Future of Robotics. Randy M. Dunse: Finding Fun and Fame in Physics with Robots; Paul Bouchier: Recent Advances in Robotics and Career Opportunities for Physicists; Brian L. Huff: The Use of Physics in the Engineering of Robots; Steve Rainwater: Robot Competitions Around the World. ***Science, Art, and Culture.*** David Hanson: Robotics in the World of Entertainment; Stephen Warton: XPower plus the Physics of Rodeo; Joe DiPrima: Singing Tesla Coils; Davey Griffin: The Science of Barbeque (Texas Style). ***Broader Impact: Partnerships and Resources to achieve Successful Public and K-12 Outreach and Engagement (jointly with FEd).*** Larry Bell: Science Museum Resources and Partnerships for Public and K-12 Outreach and Engagement; Philip Hammer: Professional Society Resources and Partnerships for Public and K-12 Outreach and Engagement; Aditi Risbud: National Laboratory Resources and Partnerships for Public and K-12 Outreach and Engagement; James Wynne: Marshaling Corporate Resources for Public and K-12 Technical Education Outreach and Engagement; Greta Zenner Petersen: University Research Center Resources and Partnerships for Public and K-12 Outreach and Engagement.

Second Conference on the Physics of Sustainable Energy: Efficiency and Renewables

A popular energy workshop is making a repeat performance. The first conference on the physics of sustainable energy was held at the University of California in Berkeley in March 2008, and the proceedings were published as #1044 in the AIP Conference Series. (For a review of the proceedings, see *Physics & Society*, July 2009, pg. 22.) In response to the positive enthusiasm about the conference, a second one is being held, again at UC Berkeley (Evans Hall 10), on March 5-6, 2011 under the sponsorship of the APS Forum on Physics and Society, the APS Topical Group on Energy Research and Applications, and the American Association of Physics Teachers. International experts will give presentations on the technical background necessary to understand issues connected with using energy more efficiently and producing it renewably.

The event sold out last time, so we recommend signing up in advance. The cost is $100 ($80 for students) for 24 talks, a 400-page book and 2 lunches, plus $35 for the banquet at the Berkeley Faculty Club. The event is being organized by Dave Hafemeister, Barbara Levi, Dan Kammen and Pete Schwartz. Register by credit card or check below. Contact dhafemei@calpoly.edu (805-544-5096) for questions. Information at www.calpoly.edu/~dhafemei. Tentative schedule:

Saturday, March 5 • 8:30 am

Energy Policy

CA State Policy, Dian Grueneich (former CA PUC Commissioner)

Science and Policy Innovations for a Low-Carbon Economy, Dan Kammen (UC Berkeley, World Bank)

Energy in the Developing World, Ashok Gadgil (LBL)

Energy & Water Connection, Michael Webber (Univ. Texas)

Environmental Effects of Fossil Fuels

NAS 2010 Study, Hidden Environmental Costs of Fossil Energy, Chris Field (Carnegie Inst. of Washington)

Studying the Causes of Recent Climate Change, Benjamin Santer (LLNL)

Non-Carbon Greenhouse Gasses, Katey Anthony (U. Alaska)

Global Circulation Models, Inez Fung (UC Berkeley)

Carbon Sequestration, Julio Friedmann (LLNL)

Decarbonizing Transportation

Transportation Mode Switching, Betty Deakin (UC Berkeley)

Electric Cars: Hybrids/PHEV/BEV, Dan Sperling (Inst. Transportation Studies, UC Davis)

Low Carbon Transportation Fuels of the Future, Tim Lipman (Trans. Sustainability Res. Ctr., UC Berkeley)

Banquet Speaker: Energy Efficiency (1970 to 2030): From Sustainability to Carbon Taxes

Art Rosenfeld (former CEC Commissioner and Fermi Award recipient)

Sunday, March 6 • 8:30 am

Enhanced Efficiency Buildings

Exploring the Limits of Energy Efficiency in Office Buildings, David Claridge (Texas A&M)

Energy Simulation Tools for Buildings, Philip Haves (LBL)

Smart Buildings Using Demand Response, Mary Ann Piette (LBL)

Appliance & Lighting Energy Standards, Greg Rosenquist (LBL)

Renewable Energy

NAS 2009 Study on Electricity from Renewable Resources, K. John Holmes (NAS Study Director)

APS 2010 Study on Integrating Renewables on the Electricity Grid, George Crabtree (APS Study Director, ANL)

Offshore Wind Power, Walter Musial (NREL)

Thermodynamic Efficient Solar Systems, Roland Winston (UC Merced Energy Research Institute)

Photovoltaic Roof Systems (Solyndra)

Photovoltaic Concentrator Systems, Steve Horne (Sol Focus)

Topics in Nuclear Power: Small Reactors and Nuclear Waste, Robert Budnitz (LBL)

Registration

Register via credit card at www.aps.org/units/fps/meetings/energy/, or send check to APS Meetings, One Physics Ellipse, College Park, MD, 20740-3844.

☐ $100 registration ☐ $80 Student ☐ $35 Banquet

Total_______

Name ______________________________

Address ____________________________

Phone ______________________________

Email ______________________________

Home Institution _____________________

ARTICLES

The French Approach to Nuclear Waste

Declan Butler

[This article is adapted from "France digs deeper for nuclear waste" published in Nature ***466****(7308), 804-805 (12 August 2010). We are grateful to Dr. Butler and* Nature *for permission to edit it. The article is at* www.nature.com/news/2010/100810/full/466804a.html*]*

The American physics community will be acutely aware of the on-again, off-again long-term nuclear waste repository proposed for Yucca Mountain, which now looks to be abandoned after two decades of work and more than $10 billion in investment (*P&S* July 2008, January 2009, April 2009, April 2010). One of the main problems is that the selection of Yucca Mountain by Congress in 1987 was, from the outset, a political rather than a scientific choice. Efforts by the United States government to find a site have been stymied by opposition from individual states, where representatives and constituents are uneasy about having a nuclear dump in their backyard. In contrast, the Canadian government established a Nuclear Waste management Organization (NWMO) to develop an approach involving significant public input for the long-term management of their nuclear fuel (*P&S*, October 2009). Similarly, European countries have taken a more scientific and stepwise approach to locating sites, which has engendered greater public confidence; for example, Sweden and Finland involved local communities in decisions from the outset, which has increased acceptability [1]. As a result, Finland and Sweden plan to open deep geological repositories in about 2020-2025, whereas Germany hopes to open its own long-term repository in 2035. Several smaller European countries have banded together to form a European Repository Development Organization to work on the concept of a shared facility.

France generates about 80% of its electricity from 58 nuclear power plants, and is a world leader in the technology. Nuclear power enjoys staunch cross-party support in the country; anti-nuclear groups enjoy little public clout.

The Bure Laboratory

Half a kilometer beneath rolling wheat fields outside the small town of Bure in the Lorraine region of northeast France, the country is preparing to dispose of its radioactive waste. In a €1-billion (US$1.3 billion) underground laboratory, the French National Radioactive Waste Management Agency (ANDRA) is testing the soundness of the rock and the technologies to contain the waste. ANDRA scientists are convinced that the rock formations can safely house highly radioactive waste, and plan an industrial-scale facility that would open deep below a site nearby in 2025. The surface-level footprint of the site will occupy about 30 square kilometers; the underground repository itself will be smaller. It would be among the world's first geological repositories for high-and medium-level long lived nuclear waste, and the largest. Patrick Landais, a geologist and scientific director of ANDRA, questions Yucca's geological suitability not least due to nearby volcanoes, and says that there are far better geological sites in the US than Yucca Mountain.

The Bure lab, authorized by the French government in 1999, has largely established the geological suitability of the area, and its findings have been endorsed by international experts. Now it is shifting into high gear, spending €100 million a year on research to pin down exactly how waste would be stored at the planned repository. ANDRA must present a blueprint for the repository to the government in 2014; if approved by the French National Assembly in 2016, construction would begin the following year. The assembly will then consider licensing the facility to open in 2025. Once completed, the repository would store all of the existing 2,300 cubic meters of high level and 42,000 cubic meters of medium-level long-lived radioactive waste which has been generated by France's nuclear power stations as well as new waste created over at least the next 20 years. The existing waste is currently being stored at temporary sites in La Hague, Marcoule and Cadarache. The economic incentives that the facility offers to the Bure region have been welcomed by local officials, and there has been little effective resistance to the facility. Mobilizing public opinion to oppose the repository is difficult because the majority of the French are indifferent to nuclear power issues. Greenpeace France's nuclear campaign does not oppose geological storage research, but has expressed concern that plans to seal the repository after a century of use would make it almost impossible to deal with a subsequent problem in the facility.

The lab itself contains no radioactive waste, and never will. Instead, researchers at Bure are focusing on testing the rock and prototype waste-containment strategies. Almost all of the research results are analyzed remotely. Once scientists have installed their experiments, the output of instruments lining the tunnels is transmitted via the Internet to ANDRA's own researchers, along with 80 collaborating labs at other

Subterranean experimental gallery of the Bure laboratory. Copyright 2006, Eric Sutre. Other photos of the facility can be found at www.andra.fr/index.php?id=itemmenu_phototheque_196_tout_1_1

research agencies and universities in France and other European countries involved in the project. A remote data-access system presents users with a three-dimensional representation of the galleries in which one can zoom in on any tunnel to find an experiment and pull up its data output and graphs in real time. Despite much remote access to the data, dozens of scientists and engineers still descend into the facility every day. This author had the opportunity to make the descent, accompanied by Dr. Landais.

Experiments

On entering into the laboratory one is greeted by galleries crammed with scientific instruments. Incessant tannoys (loudspeaker systems) and the din of pneumatic drills and earth borers at work extending the lab, fill the air. The tunnel walls are reinforced with concrete, steel ribs and bolts, but here and there the grey 150-million-year-old Callovo-Oxfordian argillaceous rock (sedimentary rock formed from clay deposits) that would seal the repository is left bare.

Experimental boreholes in the walls carry about 3,500 sensors, which take the pulse of almost every mechanical, chemical and hydrogeological aspect of the rock. The data are fed into models that characterize the rock and also predict its future behavior over periods from decades to more than a million years. The experiments ultimately aim to answer one key question: can France's most dangerous radioactive wastes be safely contained inside this 150-metre-thick layer of rock? The high-level waste includes the fission products such as cesium-134, cesium-137, strontium-90, and minor actinides such as curium-244 and americium-241. Most nuclear fuel in France is reprocessed to extract useful uranium and plutonium and to concentrate the waste. Although this high-level material comprises just 0.2% of the country's nuclear waste by volume, it accounts for 95% of its total radioactivity.

The waste is immobilized by blending it into glass in a complex vitrification process which incorporates the radionucleotides in the atomic structure of the glass, a process that was pioneered by the French. The molten glass is poured into stainless steel casks, which are then placed inside steel barrels. Robots in the Bure repository will push these barrels into 70-centimetre-diameter boreholes called alveoli, which are drilled 40 meters horizontally into the walls of the main access tunnels. The medium-level radioactive waste, which comes from used reactor equipment and reagents, would be compressed into circular cakes and piled into steel canisters before being encased in concrete and stored in the tunnels.

Scientists at Bure are already testing the stability of the glass that would be used to immobilize the high-level waste, the rates of corrosion of the stainless steel casks, and the fate of the hydrogen gas that this degradation releases. They are also assessing all the interactions between the glass, the layers of steel and the rock in prototype alveoli. The canisters are designed so that heat from radioactive decay inside does not warm their surface beyond 90°C. Tests using mock-up canisters have shown that prolonged exposure to this temperature does not cause the rock to fissure. Although the volume of high-level waste is much smaller than that of medium-level waste, it will require double the amount of storage space because the hot casks must be spaced out with empty ones to avoid overheating. The scientists are also investigating ways to reduce the volume of waste to be sent to the facility, such as extracting radioactive elements from bulky graphite fuel elements and then concentrating them in order to allow much more medium-level waste to be packed into the repository's chambers. The repository could eventually operate for at least a century, after which it would be sealed. A few thousand years later, the stainless steel would corrode away until it leaving the vitrified waste, and the rock itself, to provide containment.

The Long Term

ANDRA director Landais warns that rock is not an absolute barrier, as radionuclides would slowly diffuse through it. Of most concern at Bure are radioactive iodide and chloride anions, which are the most mobile in this type of rock. But Landais says that it would take hundreds of thousands of years for them to diffuse to the surface, by which time their low concentrations and lower levels of radioactivity would render any environmental contamination negligible. A more worrying problem is the possibility of a rock fracture, which could lead to radioactive leaks. But the research at Bure has largely confirmed that the layer of rock that would house the repository is homogenous, highly impermeable to water movement, and free from faults and seismic risk. Geologists at Bure are confident that it is a safe, predictable environment for nuclear waste: the rock is 150 million years old, hasn't budged in the past 20 million years, and won't in the next, they say. In addition, at the surface, researchers are extensively sampling the air, water and soils in a 250-square kilometer zone around the site to get a comprehensive baseline of environmental data. An observatory, created jointly in April with France's agricultural research agency, INRA, will monitor this ecosystem for at least a century.

ANDRA researchers are optimistic that their efforts will lead to the opening of a safe, secure, publicly-acceptable repository, and thereby contribute to France's continued successful program of nuclear-generated power.

[1] See D. Sarewitz, "Politicize me," Nature ***467****, 26 (2 September 2010).*

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Liquid Fuel Nuclear Reactors

Robert Hargraves and Ralph Moir

Today's familiar pressurized water nuclear reactors use solid fuel — pellets of uranium dioxide in zirconium fuel rods bundled into fuel assemblies. These assemblies are placed within the reactor vessel under water at 160 atmospheres pressure and a temperature of 330°C. This hot water transfers heat from the fissioning fuel to a steam turbine that spins a generator to make electricity. Alvin Weinberg invented the pressurized water reactor (PWR) in 1946 and such units are now used in over 100 commercial power-producing reactors in the US as well as in naval vessels.

Weinberg also pursued research on liquid fuel-reactors, which offer a number of advantages over their solid-fueled counterparts. In this article we review some of the history, potential advantages, potential drawbacks, and current research and development status of liquid-fueled reactors. Our particular emphasis is on the Liquid Fluoride Thorium Reactor (LFTR).

Before describing the characteristics of liquid-fuel reactors we review briefly in this paragraph the situation with PWRs. In a conventional PWR the fuel pellets contain UO_2 with fissile U-235 content expensively enriched to 3.5% or more, the remainder being U-238. After about 5 years the fuel must be removed because the fissile material is depleted and neutron-absorbing fission products build up. By that time the fuel has given up less than 1% of the potential energy of the mined uranium, and the fuel rods have become stressed by internal temperature differences, by radiation damage that breaks covalent UO_2 bonds, and by fission products that disturb the solid lattice structure (Figure 1). As the rods swell and distort, their zirconium cladding must continue to contain the fuel and fission products while in the reactor and for centuries thereafter in a waste storage repository.

In contrast, fluid fuels are not subjected to the structural stresses of solid fuels: liquid-fuel reactors can operate at atmospheric pressure, obviating the need for containment vessels able to withstand high-pressure steam explosions. Gaseous fission products like xenon bubble out while some fission products precipitate out and so do not absorb neutrons

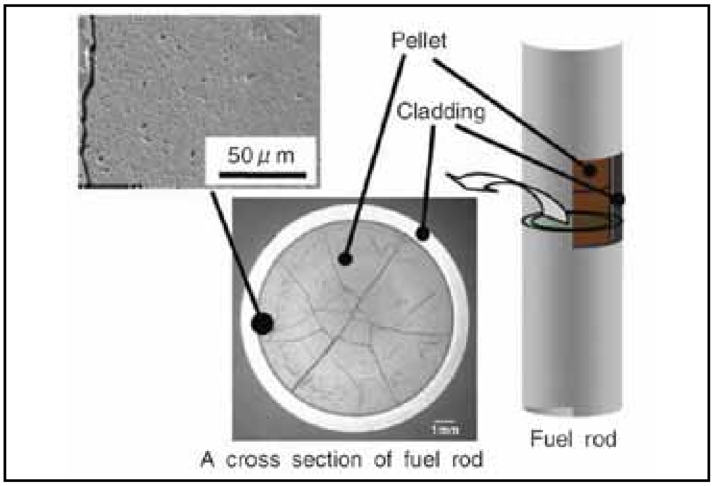

Figure 1. *Solid fuel rods are stressed by fission products, radiation, and heat. (Courtesy of Japan Atomic Energy Agency R&D Review 2008)*

from the chain reaction. Like PWRs, liquid-fuel reactors can be configured to breed more fuel, but in ways that make them more proliferation resistant than the waste generated by conventional PWRs. Spent PWR fuel contains transuranic nuclides such as Pu-239, bred by neutron absorption in U-238, and it is such long-lived transuranics that are a core issue in waste storage concerns. In contrast, liquid-fuel reactors have the potential to reduce storage concerns to a few hundred years as they would produce far fewer transuranic nuclides than a PWR.

History of liquid fuel reactors

The world's first liquid fuel reactor used uranium sulfate fuel dissolved in water. Eugene Wigner conceived this technology in 1945, Alvin Weinberg built it at Oak Ridge, and Enrico Fermi started it up. The water carries the fuel, moderates neutrons (slows them to take advantage of the high fission cross-section of uranium for thermal-energy neutrons), transfers heat, and expands as the temperature increases, thus lowering moderation and stabilizing the fission rate. Because the hydrogen in ordinary water absorbs neutrons, an aqueous reactor, like a PWR, cannot reach criticality unless fueled with uranium enriched beyond the natural 0.7% isotopic abundance of U-235. Deuterium absorbs few neutrons, so, with heavy water, aqueous reactors can use unenriched uranium. Weinberg's aqueous reactor fed 140 kW of power into the electric grid for 1000 hours. The intrinsic reactivity control was so effective that shutdown was accomplished simply by turning off the steam turbine generator.

In 1943, Wigner and Weinberg also conceived a liquid fuel thorium-uranium breeder reactor, for which the aqueous reactor discussed above was but the first step. The fundamental premise in such a reactor is that a blanket of thorium Th-232 surrounding the fissile core will absorb neutrons, with some nuclei thus being converted ("transmuted") to Th-233. Th-233, in turn, beta decays to protactinium-233 and then to U-233, which is itself fissile and can be used to refuel the reactor. Later, as Director of Oak Ridge, Weinberg led the development of the liquid fluoride thorium reactor (LFTR), the subject of this article. Aware of the future effect of carbon dioxide emissions, Weinberg wrote "humankind's whole future depended on this." The Molten Salt Reactor Experiment, powered first with U-235 and then U-233, operated successfully over 4 years, through 1969. To facilitate engineering tests, the thorium blanket was not installed; the U-233 used in the core came from other reactors breeding Th-232. The MSRE was a proof-of-principle success. Fission-product xenon gas was continually removed to prevent unwanted neutron absorptions, online refueling was demonstrated, minor corrosion of the reactor vessel was addressed, and chemistry protocols for separation of thorium, uranium, and fission products in the fluid fluorine salts were developed. Unfortunately, the Oak Ridge work was stopped when the Nixon administration decided instead to fund only the solid fuel Liquid sodium Metal cooled Fast Breeder Reactor (LMFBR), which could breed plutonium-239 faster than the LFTR could breed uranium-233.

The Liquid Fluoride Thorium Reactor

A significant advantage of using thorium to breed U-233 is that relatively little plutonium is produced from the Th-232 because six more neutron absorptions are required than is the case with U-238. The U-233 that is bred is also proliferation-resistant in that the neutrons that produce it also produce 0.13% contaminating U-232 which decays eventually to thallium, which itself emits a 2.6 MeV penetrating gamma radiation that would be obvious to detection monitors and hazardous to weapons builders. For example, a year after U-233 separation, a weapons worker one meter from a subcritical 5 kg sphere of it would receive a radiation dose of 4,200 mrem/hr; death becomes probable after 72 hours exposure. Normally the reactor shielding protects workers, but modifying the reactor to separate U-233 would require somehow adding hot cells and remote handling equipment to the reactor and also to facilities for weapons fabrication, transport, and delivery. Attempting to build U-233-based nuclear weapons by modifying a LFTR would be more hazardous, technically challenging and expensive than creating a purpose-built weapons program using uranium enrichment (Pakistan) or plutonium breeding (India, North Korea).

Work on thorium-based reactors is currently being actively pursued in many countries including Germany, India, China, and Canada; India plans to produce 30% of its electricity from thorium by 2050. But all these investigations involve solid fuel forms. Our interest here is with the liquid-fueled form of a thorium-based U-233 breeder reactor.

The configuration of a LFTR is shown schematically in Figure 2. In a "two-fluid" LFTR a molten eutectic mixture of salts such as LiF and BeF_2 containing dissolved UF_4 forms the central fissile core. ("Eutectic" refers to a compound that solidifies at a lower temperature than any other compound of the same chemicals.) A separate annular region containing molten Li and Be fluoride salts with dissolved ThF_4 forms the fertile blanket. Fission of U-233 (or some other "starter" fissile fuel) dissolved in the fluid core heats it. This heated fissile fluid attains a noncritical geometry as it is pumped through small passages inside a heat exchanger. Excess neutrons are absorbed by Th-232 in the molten salt blanket, breeding U-233 which is continuously removed with fluorine gas and used to

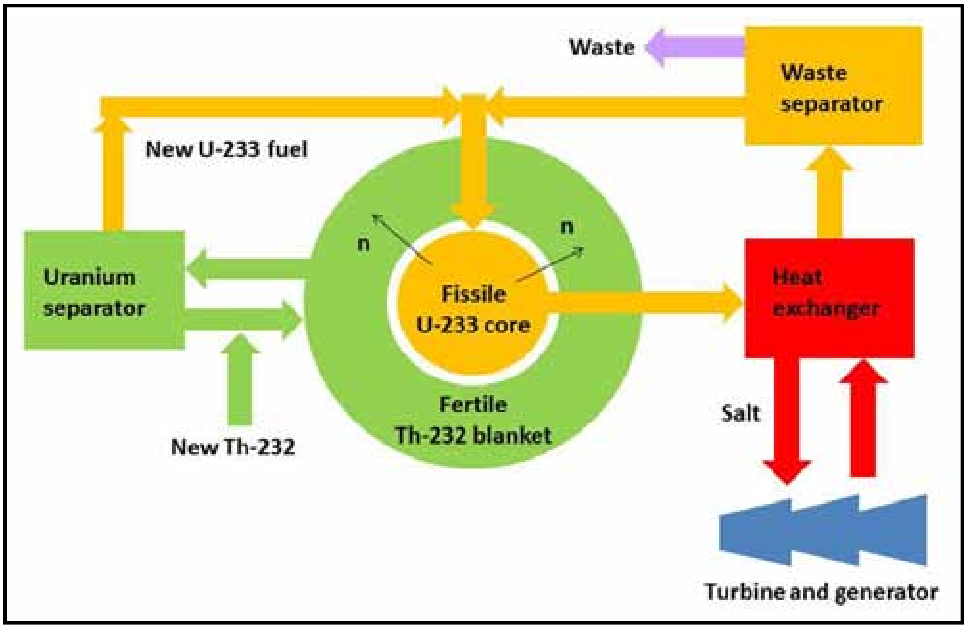

Figure 2. *In a two-fluid liquid fluoride thorium reactor the fission of U-233 in the core heats molten carrier salt (yellow). It attains a noncritical geometry as it is pumped through small passages in a heat exchanger. A separate circuit of molten salt (red), with no radioactive materials, heats gases in the closed cycle helium gas turbine which spins to generate power. Excess neutrons are absorbed by Th-232 in the molten salt blanket (green), breeding U-233 which is removed with fluorine gas. Fission products are chemically removed in the waste separator, leaving uranium and transuranics in the molten salt fuel. All three molten salt circuits are at atmospheric pressure.*

refuel the core. Fission products are chemically removed in the waste separator, leaving uranium and transuranics in the molten salt fuel. From the heat exchanger a separate circuit of molten salt heats gases in the closed cycle helium gas turbine which generates power. All three molten salt circuits are at atmospheric pressure.

LFTRs would reduce waste storage issues from millions of years to a few hundred years. The radiotoxicity of nuclear waste arises from two sources: the highly radioactive fission products from fission and the long-lived actinides from neutron absorption. Thorium and uranium fueled reactors produce essentially the same fission products, whose radiotoxicity in 500 years drops below that of the original ore mined for uranium to power a PWR. A LFTR would create far fewer transuranic actinides than a PWR. After 300 years the LFTR waste radiation would be 10,000 times less than that from a PWR (Figure 3). In practice, some transuranics will leak through the chemical waste separator, but the waste radiotoxicity would be < 1% of that from PWRs. Geological repositories smaller than Yucca mountain would suffice to sequester the waste.

Existing PWR spent fuel can be an asset. A 100 MW LFTR requires 100 kg of fissile material (U-233, U-235, or Pu-239) to start the chain reaction. The world now has 340,000 tonnes of spent PWR fuel, of which 1% is fissile material that could start one 100 MW LFTR per day for 93 years.

A commercial LFTR will make just enough uranium to sustain power generation, so diverting uranium for weapons use would stop the reactor, alerting authorities. A LFTR will have little excess fissile material; U-233 is continuously generated to replace the fissioned U-233, and Th-232 is continuously introduced to replace the Th-232 converted to the U-233. Terrorists could not steal this uranium dissolved in a molten salt solution along with lethally radioactive fission products inside a sealed reactor, which would be subject to the usual IAEA safeguards of physical security, accounting and control of all nuclear materials, surveillance to detect tampering, and intrusive inspections.

It is also possible to configure a liquid-fuel reactor that would involve no U-233 separation. For example, the single fluid denatured molten salt reactor (DMSR) version of a LFTR

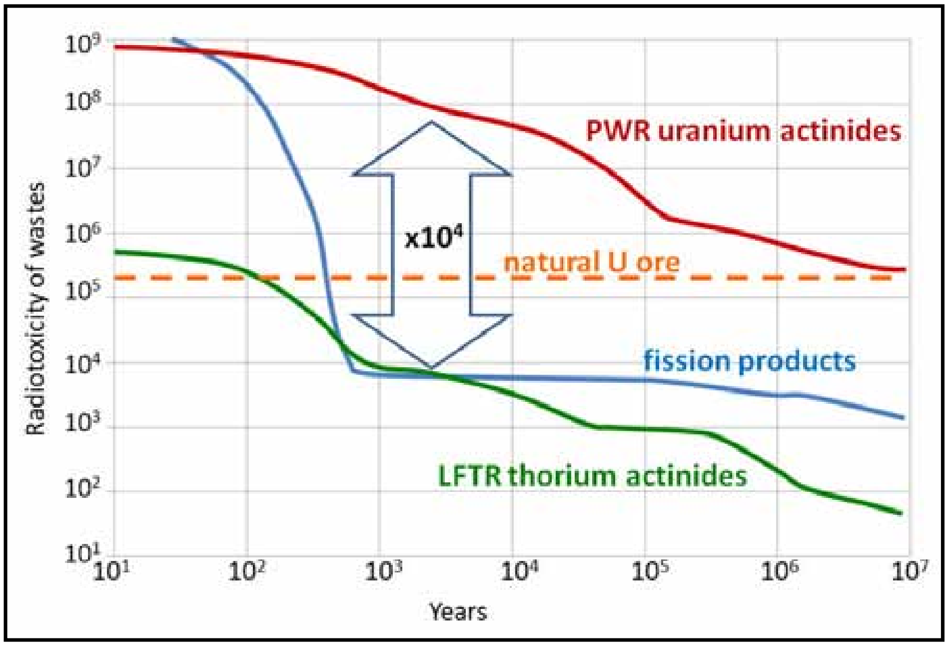

Figure 3. *A LFTR produces much less long-lived waste than PWRs. (Adapted from Sylvan David et al, Revisiting the thorium-uranium nuclear fuel cycle, Europhysics news, 38(2), p 25.)*

with no U-233 separation is fed with both thorium and < 20% enriched uranium. It can operate up to 30 years before actinide and fission product buildup requires fuel salt replacement, while consuming only 25% of the uranium a PWR uses.

Starting up LFTRs with plutonium can consume stocks of this weapons-capable material. Thorium fuel would also reduce the need for U-235 enrichment plants, which can be used to make weapons material as easily as power reactor fuel. U-233, at the core of the reactor, is important to LFTR development and testing. With a half-life of only 160,000 years, it is not found in nature. The US has 1,000 kg of nearly irreplaceable U-233 at Oak Ridge. It is now slated to be destroyed by diluting it with U-238 and burying it forever, at a cost of $477 million. This money would be far better invested in LFTR development.

Can LFTR Power be Cheaper than Coal Power?

Burning coal for power is the largest source of atmospheric CO_2, which drives global warming. We seek alternatives such as burying CO_2 or substituting wind, solar, and nuclear power. A source of energy cheaper than coal would dissuade nations from burning coal while affording them a ready supply of electric power.

Can a LFTR produce energy cheaper than is currently achievable by burning coal? Our target cost for energy cheaper than from coal is $0.03/kWh at a capital cost of $2/watt of generating capacity. Coal costs $40 per ton, contributing $0.02/kWh to electrical energy costs. Thorium is plentiful and inexpensive; one ton worth $300,000 can power a 1,000 megawatt LFTR for a year. Fuel costs for thorium would be only $0.00004/kWh.

The 2009 update of MIT's *Future of Nuclear Power* shows that the capital cost of new coal plants is $2.30/watt, compared to LWRs at $4/watt. The median of five cost studies of large molten salt reactors from 1962 to 2002 is $1.98/watt, in 2009 dollars. Costs for scaled-down 100 MW reactors can be similarly low for a number of reasons, six of which we summarize briefly:

Pressure. The LFTR operates at atmospheric pressure, obviating the need for a large containment dome. At atmospheric pressure there is no danger of an explosion.

Safety. Rather than creating safety with multiple defense-in-depth systems, LFTR's intrinsic safety keeps such costs low. A molten salt reactor cannot melt down because the normal operating state of the core is already molten. The salts are solid at room temperature, so if a reactor vessel, pump, or pipe ruptured they would spill out and solidify. If the temperature rises, stability is intrinsic due to salt expansion. In an emergency an actively cooled solid plug of salt in a drain pipe melts and the fuel flows to a critically safe dump tank. The Oak Ridge MSRE researchers turned the reactor off this way on weekends.

Heat. The high heat capacity of molten salt exceeds that of the water in PWRs or liquid sodium in fast reactors, allowing compact geometries and heat transfer loops utilizing high-nickel metals.

Energy conversion efficiency. High temperatures enable 45% efficient thermal/electrical power conversion using a closed-cycle turbine, compared to 33% typical of existing power plants using traditional Rankine steam cycles. Cooling requirements are nearly halved, reducing costs and making air-cooled LFTRs practical where water is scarce.

Mass production. Commercialization of technology lowers costs as the number of units produced increases due to improvements in labor efficiency, materials, manufacturing technology, and quality. Doubling the number of units produced reduces cost by a percentage termed the learning ratio, which is often about 20%. In The Economic Future of Nuclear Power, University of Chicago economists estimate it at 10% for nuclear power reactors. Reactors of 100 MW size could be factory-produced daily in the way that Boeing Aircraft produces one airplane per day. At a learning ratio of 10%, costs drop 65% in three years.

Ongoing research. New structural materials include silicon-impregnated carbon fiber with chemical vapor infiltrated carbon surfaces. Such compact thin-plate heat exchangers promise reduced size and cost. Operating at 950°C can increase thermal/electrical conversion efficiency beyond 50% and also improve water dissociation to create hydrogen for manufacture of synthetic fuels such that can substitute for gasoline or diesel oil, another use for LFTR technology.

In summary, LFTR capital cost targets of $2/watt are supported by simple fluid fuel handling, high thermal capacity heat exchange fluids, smaller components, low pressure core, high temperature power conversion, simple intrinsic safety, factory production, the learning curve, and technologies already under development. A $2/watt capital cost contributes $0.02/kWh to the power cost. With plentiful thorium fuel, LFTRs may indeed generate electricity at less than $0.03/kWh, underselling power generated by burning coal. Producing one LFTR of 100 MW size per day could phase out all coal burning power plants worldwide in 38 years, ending 10 billion tons per year of CO_2 emissions from coal plants.

Development Status of LFTRs

A number of LFTR initiatives are currently active around the world. France supports theoretical work by two dozen scientists at Grenoble and elsewhere. The Czech Republic supports laboratory research in fuel processing at Rez, near Prague. Design for the FUJI molten salt reactor continues in Japan. Russia is modeling and testing components of a molten salt reactor designed to consume plutonium and actinides from PWR spent fuel, and LFTR studies are underway in Canada and the Netherlands. US R&D funding has been relatively insignificant, except for related studies of solid fuel, molten salt cooled reactors at UC Berkeley and Oak Ridge, which hosted a conference to share information on fluoride reactors in September 2010.

Developing LFTRs will require advances in high temperature materials for the reactor vessel, heat exchangers, and piping; chemistry for uranium and fission product separation; and power conversion systems. The International Generation IV Forum budgeted $1 billion over 8 years for molten salt reactor development. We recommend a high priority, 5-year national program to complete prototypes for the LFTR and the simpler DMSR. It may take an additional 5 years of industry participation to achieve capabilities for mass production. Since LFTR development requires chemical engineering expertise and liquid fuel technology is unfamiliar to most nuclear engineers today, nuclear engineering curricula would have to be modified to include exposure to such material. The technical challenges and risks that must be addressed in a prototype development project include control of salt container corrosion, recovery of tritium from neutron irradiated lithium salt, management of structural graphite shrinking and swelling, closed cycle turbine power conversion, and maintainability of chemical processing units for U-233 separation and fission product removal. Energy Secretary Chu expressed historical criticism of the technology in a letter to Senator Jeanne Shaheen (D-NH) answering questions at his confirmation hearings, "One significant drawback of the MSR technology is the corrosive effect of the molten salts on the structural materials used in the reactor vessel and heat exchangers; this issue results in the need to develop advanced corrosion-resistant structural materials and enhanced reactor coolant chemistry control systems", and "From a non-proliferation standpoint, thorium-fueled reactors present a unique set of challenges because they convert thorium-232 into uranium-233 which is nearly as efficient as plutonium-239 as a weapons material." He also recognized, however, that "Some potential features of a MSR include smaller reactor size relative to light water reactors due to the higher heat removal capabilities of the molten salts and the ability to simplify the fuel manufacturing process, since the fuel would be dissolved in the molten salt."

Other hurdles to LFTR development may be the regulatory environment and the prospect of disruption to current practices in the nuclear industry. The Nuclear Regulatory Commission will need funding to train staff qualified to work with this technology. The nuclear industry and utilities will be shaken by this disruptive technology that changes whole fuel cycle of mining, enrichment, fuel rod fabrication, and refueling. Ultimately, the environmental and human development benefits will be achieved only when the cost of LFTR power really proves to be cheaper than from coal.

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REVIEWS

Reinventing the Automobile

By William J. Mitchell, Christopher E. Borroni-Bird, and Lawrence D. Burns, MIT Press, Cambridge, MA, 2010, ISBN 978-0-262-01382-6, 227 pages

For a person to move from one place to another within a city requires energy to produce and maintain the kinetic energy of motion, but with our present system of personal automobile transport, this required energy is much less than one percent of the energy in the fuel consumed. This system requires large personal expense to the person using it (now over 50 cents per mile), uses valuable and expensive space for parking, wastes lots of time due to traffic congestion, kills tens of thousands of Americans each year and seriously injures many more, causes serious environmental pollution, contributes heavily to our national economic and political problems (including two recent wars), and so on. If we could start from scratch and redesign the system, how much better could it be?

That is the question addressed in the book "Reinventing the Automobile", and it is loaded with solutions. The solution begins with small, light weight, electrically driven cars. Numerous designs are illustrated. For example, one which folds up to fit into small spaces is a four-by-four foot square that can be rotated in place to any angle and is entered and exited from the front directly onto the sidewalk, thus minimizing parking space. Still smaller is a 100-pound, 2-wheel Segway with a top speed of 12.5 miles per hour.

The solution includes a mobility internet system connecting all nearby cars that manages traffic flow, safety, parking, and electric supply, and even allows driving on auto-pilot. Congestion and collisions are greatly reduced, and convenience is enhanced. In one example, occupants can leave the car at the destination and the car will find a parking space, park itself, and later be recalled by remote control.

There is a chapter on battery charging infrastructure which includes overnight charging at home, inductive charging from parking spaces, and even charging from the road surface while driving.

There is a chapter on integrating electric cars into smart electric grids to take advantage of dynamic pricing and real time feedback loops for buying, storing, and selling electricity. This integrated system is used for trip planning to minimize travel time and parking costs; parking spaces are continuously auctioned in real time. There is a lengthy discussion of avoiding ownership costs by mobility-on-demand systems with electronic tracking and billing, and some even with one way rental; these greatly extend the fraction of time that each vehicle is used, thereby reducing vehicle costs.

Many futuristic innovations of all sorts are suggested, including advertising displayed on car dashboards rather than on billboards, transfer of speed limit signs, stop signs, and other highway signs to car dashboards, and pedestrians carrying connections to the mobility internet for their safety.

An important shortcoming of the book is that there is essentially no mention of the down-sides of many of the proposed new measures. For example, lighter-weight vehicles or abandoning impact-absorbing devices present possible safety problems, and placing billboards or highway signs on car dashboards would appear to present unsafe distractions for the driver, but these difficulties are not discussed.

The authors claim that the measures foreseen in this book will result in personal city transportation systems that are cheaper, faster, safer, and less polluting even than extensive use of mass transit and all the inconvenience that approach entails.

At only 200 pages long, the book is a fast and easy read. It is full of illustrations, diagrams, and data plots. There are many tables with relevant information, and about a hundred references to scientific and technical literature.

The final chapter discusses "how we get there from here," facing the very formidable problems in implementation. There is perhaps more optimism than many readers can accept, but the authors really seem to believe that much of this is going to happen. This reviewer can only hope they are right.

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On Fact and Fraud—Cautionary Tales from the Front Lines of Science

By David Goodstein, Princeton University Press, 2010, ISBN 978-0-691-13966-1, 168 pages.

David Goodstein is a physicist who also was vice-provost of Caltech from 1988 to 2007. He teaches a course on scientific ethics, and wrote this book for students in this course and for the general public. It's worth noting that government funding agencies require a similar course to train lab personnel in "responsible conduct of research".

Goodstein begins by surveying examples of fraud in science from the 1910's "Piltdown Man" through the frauds committed by Sir Cyril Burt (supposed heritability of IQ), William Summerlin (alleged transplantation of tissue from unrelated animals that was shown to involve drawing colored patches on mice), John Darsee (fabrication of data from medical research experiments that were never actually conducted) and Stephen Breuning (fabrication of date regarding mentally retarded patients). He then critiques 15 plausible but frequently unworkable precepts to eliminate fraud: e.g., "each author of a multi-author paper is responsible for every part of that paper". (Try to apply this precept to a paper with hundreds of authors!)

In his long second chapter Goodstein examines and then refutes the allegations of fraud C. Ian Jackson made thirty years ago against Robert A. Millikan. Jackson accused Millikan of "cooking the data" in his dispute with Ehrenhaft a century ago. Does the electron have a unique charge, or are there "sub-electrons"? These allegations were studied in exhaustive detail twenty years ago, twice by Gerald Holton and once by Allen Franklin. Yes, there are no sub-electrons; and yes, Millikan did deserve his Nobel Prize. But I must ask: Is it useful to look at these allegations yet another time?

In the next short chapter Goodstein examines two separate cases of fraud, one by Nisan Kumar and the other by James L. Urban, each research workers in Leroy Hood's biology laboratory at Caltech. Goodstein had helped write the Caltech Policy on Research Misconduct, so he was a member of the committee that applied this policy to the conduct of Urban and of Kumar. The committee decided that each biologist had committed fraud. I would like to have read more about the committee's work, and the statements made by the defendants, Kumar and Urban.

The next chapter described the evolving approaches during the 1990s to dealing with misconduct. It is supplemented by an Appendix on Caltech's policy on research misconduct. I found the chapter and appendix useful but somewhat dull.

Goodstein uses the 26 pages of Chapter 5 to tell the sad, unlikely story of cold fusion. I heard this story both on TV, and at the 1989 Washington APS meeting. I heard both Steve Jones' sober contributed paper on his extremely tiny neutron flux, and I heard much of the special night session where many physicists disputed and refuted the Pons-Fleischmann experimental results on energy from cold fusion. I wish that Pons and/or Fleischmann had attended; but already, barely a month after they announced their "discovery," the scientists (Pons and Fleischman and their supporters on one side, and many other scientists on the other) had divided into two opposing camps that weren't talking to teach other! I can't tell if Pons and Fleischmann were guilty of fraud, or merely doing "pathological science" like the "discoverer" of "N-rays" long ago. Goodstein joins the consensus that it wasn't fraud; but I don't know his reasons. Like Goodstein, I'm surprised that cold fusion is still alive and well, twenty years after its birth and apparent death. N-rays lasted only a year!

In ten short pages Goodstein looks at two recent cases of fraud in physics: by Jahn Hendrik Schön at Bell Labs and by Victor Ninov at LBNL. The former published many, many papers with fabricated data purporting to demonstrate his creation of molecular transistors. The latter fabricated data to show that he had created a new element, that of atomic number 118.

In his penultimate chapter Goodstein relates the discovery in 1987 of higher temperature superconductors. This is interesting science; but why does it belong in a book on scientific fraud?

Since I have never met a scientist who has committed fraud, I'd like to learn more about these peculiar, unusual people. Did they think they could get away with fraud? Did they generally break rules on ethical behavior? Did they cheat in their college exams? Did they drive through red lights? Did they think they could get away with fraud for months? For years? After all Sir Cyril Burt was quite successful in his fraudulent science. He became a knight; and his fraud was only uncovered years after his death as a respected scientist. Does the scientist who commits fraud like living dangerously? Is fraud really rare? After all, there were only two known fraudulent physicists in the past twenty years. Or are there many fraudulent discoveries and publications that haven't been exposed? I started getting answers to some of my questions from the case of journalistic fraud by Stephen Glass: I saw the movie "Shattered Glass" about his numerous fabricated stories published by The New Republic, and I saw his interview on "60 minutes". I'm sorry that Goodstein didn't answer some of my questions. Instead, half of his short book is spent on science that doesn't involve fraud: Millikan's oil drop experiment, cold fusion, and higher temperature superconductors.

Added note: Just after I finished my third draft of this review, I read "The Back Page" in the June 2010 APS News and found Goodstein's summary of his book. In his summary he makes two remarks on cold fusion that I question. "Many things went wrong in the course of that episode, but fraud was not one of them." And "…the final verdict [on cold fusion] is not yet in."

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The Long Thaw

David Archer (Princeton University Press, Princeton, NJ, 2009), 178 pp., $22.95 cloth, $16.95 paper, ISBN 978-1-4008-2876-0.

David Archer's *The Long Thaw* is a refreshing new addition to the plethora of books about global climate change. Unlike most texts on the subject, which tend to focus on the emission of anthropogenic CO_2 and the resulting environment impact over the next 100 years, Professor Archer's book deals with the long-term consequences of CO_2 emissions. The manuscript is neatly divided into 3 sections: the present (1900–2100), the past (<1900), and the future (>2100). The "present" section summarizes the science (e.g. radiative forcing) and evidence (e.g. the short-term temperature record) of global warming. It also includes the IPCC forecast for the next 100 years under a "business as usual" scenario. This section closely resembles the treatment found in many books on climate change, including Dr. Archer's excellent treatise *Global Warming: Understanding the Forecast*. Archer is a Professor of Geophysical Sciences at the University of Chicago and has published extensively on the global carbon cycle and its relation to global climate.

The "past" section focuses on temperature proxies (e.g. carbonates, pollen, ice core gases, tree rings, etc…) and what they tell us about historic, naturally-driven climate change. Professor Archer provides simple, intuitive explanations of complex phenomenon including Dansgaard-Oeschger events, the 8.2 kiloyear event, and the Paleocene–Eocene Thermal Maximum (PETM). Though well-written, these explanations can be difficult to follow; the text would have benefited from a more graphical presentation. The presentation of the PETM as a proxy for a large anthropogenic CO_2 release addresses Dr. Archer's central question of long-term CO_2 equilibrium by natural means. Prior to discussing any future projections, the book includes a very helpful review chapter that summarizes the past and present. It is important to note that Professor Archer is not an alarmist and repeatedly notes that current anthropogenic warming is similar to that observed in the recent past due to natural forcing.

The unique aspect of this book is its "future" section. This section details the expected fate of a large CO_2 release (e.g. the anthropogenic burning of the entire coal reserve in 200 years) over several timescales. First, CO_2 will dissolve in the ocean over an approximately 300 year time period that corresponds to the turnover time of deep ocean water. As the oceans acidify, they will absorb less CO_2 and approximately 20–40% of the release will remain in the atmosphere. Over about 5000 years, weathering reaction will bring carbonates into the ocean, helping to neutralize the acidity, and allow for more CO_2 dissolution. However, about 10 % of the release will still be in the atmosphere. This portion will very slowly (during about 400,000 years) diminish due to reactions with igneous rocks. Thus, mankind has the possibility to effect Earth's atmosphere over a very long timescale.

The final chapters in the book are dedicated to discussing the potential for catastrophic environmental changes, including thermal tipping points and dramatic sea level increases. Finally, Professor Archer suggests that a relatively small investment today can help mitigate an extremely large, long-term hazard, making the economics of climate change mitigation viable. Overall, this book provides novel insights into the fate of CO_2 in the environment and this reviewer highly recommends it for anyone interested in the science of climate change.

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