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Editor's Comments

As this issue of *P&S* was being prepared for publication, world attention was riveted on the aftermath of the Japanese earthquake/tsunami and the ongoing efforts to control the situation at the Fukushima Daiichi nuclear facility. Members of the Forum on Physics and Society extend their most heartfelt concern to our Japanese colleagues and their families.

The Japanese situation will no doubt lead to extensive debate on the role of nuclear power and to reviews of backup protocols for both existing and future plants. Our first feature article for this edition, by longtime contributor Dave Hafemeister, illustrates some back-of-the-envelope calculations of thermal rise times in reactor cores following loss-of-containment and loss-of-power accidents. By unplanned coincidence, our other two feature articles concern very different types of nuclear installations. In late 2010, there was considerable media buzz surrounding the visit of former Los Alamos National Laboratory Director Sig Hecker's visit to Yongbyon, North Korea, and his analysis of nuclear reactor development taking place there. We are pleased to be able to run an article by Dr. Hecker which presents considerably more technical detail than was contained in many media reports. Finally, Wally Manheimer offers an approach to reorienting current fusion-energy research to producing hybrid fusion-fission reactors.

News of the Forum includes a call for nominations for individuals to APS Fellowship through the Forum (deadline June 1) and a summary of Forum-sponsored sessions to be held at the APS April Meeting in Anaheim. Reviewers take a look at books on detecting pseudoscience, non-science and abuse of science for political ends, and climate change and energy in the twenty-first century.

— Cameron Reed

IN THIS ISSUE

FORUM NEWS

Fellowship Nominations due June 1

The deadline for nominations for APS Fellowship through FPS is June 1, 2011. The chairperson of the FPS Fellowship Committee is Puspha Bhat of Fermilab, bhat@fnal.gov. Nomination instructions can be found at http://www.aps.org/programs/honors/fellowships/index.cfm

FPS to Host Sessions at APS April Meeting

The annual April meeting of the APS will be held at the Hyatt Regency Orange County in Anaheim/Garden Grove, CA, from April 30 to May 3, 2011. FPS is hosting six sessions. The tentative titles of presentations are give here; not all speakers were confirmed at press time.

Session B5: Saturday, April 30, 10:45 am. ***Electromagnetic Pulse Phenomena.*** Chair: Benn Tannenbaum. Peter Huessy: EMP Threats to US National Security: Congressional Responses, Yousaf Butt: To be determined, Michael Dinallo: Nuclear Electromagnetic Pulse Review.

Session E5: Saturday, April 30, 3:30 pm. ***Nuclear Weapons at 65.*** Chair: Patricia M. Lewis. Rebecca Johnson: TBD, Jay Davis: Issues for Future Nuclear Arms Control, third speaker TBD.

Session J5: Sunday, May 1, 1:30 pm. ***Forum on Physics and Society Awards Session.*** Chair: Charles Ferguson. M. Granger Morgan: Joseph A. Burton Forum Award Talk: How a Physics Education has Influenced Practice and Graduate Education in Technically-Focused Quantitative Policy Analysis, John Ahearne: Leo Szilard Lectureship Award Talk.

Session Q5: Monday, May 2, 10:45 am. ***Physics and Engineering of Deep Water Drilling.*** Chair: Peter D. Zimmerman. Brian Clark: Physics and the Quest for Hydrocarbons, Kenneth Gray: An Introduction to Deepwater Drilling, Jonathan Katz: Viscoelastic Muds — Top-Kill in Rapidly Flowing Wells.

Session R5: Monday, May 2, 1:30 pm. ***The Status of Arms Control.*** Chair: Pierce Corden. Sidney Drell: What Happens to Deterrence as Nuclear Weapons Decrease Toward Zero?, Marvin Adams: Confidence in Nuclear Weapons as Numbers Decrease and Time Since Testing Increases, Edward Levine: Securing Support from a Skeptical Senate for Further Strategic Arms Controls.

Session Y5: Science Diplomacy. Chair: Harvey Newman. Barry C. Barish: Science Diplomacy in Large International Collaborations, Neal Lane: A Scientist's Approach to Diplomacy—First, Listen and Learn, Norman P. Neureiter: Science Diplomacy in Action. Sponsored jointly with the Forum on International Physics.

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

ARTICLES

Thermal Rise Time in Nuclear Reactors after Loss of Coolant or Loss of Power Accidents

David Hafemeister

[Prof. Hafemeister's manuscript was prepared on March 22, 2011, just eleven days after the Japanese earthquake and tsunami. The situation at the Fukushima Daiichi nuclear power plant will no doubt evolve rapidly over the coming weeks. For readers wishing to keep up with the latest developments, updates on the situation in Japan prepared by the MIT department of Nuclear Science and Engineering are available at http://mitnse.com/. Information on safety and oversight at US nuclear plants in 2010 is given in a Union of Concerned Scientists (UCS) website at http://ucsusa.org/nuclear_power/nuclear_power_risk/safety/nrc-and-nuclear-power-2010.html?utm_&utm_medium=Lochbaum&utm_campaign=SP-Lochbaum-3-17-11. Another UCS website, http://allthingsnuclear.org/tagged/Japan_nuclear, has successive news stories and helpful graphics, as well as links to other useful sites – Ed.]

On March 11, 2011, a magnitude 9.0 earthquake from a "reverse fault" struck northeastern Japan. The Fukushima Daiichi site on the Pacific Ocean, 240 km north-east of Tokyo, houses six boiling water reactors, three of which were in operation and three in maintenance at the time of the earthquake. It appears that the three-operating reactors shut down without a loss of coolant accident (LOCA), but the accompanying tsunami, which arrived 15 minutes later, disabled back-up electrical generators. This prevented pumping of cooling water to the reactors and their spent fuel ponds. The ensuing damage and radioactive release is the worst accident since the Chernobyl accident in Ukraine on 26 April 1986. The Chernobyl accident was particularly bad since the burning of its carbon moderator propelled 3-4% of the radioactive core into the atmosphere from a reactor without a containment dome. The radioactive releases from the Fukushima site will, most likely, be far less than was the case Chernobyl, but the clean-up of the Fukushima reactors and spent fuel ponds will be very significant. The Three Mile Island Accident of 28 March 1979 released only minor amounts of radioactivity, but the cleanup cost $1 billion and took eight years.

In this article, I use some basic reactor and thermal physics to estimate the available response time before a light water reactor core begins to melt. I consider two types of accidents: A loss of coolant accident (LOCA) and a loss of power accident (LOPA). The calculated response time for a LOCA is about 1 minute, and, for a LOPA, about 0.5-1 day, but individual circumstances cause variations on these results. These calculations are based on material presented in Ref. 1.

Helicopters and water cannons failed to cool the reactors and the spent fuel ponds. As a last-gasp effort, corrosive seawater with boric acid was flooded on reactors 1, 2 and 3, but without the use of their internal pumps. It is speculated that rapid deployment of portable generators on land or ships to give power to the reactors' pumps could have lessened the severity of the Fukushima accident. First, I will summarize the status, one week after the earthquake-tsunami of March 11, of the six Fukushima Daiichi (FD) reactors and spent fuel ponds [2]:

FD-1: Hydrogen from oxidation of zircaloy cladding (over 95% zirconium) exploded on March 12, destroying the secondary confinement roof, but the primary containment was said to be intact.

FD-2: Hydrogen explosion on March 15 breached primary containment, causing a partial meltdown. Iodine-131 (8-day half-life) was observed in Tokyo at a distance of 240 km on March 19 and its level in spinach at a distance of 70 km was 27 times the limited level. On March 20, electrical power was reestablish at unit 2, with the other units to follow. Water was added to pond 2 on March 20.

FD-3: Hydrogen explosion on March 14 destroyed the secondary confinement roof and walls. Pond 3 was filled on March 20.

FD-4: Reactor was shut down three months ago with the transfer of all of its spent fuel to the spent fuel pond. Full-core discharges are rarely done in the U.S., where only the oldest fuel is usually removed. The young, very hot spent fuel heated pond water to boiling, with a report that pond had no water, starting a fire. This is consistent with the last-measured temperature of 84°C (183°F), as compared to the usual temperature of 25°C (77°F). Pond 4 was filled on March 20.

FD-5: Reactor was shut down, but the pool's last-measured temperature was 63°C (145°F), as compared to the usual temperature of 25°C (77°F).

FD-6: Reactor was shut down, but the pool's last measured temperature was 60°C (140°F), as compared to the usual temperature of 25°C (77°F).

Loss-of-Coolant Rise Time

I first calculate the thermal rise time of a light water reactor (LWR) core after a loss-of-coolant accident. Thermal rise is the time for the core to get sufficiently hot to begin an exothermal reaction between zircaloy and water. The calculation is based on the following assumptions [1]:

- Emergency core-coolant water (ECCS) water does not arrive until fuel rods are over 1370°C, when zircaloy cladding and water exothermically release hydrogen. This happens below its melting point of 2200°C.
- Core mass is 105 kg UO_2 for 1 GWe reactor. [Fukushima reactor #1 is rated at 460 MWe, reactors 2-5 at 784 GWe, and reactor 6 at 1.1 GWe].
- LWR thermal efficiency is $\eta = 1/3$.
- Average fuel temperature is 400°C before a LOCA.
- Thermal power from beta decay after LOCA (P_o = 3 GWt):

$$P = P_o(0.0766t^{-0.181}) \qquad 0 < t < 150 \text{ sec}, \qquad (1)$$
$$P = P_o(0.130t^{-0.283}) \qquad 150 \text{ sec} < t < 4 \times 10^6 \text{ sec}. \qquad (2)$$

These equations give 7.7% of operating thermal power at 1 second, 3.7% at 1 minute, 1.3% at 1 hour, 0.5% at 1 day, 0.3% at 1 week, and 0.2% at one month, all of which conform to the measured data.

The thermal rise time is obtained by equating the heat needed to raise the core to 1370ºC to the time integral of thermal power P. The heat needed to raise the core to 1370ºC is

$$Q = Nc(\Delta T), \qquad (3)$$

where N is the number of moles of UO_2, c is the UO_2 molar specific heat, and ΔT is the temperature rise for the core to be 1370°C, that is, ΔT = 1370°C – 400°C = 970°C. The number of moles of UO_2 in the core is

$$N = (10^8 \text{ g})/(238 + 32)\text{g/mole} = 3.7 \times 10^5 \text{ moles}. \qquad (4)$$

The high-temperature specific heat, $c = 3R = 24.9$ J/mole-°C, is used since the temperatures are considerably above the UO_2 Debye temperature of 100 K. Thus, the heat needed to raise the core to its critical temperature is

$$Q_{rise} = Nc(\Delta T) = (3.7 \times 10^5 \text{ moles})(24.9 \text{ J/mole-°C})$$
$$(970\text{°C}) = 8.9 \times 10^9 \text{ J}. \qquad (5)$$

The thermal rise time is obtained by equating Q_{rise}, to the time integral of the beta decay power,

$$Q_{beta\ decay} = \int_0^t P\,dt = \int_0^t 0.0766(3 \times 10^9)t^{-0.181}dt =$$
$$(2.8 \times 10^8)t^{0.819} \text{ J} = 8.9 \times 10^9 \text{ J}. \qquad (6)$$

Solving for t gives a thermal rise time of 68 sec, which is close to the published values of 1 minute, calculated with the heat equation [3]. Since the time scale for a LOCA is only a minute, essentially all beta-decay heat is trapped in the core.

Loss-of-Power Rise Time

A more gradual LOCA almost happened in 1975 when a workman at the Brown's Ferry, Alabama, boiling water reactor (BWR) used a candle to check airflow and inadvertently set fire to electrical cables, cutting off electrical power for cooling pumps. Beta-decay heat began evaporating the water coolant, which in turn initiated a process that would have uncovered the core and begun a LOCA. The beta-decay heat needed to evaporate 700 tonnes of water is

$$Q_{evap} = mL_{evap} = (7 \times 10^5 \text{ kg})(2.27 \text{ MJ/kg}) =$$
$$1.6 \times 10^{12} \text{ J}. \qquad (7)$$

Setting Q_{evap} equal to the integrated beta-decay heat, over the two time regions gives t = 19 hours, similar to the stated 13 hours available to recover the situation.

LOCA in Spent Fuel Ponds

The Fukushima spent fuel ponds are 12 meters deep, with 8 meters of water over the tops of the spent fuel assemblies. Pond water can be lost through holes in the concrete and by evaporation from the radioactive heat of the spent fuel. After one year, spent fuel radioactive heating is 15 kW/tonne, and at 10 years it falls to 2 kW/tonne. The spent fuel problem was exacerbated in the United States because the density of spent fuel in the ponds was increased as a result of the 1977 decision not to reprocess spent fuel. Increasing the density of fuel rods gives additional heating density and reduces the paths to remove heat by radiation and convection. Some parameters give temperatures over 900ºC in a spent fuel pond after a LOCA, a point where zircaloy cladding spontaneously ignites in air [4]. The problem could be lessened by moving some rods to a geological repository, or by placing them in surface storage, which is happening in the U.S. at this time. Damage could be mitigated after loss of coolant in the ponds by plugging pond holes with quick-setting material, pouring water on the ponds, or using large air blowers.

A Final Comment

Further data and analysis by experts are needed before serious conclusions on the Fukushima accident can be made. However, it initially seems that rapid deployment of portable generators on trucks or on ships to the Fukushima site could have made a considerable difference. Cables would be needed to deliver the power, but this should have been possible. Crews would experience some radiation, but less than that received by the fifty workers inside the plants. These generators could have provided electricity to drive the internal pumps at the reactors to bring water into the reactors and the spent fuel ponds. It took nine days to establish a 1.5 km power line to reactor 2 on March 20, with power to follow at the other reactors.

References

[1] *D. Hafemeister,* Am. J. Phys. **50***(8), 713-720 (1982) and* Physics of Societal Issues *(Springer, New York, 2007), pp. 171-3.*

[2] New York Times: *16 March 2011 (pp. A1, A7-9) and 18 March 2011 (A1, A11-12).*

[3] *A. Nero,* A Guidebook to Nuclear Reactors *(University of California Press, Berkeley, 1979), p. 54.*

[4] *R. Alvarez,* et al, *"Reducing the hazards from stored spent power-reactor fuel in the United States,"* Science and Global Security *11, 1–51, 2003.*

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Where is North Korea's Nuclear Program Heading?

Siegfried S. Hecker

[This article is an edited version of a report prepared by Dr. Hecker soon after his return from North Korea's Yongbyon Nuclear Complex in November, 2010; we are grateful for his permission to run it. A related article appeared as a "Back Page" in APS News (March, 2011). Dr. Hecker's full article and related reports can be found at his website, http://cisac.stanford.edu/people/siegfriedshecker/. Dr. Hecker is a Professor (Research) of Management Science and Engineering, a Senior Fellow at the Freeman Spogli Institute for International Studies, and Co-Director of the Center for International Security and Cooperation, all at Stanford University. Trained as a metallurgist, he is regarded as one of the leading experts in the world on the properties of plutonium, and served as Director of the Los Alamos National Laboratory from 1986-1997 - Ed.]

On November 12, 2010, John W. Lewis, Robert Carlin and I visited North Korea's Yongbyon Nuclear Complex. There we were shown a 25 to 30 megawatt-electric (MWe) experimental light-water reactor (LWR) in the early stages of construction, along with a modern uranium enrichment facility. This reactor is North Korea's first attempt at LWR technology. These facilities appear to be designed primarily for civilian nuclear power as opposed to boosting North Korea's military nuclear capability.

This visit allowed us to answer some questions about Pyongyang's nuclear directions, but it also raised many more. In this article I describe our visit and offer some comments on how the response of the United States and its partners to these developments may help to shape whether Pyongyang will rely more on bomb development for diplomatic leverage or begin a shift toward nuclear electricity, which it desires both for economic and symbolic reasons.

Yongbyon Nuclear Scientific Research Center

This trip was my seventh to North Korea and my fourth to the Yongbyon complex, which is located about 90 km north of Pyongyang. During my first visit in January 2004 I was shown a sample of plutonium metal that had been reprocessed from spent fuel rods that had been stored since 1994 as part of the Agreed Framework, and which was subsequently used as bomb fuel for North Korea's first nuclear test of 2006 [1]. During all of my previous trips to North Korea, government officials and technical specialists denied the existence of any uranium enrichment activities. Following their 2009 rocket launch and second nuclear test, Pyongyang expelled the U.S. technical team and international inspectors and declared that it would build its own light-water reactor (LWR) and produce its own fuel. For this visit, I asked to see the key nuclear sites in order to judge their current status and to see if the enrichment technology that they announced at that time was successful [2]. Our visit was supported by a number of foundations, including the Ploughshares Foundation, the Carnegie Corporation, and the MacArthur Foundation.

We were met by a small technical team and representatives of the General Bureau of Atomic Energy. The senior technical official gave the following introduction: "In the 1980s and 1990s, we agreed to give up our reactors for LWRs, 2,000 Megawatt-electric (MWe) by 2003. In the early 1990s we built 50 and 200 MWe reactors (of gas-cooled, graphite-moderated design). Now they have become ruined concrete structures and iron scrap. We have not been able to contribute to the national demand for electricity. So, we decided to make a new start. For us to survive, we decided to build our own LWR. On April 15, 2009, the Foreign Ministry stated that we will proceed with our own LWR fuel cycle … Our nuclear program has not proceeded as expected, we have not delivered electricity and that has impacted the economic condition of our country. We will use our economic resources to solve the electricity problem. We are willing to proceed with the Six-Party Talks and the September 19, 2005 agreement, but we cannot wait for a positive agreement. We are trying our best to solve our own problems. We will convert our center (Yongbyon) to a LWR and pilot enrichment facility. It is a high priority to develop uranium enrichment. We will have some difficulties with this, but we are proceeding with the LWR fuel cycle. We have designated a site for the LWR and also for uranium enrichment – it is the first stage, so it is first priority. The construction is completed and the facility is operational. You will be the first to see this facility." [3]. Unlike during my previous visits to Yongbyon, the technical team clearly had instructions to show us only the basics at two facilities and answer a minimum of questions. We were hurried along at every stage but eventually spent 3.5 hours at the site before lunch. The chief engineer of the 5 MWe reactor showed us the site and answered questions, but only when pressed.

Experimental 25 to 30 MWe LWR construction

At the 5 MWe reactor site we were taken to a construction site that had been identified previously from overhead imagery [4]. A large excavated pit roughly 40 meters by 50 meters by 7 meters deep containing a concrete foundation 28 meters square with round concrete preforms for the reactor containment vessel was visible. The containment vessel is designed for a power level of 100 MW (thermal) and was about one meter high at the time we saw it. We were told it will be 22 meters diameter, 0.9 meters thick and 40 meters high. We were not told the electrical power but were informed that the conversion efficiency is typically 30 percent, so I estimate the electrical power to be 25 to 30 MWe.

This power level is much smaller than the two 1,000 MWe LWRs that were to have been constructed as part of the KEDO project at the Kumho (North Korea) site [5]. They explained that the LWR design is different from their experience base of gas-graphite reactors and so they are building a small prototype first. Once they have mastered this technology they will build a bigger LWR. However, even with the 25 to 30 MWe reactor they will build two electrical generators that will supply electricity to the local communities and be hooked into the national grid. The chief engineer said that construction was started on July 31, 2010, and that the target date for operations is 2012. This seemed to us unreasonably optimistic, but coincides with the centenary of Kim Il-sung's birth. There were nearly 50 workers on the floor. We enquired about reactor safety analysis and practices; they claimed to have excavated down to bedrock and to have performed seismic analysis of the site.

The pressure vessel will be fabricated out of high-strength steel. The chief engineer said that they will be able to manufacture it and all other reactor components domestically. I asked if they have a nuclear regulatory agency; the response was that the National Nuclear Safety Commission has oversight and has inspectors on-site.

The reactor will be fueled with uranium dioxide fuel enriched to 3.5%, typical of LWR fuel but very different from the metallic uranium-alloy fuel rods used in the gas graphite reactor. A full load of fuel will comprise four metric tons of uranium. We were told that North Korea has ample domestic uranium ore resources. They were not certain what cladding material would be used, stating that they are still working on many of the details. The reactor design team is a young group without reactor design experience, but they are being mentored by the experienced gas-graphite reactor designers. The new designers are in their 40s, graduated from North Korean universities, and have spent their careers at Yongbyon. They have not brought any of the North Korean KEDO LWR team members to Yongbyon at this time but may do so for the operational phase. (The KEDO team did not necessarily have design experience because the reactors to be provided were to come from South Korea.) I had expected the old design team from the gas-graphite reactors to be involved. My hosts said that they specifically tasked a fresh design team because this was a new technology.

Uranium enrichment facility

At the fuel fabrication plant we entered a building that appeared to be a new but which we identified later as the former metal fuel rod fabrication building which I had visited in February 2008 to verify disablement actions. The view through the windows of the second-floor observation deck into two long high-bay areas was stunning. Instead of seeing the few small cascades of centrifuges which I believed to exist in North Korea, we saw a modern, clean plant of more than a thousand centrifuges all neatly aligned and plumbed. We were told that construction had begun in April 2009 and was completed a few days before our visit. Overhead imagery now shows a building with a blue roof about 120 meters long (see http://www.globalsecurity.org/wmd/world/dprk/yongbyon-ffp-imagery-02.htm).

We estimated the centrifuges to be about 8 inches in diameter and approximately 6 feet high. They looked like smooth aluminum casings (no cooling coils visible) with three small stainless steel tubes emanating from the top to central plumbing that ran the length of the facility. In response to persistent questioning, the chief process engineer told us that the facility contained 2,000 centrifuges in six cascades [6]. He would not provide us with the physical dimensions, stating that the United States would also not release such proprietary information. When asked if they were Pakistani P-1 centrifuges, he said no [7]. When pressed, he said the rotors were made of alloys containing iron, which likely makes them P-2 models [8]. He claimed all components were manufactured domestically, but modeled after the centrifuges at Almelo (a URENCO facility in the Netherlands) and Rokkasho-mura (a Japan Nuclear Fuels facility). We were able to extract the most important detail, the enrichment capacity, which he said was 8,000 kg SWU/year [9]. With this capacity North Korea could produce up to 2 tonnes of LEU per year, or, if the cascades were reconfigured, up to 40 kg HEU.

The control room was astonishingly modern. Unlike the reprocessing facility and control room for the gas-graphite reactor, which looked like 1950s U.S. or 1980s Soviet instrumentation, this control room would fit into any modern American processing facility. Five large panels had numerous LED displays of operating parameters. Computers linked to flat-screen monitors displayed flow diagrams and numbers, but we were ushered past too quickly to tell what they signified.

I expressed surprise that they were apparently able to get cascades of 2,000 centrifuges working so quickly, and asked again if the facility is actually operating now. We were given an emphatic "yes". We were not able to independently verify this, although it was not inconsistent with what we saw. We attempted to probe more deeply into their claims of indigenous fabrication but received no concrete answers. The technical official claimed that they produce uranium hexafluoride as feed material for gas centrifuges, material which they had never admitted having produced in the past [10]. I also asked again about the fuel – will it be UO_2 and how will they make it? He said that the process for learning how to make UO_2 was difficult but had begun, and confirmed that they are currently enriching uranium in the facility. When I pointed out that the outside world will be concerned about their ability to convert the facility to make HEU, he stated that anyone can tell by looking at the monitors in the control room that the cascades are configured for LEU. Besides, he said, they can think what they want.

Status of existing plutonium production facilities

We were not taken to the plutonium production facilities, but the 5 MWe reactor, which is adjacent to the LWR construction site, appeared dormant. We were told that it is in stand-by status with regular maintenance. We were reminded that the cooling tower had been destroyed (June 2008), but the chief engineer was confident that they could restart the reactor should they decide to do so; I estimate that it would require approximately six months to do so. We were told that fresh fuel which could be used to refuel the reactor was still stored in the same warehouse in which I last saw it in 2008. The 50 MWe reactor, which was near completion in the mid-1990s but abandoned during the Agreed Framework, was being dismantled with large cranes. No activity was apparent at the reprocessing facility as we drove past it.

To summarize: The 5 MWe reactor has not been restarted since it was shut down in July 2007. The spent fuel rods were reprocessed following North Korea's termination of the Six-Party talks in April 2009. No new fuel has been produced and the fresh fuel produced prior to 1994 (sufficient for one more reactor core) is still in storage. Pyongyang has apparently decided not to make more plutonium or plutonium bombs for now. My assessment is that they could resume plutonium operations within approximately six months and make one bomb's worth of plutonium per year for some time to come.

Discussion

The findings from this trip answer many questions about the direction of North Korea's nuclear program, but they also raise at least as many. I will give a preliminary analysis here.

The plutonium program associated with the now shut-down 5 MWe graphite reactor remains frozen, and has perhaps even taken another step backward. They have converted the metal fuel rod fabrication facility into the centrifuge cascade halls, thereby making it more difficult to make fuel for the plutonium production reactor. The LWR will produce plutonium, but it is much less suitable for bombs than that from the 5 MWe reactor. In addition, the reprocessing facility operations would have to be reconfigured to reprocess the LWR fuel. My previous estimate of the North Korean plutonium inventory from its 5 MWe reactor of from 24 to 42 kilograms (sufficient for four to eight primitive nuclear weapons) still stands [11].

A North Korean uranium enrichment program has long been suspected. I believe that they started early, perhaps in the 1970s or 1980s, but did not accelerate the effort until their dealings with A.Q. Khan in the 1990s [*Editor's note: Khan is regarded as the father of the Pakistani nuclear-weapons program. He was involved with proliferating smuggled URENCO centrifuge technology, and has been accused of proliferating* *weapons technology to Iraq, Libya, Iran, and North Korea*.] However, the 2,000-centrifuge capability significantly exceeds my estimates and that of most other analysts [12]. We were not able to confirm that the facility is fully operational. It typically requires much time to bring cascades of this size into full operation [13]. Nevertheless, they have either done so or are most likely capable of doing so shortly. The LEU capacity is consistent with the requirements of the LWR under construction. It would have to be expanded significantly if North Korea builds a larger LWR in the future. Whether LEU or HEU is produced in the facility is easy to monitor with on-site presence or on-site instrumentation. However, the greatest concern is that a facility of equal or greater capacity configured to produce HEU exists somewhere else. Such a facility would be difficult to detect as demonstrated by the fact that this facility was undetected in the middle of the Yongbyon fuel fabrication site. The only factors that would limit North Korea's ability to build more are the procurement or production of specialty materials and pieces of equipment such as maraging steel, high-strength aluminum alloys, ring magnets, frequency converters, special bearings, vacuum equipment and flow meters. We have little knowledge of the North's indigenous fabrication capabilities. If North Korea claims its uranium program is strictly peaceful, then the burden of proof is on it, especially since they continued to deny it during the Six-Party negotiations. [*Editor's note: maraging steels are ultra-high-strength steels that derive their strength from precipitation of intermetallic compounds containing Ni, Co, Mo, and Yi. They are very machinable and weldable, and suffer little dimensional change after being heat-treated. They are used in products as diverse as rockets, fencing blades, golf clubs, and, centrifuges*.]

One of the most puzzling issues is how they got this far? Albright and Brannan recently presented a detailed analysis of the status of North Korea's uranium enrichment program [4]. Their work demonstrates a clear pattern of cooperation and exchange with Pakistan, including crucial elements such as training of North Korean technical specialists at the Khan Research Laboratory. They also show a troubling procurement scheme, particularly with commercial entities in China. I have previously stated my concern about potential cooperation and exchanges in uranium technologies between North Korea and Iran. However, a detailed analysis and reevaluation taking into account the findings from this trip is now in order. A better understanding is important because it will help us better judge the capacity of current and planned enrichment capacity.

It is an understatement to say that trying to discern North Korea's motivations is difficult. In an essay published elsewhere I argued how an initially security-driven motivation for the bomb took on important domestic and international dimensions [11]. Pyongyang has clearly stated that it will retain its nuclear weapons as a deterrent so long as current U.S. policies persist. North Korean officials with whom we met on this trip made it abundantly clear that there will be no denuclearization without a fundamental change in U.S. – North Korean relations. Pyongyang has seriously pursued nuclear electricity; it has both practical and symbolic importance [14]. It views LWRs as the modern path to nuclear power, and was prepared several times in the past to trade its bomb-fuel producing reactors for LWRs. This time we were told, "We have given up; we will do it on our own." They can claim with some justification that the uranium enrichment program is an integral step toward an LWR and nuclear electricity.

I believe that although this peaceful program can be diverted to military ends, the current revelations do not fundamentally change the present security calculus of the United States or its allies. Pyongyang has gained significant political leverage already from the few plutonium bombs they have. Building more sophisticated bombs that can be mounted on a missile is better done with plutonium than HEU. However, the production of large quantities of HEU and additional nuclear tests would allow them to increase the size of their arsenal. Even more troubling would be the potential of export of fissile materials or the means of producing them, means which now include centrifuge technologies. For these reasons, the United States should not sit idly by.

Where do we go from here?

Is Pyongyang really pursuing a modern nuclear electricity program? If so, what are its chances of success without outside help? Have they decided to abandon their plutonium production complex or at least keep it dormant? Do they have additional centrifuge facilities that could be dedicated to producing HEU bomb fuel? How did they acquire centrifuge technology at such a level of sophistication and when? Why did Pyongyang decide to show us the facilities now and how does this fit into their broader strategy of how to deal with their domestic and international challenges?

Much more work will have to be done by many more analysts to address these questions. One thing, however, is certain: these revelations will cause a political firestorm. Some will use them to prove that Pyongyang cannot be trusted. Some will use them to justify the October 2002 U.S. decision to confront Pyongyang about uranium enrichment, a confrontation which resulted in termination of the Agreed Framework. Some, most likely China and Russia, will claim that North Korea is within its sovereign rights to develop nuclear energy. The issue is complicated by the inherently dual-use nature of nuclear technology. It is possible that Pyongyang's latest moves are directed at generating much-needed electricity. Yet, the military potential of uranium enrichment technology is serious. Waiting for Pyongyang to return to the Six-Party talks on terms acceptable to the United States and its allies will only exacerbate the problem. A military attack is out of the question. Tightening sanctions further is likewise a dead end, particularly given the advances made in their program and the economic improvements we saw in general in Pyongyang. The only hope appears to be engagement. The United States and its partners should respond to these latest developments so as to encourage Pyongyang to finally pursue nuclear electricity in lieu of the bomb. That will require addressing North Korea's underlying insecurity. A high-level North Korean government official told us that the October 2000 Joint Communiqué, which brought Secretary Madeleine Albright to Pyongyang, is a good place to start [15].

Notes and References

[1] *The "Agreed Framework" referred to in Dr. Hecker's article was signed in October 1994 between North Korea and the United States. The agreement provided for replacing North Korea's already-operating graphite-moderated 5 MWe reactor and associated plutonium-processing plant and 50 MWe and 200 MWe reactors then under construction with two 1000 MWe Light-Water Reactors (LWRs) by 2003, and for normalization of relations between the two countries. The agreement was to be implemented by the Korean Peninsula Energy Development Organization (KEDO), a consortium of several nations including the United States. Construction of the first LWR did not begin until August, 2002. However, in October, 2002, a U.S. delegation confronted North Korea with a U.S. assessment that the North Koreans had a uranium enrichment program. In January 2003, North Korea announced its withdrawal from the Nuclear Non-Proliferation Treaty. In December, 2003, KEDO suspended work on the LWR project, and terminated the project altogether in May, 2006. North Korea tested nuclear weapons in October, 2006, and May, 2009. However, they did not restart work on the two reactors that were frozen under the agreement, and the plutonium-producing 5 MWe reactor was shut down in July, 2007. A detailed description of the Agreed Framework can be found at the website of the Arms Control Association at*

http://www.armscontrol.org/factsheets/agreedframework;

Their site also hosts a detailed chronology of North Korean Nuclear developments form 1985 to the present; see http://www.armscontrol.org/factsheets/dprkchron. The Joint Communiqué referred to at the end of the article is also described at this website. Secretary of State Madeleine Albright visited North Korea in October, 2000, and the communiqué was issued on October 12 of that year. The relevant portion reads: "The two sides stated that neither government would have hostile intent toward the other and confirmed the commitment of both governments to make every effort in the future to build a new relationship free from past enmity." A January 7, 2003 joint statement from the United States, Japan, and South Korea reaffirmed this commitment in writing, stating that the United States "has no intention of invading North Korea."- Ed.

[2] *In a September 4, 2009 letter to the President of the UN Security Council, the North Korean permanent representative to the United Nations stated that North Korea's "experimental uranium enrichment has successfully been conducted to enter into completion phase." (Korean Central News Agency – KCNA).*

[3] *This quote is based on our notes of the interpreter's version of the technical official's comments. The September 19, 2005 date refers to the Joint Statement of the Fourth Round of the Six-Party Talks. The statement can be found at*

http://www.fmprc.gov.cn/eng/topics/dslbj/t212707.htm

[4] *David Albright and Paul Brannan, "Taking Stock: North Korea's Uranium Enrichment Program," http://isis-online.org/uploads/isis-reports/documents/ISIS_DPRK_UEP.pdf*

[5] *The Korean Peninsula Energy Development Organization (KEDO) project was to have the United States and other parties build two 1,000 MWe LWRs for North Korea at the Kumho site. It was established in March 1995 as part of the Agreed Framework. The LWR project was terminated in 2006.*

http://www.nti.org/e_research/official_docs/inventory/pdfs/kedo.pdf

[6] *The chief process engineer told us at the outset that they did not want to show us this facility, but their superiors told them to do so. Consequently, they showed us as little as possible, did not volunteer any information, and hurried us along as much as possible.*

[7] *The P-1 designation refers to the Pakistani design copied from the least advanced URENCO centrifuges. These contain high-strength aluminum alloy rotors and high-strength aluminum alloy casings.*

[8] *P-2 centrifuges were based on the German G-2 design developed as part of the URENCO consortium. These typically have high-strength steel rotors that can by spun much faster than the aluminum rotors, thereby increasing the throughput.*

[9] *The kg SWU is an acronym for kg of separative work units. It refers to the amount of isotope separation achieved (separating the fissile U-235 isotope from the non-fissile U-238 isotope).*

[10] *In spite of prior North Korean denial, the nuclear materials recovered in Libya in 2003 when Col. Gadaffi relinquished his nuclear weapons program were reputed to include a shipment of uranium hexafluoride from North Korea.*

[11] *Siegfried S. Hecker, "Lessons learned from the North Korean nuclear crises," Daedalus, Winter 2010, pp.44-56.*

[12] *For example, see Hui Zhang, "Assessing North Korea's uranium enrichment capabilities," Bulletin of the Atomic Scientists, 18 June 2009. See also Ref. [4].*

[13] *It took Iran about 20 years to procure, build and operate cascades of this size. Iran has roughly 8,000 centrifuges installed with 4,000 P-1s working for a total capacity of ~ 4,000 kg SWU.*

[14] *Siegfried S. Hecker, Sean C. Lee and Chaim Braun, "North Korea's Choice: Bombs over Electricity, "The Bridge, Vol. 40, No. 10, Summer 2010, pp. 5-12.*

[15] *For some further analysis of the situation, see*

http://www.foreignaffairs.com/articles/67023/siegfried-s-hecker/what-i-found-in-north-korea

and http://www.thebulletin.org/web-edition/features/redefining-denuclearization-north-korea-0

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The Case for Fission-Suppressed Hybrid Fusion

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For over a decade, I have advocated that current research efforts directed at developing fusion reactors shift their focus from pure fusion to a design known as fission-suppressed hybrid fusion [1-5]. The easiest fusion reaction combines a deuteron and a triton to produce a neutron of kinetic energy 14 MeV and an alpha particle of energy 3.5 MeV. However, because of the Coulomb repulsion between the deuteron and the triton, this can only be achieved in a hot, dense plasma. Production of electric power with pure fusion uses the neutron's kinetic energy to boil water. Fission-suppressed hybrid fusion follows all the same steps, but also uses the neutrons to breed ten times more fuel, to be burned elsewhere in conventional fission reactors. My reasons for advocating this innovation are twofold: first, I believe that the world will need 10-30 terawatts (TW) of additional carbon- free power by mid-century, and secondly I feel that the progress of pure fusion is too slow to meet this need [2]. Fission-suppressed hybrid fusion (also called fusion breeding), just might, since it makes many fewer demands on the fusion reactor, and it also fits well into today's nuclear infrastructure. References 1-5 spell out in much more detail development paths which might make this a reality by mid century or later. They also give very rough cost estimates based on International Tokamak Experimental Reactor (ITER) costs. In this article I review the possibilities for various approaches to meeting world energy demand, the status of current fusion programs, describe the fission-suppressed hybrid fusion concept, and offer a proposal for how an 'energy park' comprising both light-water reactors (LWRs) and a fusion reactor could be configured.

World energy demand

Let us first consider how one might achieve 10-30 TW of carbon free energy by midcentury. The options are few. Unfortunately there is no risk-free, universally agreed upon approach. However, many argue that any solution must have a very large nuclear component. I concur. But like any other energy option, nuclear has its own set of issues including fuel supply, proliferation and disposal of spent fuel, the subject of this and my earlier work [1-5]. I, and many others had assumed that nuclear energy's nearly impeccable safety record in the west over the last 30 years, as well as a new generation of even safer reactors, had put the issue of reactor safety to rest. With the recent disaster in Japan involving the Fukushima nuclear complex, the entire issue of reactor safety must be reexamined. But nuclear power certainly cannot be simply abandoned either, any more than oil can because of the Gulf BP spill, or coal can because of innumerable coal mining disasters.

Today, once-through nuclear produces about 350 GWe, or about 1 TWth with light water reactors (LWR's). Freidberg and Kadak make the case that LWRs are so well established that they will be the nuclear reactor of choice for quite some time [6]. They estimate that there is about 500-1000 TWyrs of uranium fuel: "For the foreseeable future, the most economical way to obtain fuel for LWRs is to dig it out of the ground." Of course, this depends on how far ahead one can foresee, how long it takes to develop alternatives, and how accurate the estimate is. For instance, Hoffert, et al. estimate a fuel resource of 60-300 Twyrs [2]. It is far beyond the scope of this work to sort through the conflicting claims as to economically available uranium ore, but there is no dispute about one thing: a once-through nuclear economy based on LWRs uses only about 1% of the available fuel. Fission or fusion breeders potentially use all of it. This author does not believe the world is so well endowed with fuel that we can afford to discard 99% of it.

While conventional 'renewable' sources (solar, wind and biofuel) can play some role, they can never produce power on the necessary scale. The world will learn this, but with so much hoopla and government support, it will learn the hard way. Many European countries, including Spain and Denmark, which mandated large subsidies for renewable energy, are backing off as the cost becomes apparent. These costs are not difficult to estimate. Wind and solar currently receive government subsidies of about $0.1/kwhr [3]. Without it, large parts of the industry would simply collapse, now and for the foreseeable future. In the unlikely event that it could even be done, the complete transition in the USA (0.5TWe) to renewable sources would cost the government about $500 billion per year — real money. Realistically, the only options for providing truly sustainable carbon-free power on the scale required at any time in the foreseeable future are fission and fusion breeding (and possibly pure fusion many decades later). While fission breeding is much closer at hand, fusion breeding has the potentially overwhelming advantage of being about an order of magnitude more prolific as a fuel producer.

Recently, hybrid fusion has been receiving more attention [6-9]. Freidberg and Kadak have recently summarized the situation, looking into subcritical nuclear reactors, where the fission and fusion reactors are in a single reactor (also called fast fission), the use of fusion neutrons to burn actinide nuclear waste, and the fission suppressed option described below [6].

(Actinides are the elements like plutonium which are beyond uranium in the periodic table.) Fast fission would involve a much more complicated and dangerous reactor, essentially a fusion reactor of perhaps several hundred megawatts (MW) deep inside a fission reactor of perhaps 3 gigawatts (GW). Such a design would not fit readily into the current nuclear infrastructure. Fission suppressed hybrid fusion is hardly a new idea: it was first proposed by Andrei Sakharov in 1950, and Hans Bethe advocated it in 1979 [10, 11]. Yet despite this pedigree, the idea has never really caught on. I have long argued that now is the time to reconsider it; indeed, I consider it to be the only viable hybrid fusion option. But first, let us examine the situation with pure-fusion research.

Pure fusion: The current situation and the long road ahead

Fusion research has been supported worldwide with billions of dollars for over 50 years now. For most of this time, the predictions of a single demonstration reactor have been 35 years in the future. It is at least that far off today. Never have generations of scientists worked so long on such a tough problem; never have generations of sponsors been so patient.

Fusion research has indeed made enormous progress [1-5] and is now is concentrated at two facilities, the ITER in France, and the National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory (LLNL) in California. Each is gigantic in size, is years behind schedule, and is billions of dollars more costly than original estimates. ITER was first proposed in 1985, approved in 2005, and should be constructed by 2020. It is a tokamak, which utilizes magnetic confinement of the plasma. NIF is a Megajoule laser which took over a decade to design and build. Fusion devices require input power, typically neutral beams or microwaves for magnetic fusion, or lasers for inertial fusion. At breakeven the ratio of fusion power to driver power, known as Q, is unity.

A tokamak contains a plasma confined by both a large toroidal magnetic field and a smaller poloidal field. Laser fusion works by irradiating a target with intense radiation. As the outer part of a millimeter sized target ablates, an opposite inward force compresses the core. While the compressed target is transparent to fusion neutrons, the alphas are locally absorbed, producing a propagating fusion burn wave as the target flies apart. This is called ignition. If all goes well, ITER could give breakeven in about 2025, and perhaps achieve a planned Q of 10 some years later. NIF could achieve ignition in 2-3 years. But as typical for any power plant, the efficiency of the conversion of thermal (i.e., fusion neutron) power to electrical power is itself of order 1/3. Beyond that, the efficiency of the conversion of this electrical power to microwaves or neutral beams is itself about 1/3, so any magnetic fusion device needs a Q of at least 10 before it can do any more than power itself. Laser efficiency is much lower, so a laser fusion power plant would need a still higher Q.

Tokamaks have at least two difficult problems to overcome, which, while likely solvable, are still outstanding after 50 years of research. First, they are inherently pulsed devices. Their current is driven by discharging an inductor, which can store only so much energy. However, they must be run in a steady state. Perhaps more important, tokamaks frequently disrupt; that is, they can suddenly release all or a large part of the plasma and poloidal magnetic field energy. Up to now tokamaks have stored only about 10 megajoules; ITER will store about 800 megajoules, about the energy of a 400 pound bomb. If this energy is suddenly released in a major disruption, it is not unreasonable to fear that the superconducting toroidal field coils might suddenly and uncontrollably quench, as has happened already once in the Large Hadron Collider in CERN. If the toroidal field energy is released in a major disruption, this 400 pound bomb becomes 4000 pound bomb. Clearly, for pure fusion or fusion breeding operation, ITER must be designed so as not to allow even a single major disruption. For either a fast fusion configuration or an actinide burning configuration, the tokamak would be surrounded by a ton or so of plutonium, a requirement that makes lack of disruptions all the more pressing a requirement.

As regards lasers, the construction of NIF is now complete and the ignition campaign is underway. However, NIF's role is nuclear weapons research. LLNL has chosen glass lasers, which have no average power capability; their sponsor does not require any. If they wish to extrapolate to a power plant they would need a completely different laser system. Furthermore, consistent with their goal of weapons research, their target chamber is hard wired into a configuration called indirect drive; symmetric laser illumination of a spherical target is not readily possible in NIF. The target is in a hohlraum, which is itself irradiated by the laser (a hohlraum is a cavity whose walls are in radiative equilibrium with the radiant energy within the cavity). The walls are heated to 250-300 eV and black body radiate. This radiation symmetrically illuminates and implodes the target. Calculations show that gain is sacrificed with indirect drive. But even granting a gain of 100, a NIF pulse would produce 100 megajoules of neutron energy, or about 33 megajoules of electric energy, i.e. 9 kilowatt hours, worth about a dollar. Current hohlraums cost about $10,000 and use a great deal of expensive material such as gold. Once LLNL completes its first ignition campaign, if it can get support for an energy program, perhaps it could reconfigure its optics and target chamber so symmetric illumination is possible. While certainly a costly and time consuming effort, this

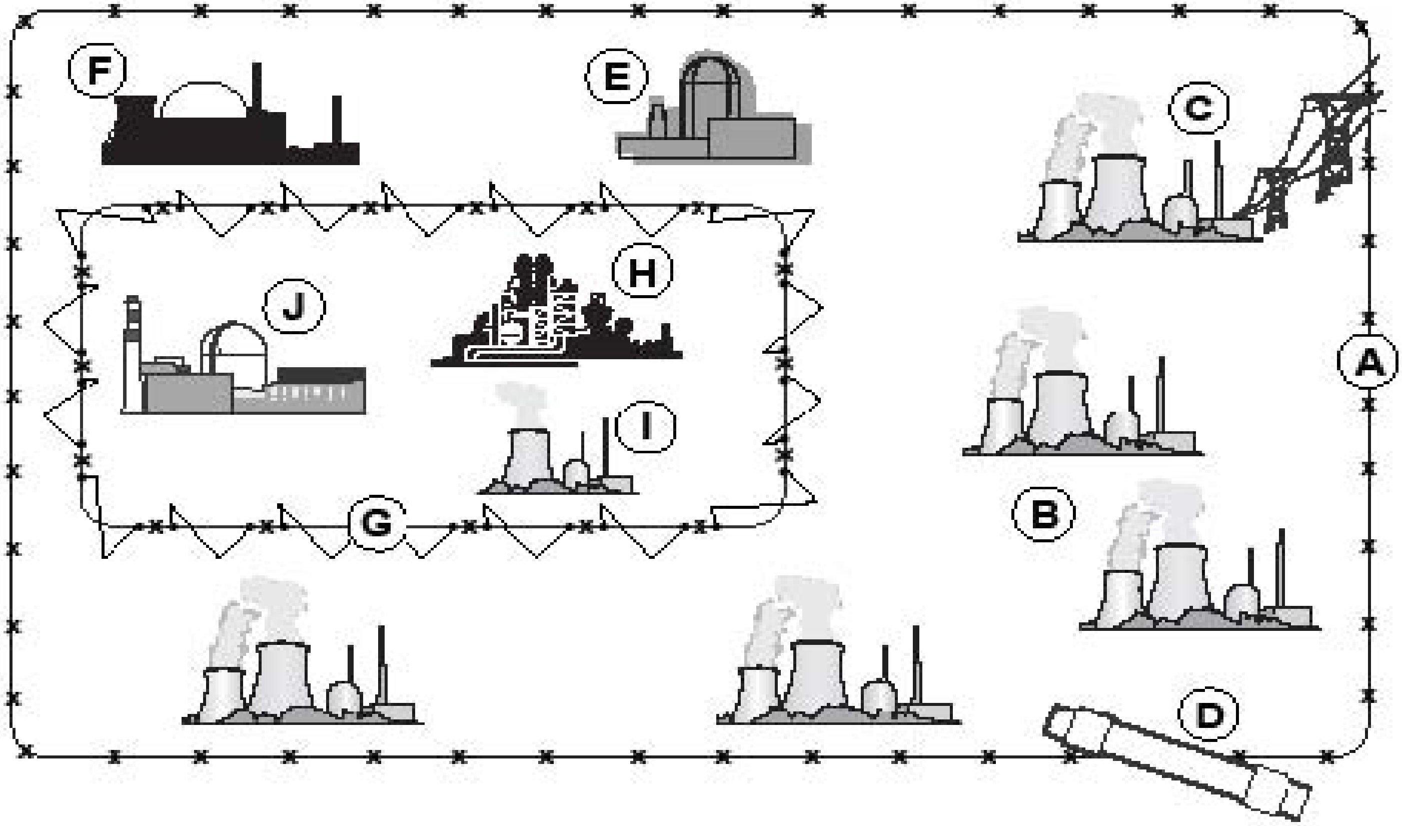

Figure 1: Schematic of an energy park: Inside a low security fence (A), five 900 M-We light water reactors (B), electricity going out (C), hydrogen and/or liquid fuel pipeline (D), cooling pools for radiation products (E), hydrogen and/or liquid fuel factory (F). Inside a high security fence (G), unburned or undiluted actinides; the separation plant (H), the actinide burner (I), and the fusion reactor (J).

would be the fastest and cheapest route to megajoule direct drive experiments. Also, the NIF laser has an efficiency of order 1%. LLNL has proposed solid state diode-pumped lasers and the Naval Research Laboratory (NRL) has proposed KrF lasers, both of which could have sufficient average power and efficiency. Possibly one or the other could be built on the scale of NIF in a decade or so.

Clearly, pure fusion has a very long and difficult road ahead; it has no chance of producing large scale, economical power by mid-century; its most optimistic advocates admit this. This author even has asserted that because of inherent limits on density, pressure and current in tokamaks, it is doubtful that they will ever be economical pure fusion devices, but could well be economical hybrid fusion fuel suppliers [4].

Fission suppressed hybrid fusion: A possible short cut

Today's nuclear infrastructure is based on LWRs, and this will probably be the case in mid-century as well [6]. Thus it is important that fission suppressed hybrid fusion fits in as readily as possible into current nuclear technology. The central idea of fission-suppressed hybrid fusion is to use the fusion-created neutrons to breed nuclear fuel while minimizing fission reactions in the fertile blanket. This means that the blanket must be, for instance, a liquid, perhaps a molten salt with the fertile material dissolved in it. The fissile material produced is continuously removed.

As to the fuel, there are two alternatives: to breed Pu-239 from U-238, or to breed U-233 from Thorium. The proliferation risks associated with the use of plutonium in the raw fuel likely dictate the thorium cycle [1-5]. The fertile material, in which the fissile material is dissolved, could be either U-238, Th-232, or a mixture. There are advantages and drawbacks to each. The former raw fuel would be much more proliferation resistant, while the latter produces many fewer actinides.

Through Monte-Carlo calculations, one can determine the ultimate fate of a fusion neutron in blankets of various materials and geometries. In one fission-suppressed configuration, Moir has calculated that each fusion neutron produces about 0.6 U-233 atoms, the triton sustaining the fusion reaction, and about eight additional MeV for a total of about 24 MeV, the breeding reactions being exothermic [12]. However, when this U-233 is burned in fission reactor it releases about 200 MeV, so in this particular case a single fusion reactor can fuel about 5 LWR's of equal power. In contrast, it takes two fission breeders to fuel one LWR of equal power. *This is the tremendous advantage of* *fusion breeding over fission breeding*. Fusion breeding has an additional advantage as well. A fission breeder needs a large amount of fissile material to start up, whereas a fusion breeder requires none. This is why, in this author's opinion, it is essential to attempt to develop fusion breeding even though fission breeding is presently much closer to reality.

To see the enormous potential of fusion breeding, consider the originally proposed ITER (Q=10, 1.5 GW of fusion power) as a potential commercial reactor. Assume both electricity and the fusion driver are produced with an efficiency of 1/3. The 1.5 GW of fusion power then produces about 500 MW of electric power. However the microwaves or beams needed to drive the reactor take 150 MW (recall Q=10), that is 450 MW of the raw electric power, leaving all of 50 MW for the grid. But now consider the same reactor, but run as a fusion breeder. The output power is now increased by the breeding to 2.4 GW, or 800 MWe. But it would also produce about 13 GW of nuclear fuel, enough for five 900 MWe conventional reactors. Now 5 GWe goes out to the grid, an increase of two orders of magnitude over pure fusion. Thus, instead of being a stepping stone to who knows what sort of demonstration, decades and decades after completion of ITER, an ITER-sized reactor could be an end in itself.

As another example, now consider an ITER-sized reactor driven by a 1 MJ laser. Take the laser efficiency to be 0.1 and Q = 100 and a repetition rate of 15 Hz. At an electrical generation efficiency of 1/3, it sends 350 MW to the grid. This is possibly economical, but in a system of its size is more likely marginal. However, run in a fission suppressed hybrid mode, it would also produce 4.5 GWe of nuclear fuel, an order of magnitude increase. But suppose technical development stops short, so that laser efficiency is 0.05 and Q = 50. Then in a pure fusion mode there would be no power for the grid, but in a fission suppressed hybrid mode, it would still produce 2.2 GWe of nuclear fuel.

Obviously, the demands of fission suppressed hybrid fusion on the fusion reactor are much less than for pure fusion; so much so that fusion breeding even has a reasonable chance of supplying large scale power by mid century [1-5].

The energy park

One possible sustainable model for world development is "the energy park", introduced by the author and shown schematically in Fig (1) [3-5]. The concept is preliminary, and is introduced as what might be described as more than a dream but much less than a careful plan. In it, a single ITER sized, 800MWe fission suppressed hybrid fusion reactor ("J" in the Figure) fuels five LWR's of about 900 MW each ("B"). The spent fuel is reprocessed and is separated into three categories, fission products such as cobalt 60, the original fertile material (say U-238), and actinides such as plutonium. The energy park would store the fission products, which would have half-lives of about 30 years, in cooling pools or dry cask storage on site until they became inert, perhaps after 300-600 years. This is a time human society can reasonably plan for. The U-238 is recycled.

Because of its 24,000-year half-life, plutonium will always be a significant proliferation risk, so geological repositories such as Yucca Mountain must be extremely secure and certified for hundreds of thousands of years. This is difficult to do with any credibility. Instead, in the energy park, the plutonium and other actinides are burned in a sixth reactor ("I" in the Figure), a fast neutron reactor, such as an integral fast reactor (IFR), but run with as low a conversion ratio as possible. (The conversion ratio is the ratio of bred fuel to input fuel; above unity it is a breeder, below it is a burner.) The IFR can run with any transuranics as fuel and can be run either as a breeder or burner. Furthermore, it has demonstrated passive safety [13,14]. That is when a component fails, the reactor, without human intervention safely shuts off. Once burned, the ashes would have no proliferation risk. Hence the need for geological disposal would be eliminated or greatly reduced.

Energy parks could provide economical, carbon free power, with no long-lived waste and no proliferation risk. They could sustain the world at 30 TW at least as far into the future as the dawn of civilization was in the past.

References

1. *W. Manheimer, Fusion Technology, 36, 1 (1999).*
2. *M. Hoffert et al, Science, 298, 981 (2002).*
3. *W. Manheimer, Journal of Fusion Energy, 4, 131 (2001; published 2003), 23, 223 (2004), and 25, 121 (2006).*
4. *W. Manheimer, J. of Fusion Energy, 28, 60 (2009).*
5. *R. Moir and W. Manheimer, Hybrid Fusion Fission, chapter 14, Fusion Technology, T. Dolan, Springer Verlag, to be published 2011.*
6. *J. Freidberg and A Kadak, Nature Physics, 5, 370 (2009).*
7. *W. Stacey et al, Nucl. Technology, 162, 53 (2008).*
8. *M. Kotschenreuther et al, Fusion Eng. Design, 84, 83 (2009).*
9. *E. Moses et al, Fusion Science and Technology, 56, 547 (2009).*
10. *A. Sakharov, Memoirs, Vintage Books, 1990, p 143.*
11. *H. Bethe, Physics Today, May 1979.*
12. *R. Moir, Fusion Technology, 8, 465 (1985).*
13. *Y. Chang, Physics & Society, April, 2002.*
14. *W. Hannum, G. Marsh and G. Stanford, Physics & Society, July 2004.*

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REVIEWS

Nonsense On Stilts: How to Tell Science from Bunk

Massimo Pigliucci, Univ. Of Chicago Press, Chicago, IL, 2010, 332 pp., ISBN-13: 978-0-226-66785-0 (cloth), 978-0-226-66786-7 (paperback)

There are many reasons for writing for the public about pseudoscience and its relation to science. The first and most obvious is the writer's desire to alert readers to the hazards of confusing the two. A second is that pseudoscience, skillfully unveiled, can be entertaining indeed. And a third, to which I will return, is to clearly distinguish between science and pseudoscience.

For these reasons and others, a considerable literature has accumulated on the subject, each work reflecting its author's perspective. The classic *Fads and Fallacies In the Name of Science* by Martin Gardner is over a half-century old. Among recent offerings, Robert Park's *Voodoo Science* stands out.

The demarcation problem – the third reason – has attracted the attention of philosophers of science. The distinction between science and pseudoscience is not always obvious, and the very definition of science requires some care. The best philosophically oriented work up to now has been Daisie and Michael Radner's brief *Science and Unreason*. Now Pigliucci has undertaken a more thorough survey of the demarcation problem, with many more examples. His background as biologist and philosopher has prepared him well for this task, as has his long-standing interest in pseudoscientists, quacks, and screwballs.

Pigliucci approaches his task systematically. He points out that a good general definition of science must be broad enough to encompass not only the physical sciences (which have been used as models by many philosophers of science) but also the "softer" sciences (e.g., the life sciences) and the "almost sciences" – scientific theorizings that presently have scanty evidential bases. In this category he places string theory, SETI, evolutionary psychology, and quantum mechanical interpretations. Many readers will argue that these are not so much "almost sciences" as scientific fields where a paucity of hard data leaves much room for speculation.

He then considers two practical matters. The first is media's frequent mishandling of science and pseudoscience – a distinction not always clear to reporters. The second is the distorting role often played by think tanks with political missions. Two chapters concern prominent present-day examples, global warming and intelligent-design creationism.

The next two chapters get back to philosophy and are the best in the book. They constitute a history of natural philosophy from classical Greek times, and its evolution into modern science. Pigliucci approaches this with gusto and skill.

Two chapters follow on "The Science Wars." Pigliucci takes this term to cover much more than the silly "postmodern" stuff that Alan Sokal exposed so hilariously in his 1996 hoax paper, "Transgressing the Boundaries: Toward a Transformative Hermeneutics of Quantum Gravity." He includes such subjects as the eugenics movement of the early 20th century, and a not entirely impersonal attack on the iconoclastic views of philosopher Paul Feyerabend. He also considers, briefly but neatly, Thomas Kuhn's views of the nature of science. Kuhn was aware of his reliance on physical-science models and promised to extend his arguments to the life sciences, but never did so. As a biologist, Pigliucci is sensitive to this imbalance.

Under the same heading, he makes strong criticism of such prominent scientists as Steven Weinberg, Stephen Hawking and Richard Dawkins, whom he accuses of "scientism, a term that sounds descriptive but is in fact only used as an insult." In his view, such writers overreach the bounds of science in claims of having seen "the mind of God" (Hawking) or having used science to refute "the God hypothesis" (Dawkins.) He finds a root of this view in the "oversized ego … likely to be an ingredient for becoming a scientist." But, scientist-turned-philosopher that he is, Pigliucci finds "a major reason [for such views in] widespread ignorance of, or even contempt for, philosophy." Subsuming such a wide range of subjects under the heading "Science Wars" may be polemically convenient, but I thought it not terribly useful.

Pigliucci then adds another essential ingredient to the mix – the issue of expertise. No one can have deep insight into all of science, and the need for trustworthy experts is ever-present. Unfortunately, frauds, quacks, and screwballs can all claim to be experts, and they often acquire broad credence. Pigliucci discusses a number of examples, including economist Bjørn Lomborg's expansions on global warming, biochemist Michael Behe's on irreducible complexity, and physician Deepak Chopra's on "quantum mechanical elixirs of youth." There follows a fine discourse on the crucial questions of choosing a real expert and telling an expert from a phony.

In the concluding chapter, Pigliucci argues that one cannot define science, or distinguish it from its imitators, in a sentence or two. Nevertheless, there are reliable ways of doing so on a case-by-case basis. Most scientists will agree.

Concerning the book's weaknesses: Although Pigliucci uses biological examples well in his account, physicists will find flaws in his accounts of physical phenomena. A few examples:

It is not true that wave-particle duality is inherent in Young's two-slit interference experiment. The result did indeed favor a wave picture of light over a particulate one, but Young's contemporaries did not regard his work as having "settled the dispute." Newton had, after all, observed single-slit diffraction (of which Pigliucci seems unaware, as he asserts that a single-slit experiment displays purely particulate results.) And Newton had offered a plausible if incomplete explanation in particulate terms. It was Fresnel's equations, almost two decades after Young, that settled the issue with their comprehensive wave-based description of reflection, refraction, transmission, and polarization. The issue of wave-particle duality has one root in this matter, but involves much more. Einstein's 1905 insight into the particulate characteristics of light was based on quite different considerations. It was not light diffraction but de Broglie's magnificent 1926 symmetrization that led to experimental detection of electron diffraction in 1929. More important from a philosophical point of view, Pigliucci misses the central point: Waves and particles are ideal abstractions. Photons and electrons are real entities whose behavior, under proper conditions, is well explained by models based on those abstractions. His analogical argument that Mars is always a planet and not a star has no value and bespeaks a basic misunderstanding.

In discussing Galileo's *Dialogue*, Pigliucci writes, "A busy Urban VIII skimmed through the manuscript and gave the imprimatur." But of the five imprimaturs conferred, three are by Florentine church and civil officials, one is a buck-passing referral, and the remaining one, in Rome, is by Niccolò Riccardi, the Master of the Sacred Palace; the Pope did not confer a formal imprimatur. Galileo's conviction and sentencing, though they were surely a "sad ending," by no means concluded his "life and career," considering that he published his *Discourses* during that period. And he did not escape "burning at the stakes [sic]" on account of his friendship with the Pope.

Pigliucci also gets Galileo's famous falling-body thought experiment wrong. When a light and a heavy body are connected by a string and dropped, it is true that according to Aristotle the two fall slower than the heavy body itself (because the light body holds it back) and the two fall faster than the light body itself (because the heavy body pulls it.) But there is no contradiction here; both can be true at the same time, the pair falling at some intermediate speed. Pigliucci misses the real contradiction: the two bodies together constitute a still heavier body that, according to Aristotle, should fall faster than the heavy one by itself.

Cold fusion is not alleged to be a "chemical phenomenon that … fus[es] atoms" but a nuclear fusion phenomenon that takes place in a more or less standard electrochemical cell.

Finally, it was disconcerting that the manuscript seems never to have passed a copy editor. There is disregard of the pesky distinction between "like" and "as." We read "sprinkle" for "sprinkler," "tale" for "tail," "flaunted" for "flouted," "subsided" for "subsidized," "mathematics were" for "mathematics was," "spinal chord" for "spinal cord," "mantel" for "mantle," "forcefully" for "forcibly," "shelve" for "shelf," inter alia. And the English word Renaissance is not from the Italian but a direct borrowing from the French. (The Italian is *rinascimento*.)

In spite of these shortcomings, *Nonsense On Stilts* is a good read and a worthy addition to the literature on pseudoscience and its cousins.

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Beyond Smoke and Mirrors: Climate Change and Energy in the 21st Century

Burton Richter, Cambridge University Press, Cambridge, UK, 2010 (226 pp.), $29.99 paperback ISBN 978-0-521-74781-3, $99.00 hardback ISBN 978-0-521-76384-4

This book is a call to action. It is written by a concerned grandfather who happens also to be a Nobel laureate in physics, a former director of SLAC, and a member of many US and international committees for the study of climate change and energy issues. The title *Beyond Smoke and Mirrors* is meant as a double entendre. First, "smoke" refers to pollution of the atmosphere by greenhouse gases, and "mirrors" relates to one possible solution, namely, concentrated solar energy. The other, more ominous, meaning is that the book aims to reveal the "real story behind the collection of sensible, senseless, and self-serving arguments" that have characterized the climate debate. Incidentally, one should not confuse this book with another titled *Beyond Smoke and Mirrors: Mexican Immigration in an Era of Economic Integration* by Douglas S. Massey.

This slim volume is divided into three parts, all of which are easily accessible to undergraduates and adults who read *Scientific American* or the science section of the New York Times. Part I deals with atmospheric physics and chemistry.

There is incontrovertible evidence of a rapid rise in atmospheric carbon dioxide levels, from a pre-industrial level of 270 ppm at the end of the 18th century to the current level of about 380 ppm. The climatic implications of this 40% increase are brought home by comparing Earth's climate with that of Mars, with no greenhouse effect, and Venus, with a runaway greenhouse effect. To be sure, our climate models are imperfect at predicting the exact rate of temperature rise, because of the many complicated interactions and feedback mechanisms between the oceans, biosphere, and atmosphere. However, Richter argues that the consequences of inaction are too dire for the issue to be ignored until our models can be perfected. This is true even if we choose to believe the most optimistic predictions of temperature increase, and to disregard the possibility of a catastrophic "tipping point" in the Earth's response to increased carbon levels.

Part II deals with energy alternatives that may help curtail greenhouse emissions and stabilize the atmospheric carbon dioxide level at, say, 550 ppm. The discussion compares the emissions caused by the production of base-load electricity using natural gas and nuclear fuel instead of coal and oil, and also compares these with such "renewable" sources as solar, hydroelectric and geothermal power, and wind and wave energy. Here, Richter comes out strongly–perhaps too strongly--in favor of nuclear energy. Unfortunately, this pits the climate problem against the other existential problem of our times, namely the annihilation of mankind by nuclear weapons. Although Richter claims that there are technical solutions for the storage of nuclear waste, and political solutions for the prevention of nuclear proliferation, his arguments are somewhat less than convincing. In addition, the decade or more needed to commission and build new nuclear power plants means that they will contribute to reducing carbon levels only after 2020.

On the subject of solar photovoltaic (PV) cells for electricity generation, Richter feels that widespread adoption still requires a major decrease in cost. This may have been true at the time of the book's writing; however, in the eighteen months leading up to its publication, the cost of PV modules dropped some forty percent. In the US, since the 1990's, the cost of solar PV electricity has gone from five times to just twice the cost of electricity from fossil fuels and wind. As a result, the DOE is expected to issue a new set of goals for 2030, with solar PV providing as much as ten percent of US electricity requirements.

Part II also deals with improving energy efficiency in transportation and buildings. In this regard, it is noteworthy that California is taking the lead in the US with its zero net energy (ZNE) building requirements, but that the US is lagging much of the developed world. For example, Israel, Spain, Germany, India, China, and South Korea all mandate the use of solar energy for domestic heat and hot water, whereas the US does not.

Part III is a streamlined discussion of national and world policy options, such as cap and trade, emission fees, and the 1997 Kyoto protocol. The book does not deal with the December 2009 Copenhagen summit on climate change. The difficulties of formulating a global policy for limiting greenhouse gas emissions are daunting. First, climate change occurs over long time scales, so it is easily pushed off the public agenda by other, more immediate problems. Second, limits on carbon emissions face steep political opposition whenever they inhibit short-term economic growth. Third, because the emission of greenhouse gases into the atmosphere is a global problem, it only can be solved through a worldwide consensus of developed and developing nations. As Richter emphatically points out, "politics–particularly international politics–is much harder than physics." This is all too true.

One of the most refreshing aspects of this book is its candor, or political incorrectness. Each major energy or policy section ends with a list of winners, losers, and maybes, in which Richter clearly states his evaluation of competing solutions. For example, Richter classifies the use of US biofuels based on corn ethanol as a definite loser, saying that it can have only bad effects on food prices with little if any effect on climate change. Examples of clear winners are an emission fee on gasoline, which will encourage consumers to buy cars with better mileage, and federal mile-per-gallon standards for the auto industry.

The book ends with an exhortation: "If we do nothing, it is our grandchildren who will begin to see the worst effects of climate change, and it is our grandchildren for whom we should all be working." Richter deserves our thanks for devoting his time and energy to convincing the general public that "business as usual" is no longer an option, and that a concerted effort is urgently needed to keep greenhouse Earth livable.

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