The Future of Nuclear Energy

Richard L. Garwin
IBM Fellow Emeritus
IBM Thomas J. Watson Research Center
P.O. Box 218, Yorktown Heights, NY 10598
RLG2@us.ibm.com, www.fas.org/RLG/, www.garwin.us

A presentation in the
Transforming Energy Lecture Series
Sponsored by the Univ. of Maryland Energy Research Center
College Park, MD

December 9, 2011

Abstract

The pre-Fukushima view of a renaissance in nuclear energy technology has been replaced by the recognition that we must modify our approach if nuclear power is to regain public support and to be able to compete on the basis of economics and safety with other sources of energy in the near and long term. The talk discusses the question of secure fuel supply, accident risks, the role of fuel reprocessing, and potential for future breeder reactors.

Overview

Civil nuclear power has been deployed on a large scale, accounting for ~15% of world electrical power production. Such plants could be replicated, with modest improvements, to deliver a much larger fraction of a much increased demand for electrical power, at affordable cost but not competitive with the price for fossil plants fueled with natural gas, for instance, at least in the United States. Producing essentially no $C0_2$ or other greenhouse gas, nuclear plants contain (mostly successfully) an enormously hazardous brew of radioactive materials, ranging from plutonium produced in the fuel to long-lived fission products. From the very first, the application of nuclear power was dominated by the need to prevent leaks of such material, especially in the form of catastrophic accidents, of which there have been remarkably few of commercial powers reactors--Windscale in the UK (1957); Three-Mile Island in Pennsylvania (1979); Chernobyl in the Ukraine (1986); and Fukushima Dai-ichi (FDI) in Japan (2011).

In 1977 I co-authored (with John Steinbruner, Tom Schelling and others) an assessment[1] of the future of U.S. nuclear power, which book was on President Carter's desk the day he took office. In 1975 I had been an author of an American Physical Society study of light-water reactor safety,[2] and in 1979, another book, “Energy: The Next Twenty Years.”

1 “Nuclear Power Issues and Choices,” by the Ford Foundation-MITRE Corporation, March 1977.

2 “Report to the APS by the Study Group on Light-water Reactor Safety,” R.L. Garwin co-author with H.W. Lewis, et al,.Reviews of Modern Physics, 47, Supplement No. 1, June 1975

Unlike coal, for which the public hazard is dominated by air pollution and mining and transport accidents, nuclear power hazards are dominated by the prospect for melting of the fissile core of a large reactor, with the radioactive burden escaping from the containment and being deposited on the ground and on people, contributing to latent cancer with an upper limit of some tens of thousands of latent cancer deaths. Thus, my estimate of latent cancer deaths from the Chernobyl disaster is about 30,000. I provide here for reference a figure from a 2005 paper on comparative expected mortality from various energy technologies3, per gigawatt-yr (electric-- GWe-yr)— the output of a typical modern nuclear reactor.

[3] "Accident Risks in the Energy Sector: Comparison of Damage Indicators and External Costs" by S. Hirschberg, P. Burgherr, A. Hunt. To be found at http://gabe.web.psi.ch/pdfs/PSAM7/0751.pdf

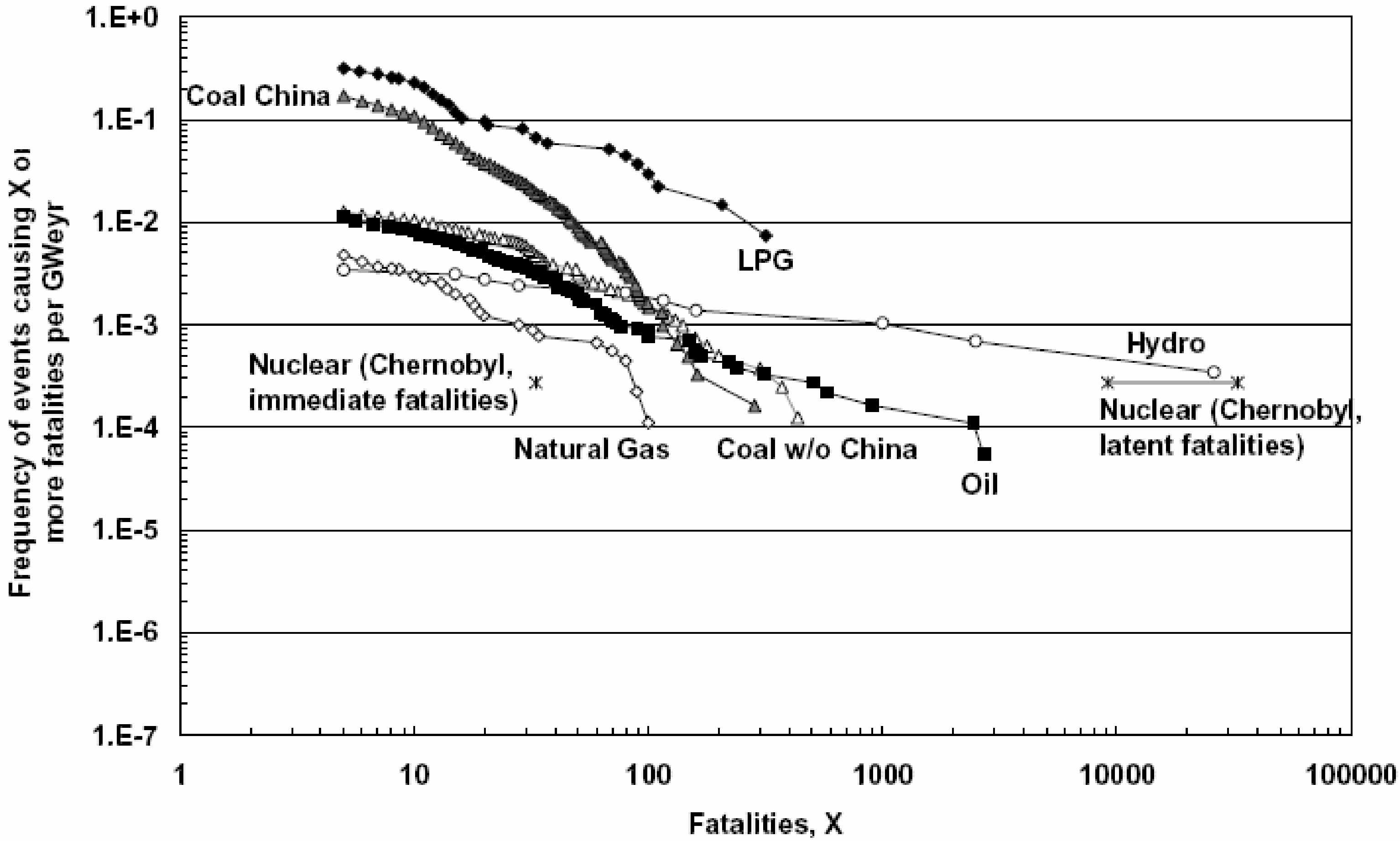


Figure 4: Comparison of frequency-consequence curves for full energy chains in non-OECD countries with partial reallocation for the period 1969-2000. The curves for coal w/o China, coal China, oil, natural gas, LPG and hydro are based on historical accidents and show <u>immediate</u> fatalities. For the nuclear chain, the <u>immediate</u> fatalities are represented by one point (Chernobyl); for the estimated Chernobyl-specific <u>latent</u> fatalities lower and upper bounds are given.

The main problem with the future of nuclear power is moving forward from the present, because the existing 400+ power reactors in the world cannot be made greatly safer than they are, although bringing them up to best practices will help a lot in actual hazard. Those who would like to know more about the fundamentals of nuclear power (and nuclear weapons) could do worse than to read my 2001 book with Georges Charpak[4]. This was expanded in a 2005 book[5] (in French), which is being updated by myself and Venance Journe, following the death of our collaborator, Georges Charpak.

For future nuclear power, there are four requirements:

1. Competitive cost
2. Reasonable safety
3. Affordable supply of fuel
4. Adequate and safe management and disposal of spent reactor fuel.

---

[4] "Megawatts and Megatons: A Turning Point in the Nuclear Age?" by R.L. Garwin and G. Charpak, Alfred A. Knopf, Publisher, New York, Oct. 2001.

[5] "De Tchernobyl en tchernobyls," by G. Charpak R.L. Garwin, and V. Journe, Odile Jacob, Sept. 2005.

DEALING WITH CURRENT REACTORS

Of the 439 power reactors operating in the world today,[6] there are 359 light-water reactors (LWR) that use ordinary water for heat transfer and for moderating the neutrons (265 PWR and 94 BWR), 44 heavy-water reactors with D_20 rather than H_20 for moderation and coolant, 18 gas-cooled, and 12 graphite-moderated with light-water cooling. The future lies with LWRs, until breeders may eventually be economical if uranium supply costs rise sufficiently and if reactor designers and builders manage to bring down the capital cost of the breeders. More about this later.

It would help little to replace current LWRs instantly by the most advanced LWR designs available, as regards fuel supply management and disposal of spent reactor fuel. As for cost, reactors now in operation have a substantial cost advantage over a new reactor, as was discovered in Sweden, with the (former) mandatory phase out of nuclear power. Now fully depreciated, Swedish nuclear power is very cheap, because capital

6 http://www.world-nuclear.org/info/inf32.html

cost is by far the largest contributor to cost of nuclear electric power. So that leaves relative safety of current LWRs compared with the future, to which I would add “surety,” which is the robustness of a facility against intentional harm, such as terrorist attack.

Fukushima Dai-ichi (FDI) sorely tested our current safety practices, by a rare combination of insult-- earthquake followed by a large tsunami. Obviously, nuclear reactors in central France or in Kansas will not be subject to the same threat, but that is little consolation because there are many paths to the intermediate state from which damage and destruction to the reactors resulted. That intermediate is station blackout-- SBO. In fact, any of the world's 94 BWRs (35 in the United States), would respond in similar fashion if off-site power were eliminated and the emergency diesel generators (EDG) could not be kept operating to run valves and pumps, as well as lights and instrumentation.

Tokyo Electric Power Company (TEPCO) is far from the only nuclear operator in the world to site safety-response equipment in such a manner that it is vulnerable to the same insult that called it into play, e.g., the personal dosimeters at FDI and electrical switch gear flooded by the tsunami. Furthermore FDI is not the only instance of reactor construction that either at the time or later was discovered to be on a more perilous site than had been taken into account in the initial approval and construction. In the case of FDI, marker plaques showed the incidence of monster tsunamis in historic time[7] that dwarfed even the 15-m flood of that from the Tohoku earthquake and tsunami of March 11, 2011. Indeed, a year-2002 assessment of the FDI site led TEPCO gradually to waterproof some of its electrical connection gear, essential to survival of a tsunami[8]. The location of diesel generators in the basement of buildings that could be flooded, and fuel tanks that could be swept away by the tsunami sealed the fate of four of the six reactors at FDI.

Ironically, for the construction of reactors 1-4 at FDI, a bench had been scraped away by some 20 m, largely to reduce the pumping power required to lift seawater to the ultimate heat exchangers, thus imperiling the plant.

---

[7] In Miyako City, a monument at 60 m above sea level warns of building below that level; the Tohoku tsunami had a runup of 39 m.

[8] A good, readable report by IAEA is available at http://www-pub.iaea.org/MTCD/Meetings/PDFplus/2011/cn200/documentation/cn200_Final-Fukushima-Mission_Report.pdf

There is now much information available on the FDI disaster, and much to be learned not only in keeping reactors safe but in reducing damage to the neighboring population and environment even if the reactors are destroyed. And there is even more to be learned about the neglected subject of cleanup of vast areas from the deposition of highly radioactive fission products[9].

Finally, there remains an active and concerted reluctance to multiply two numbers to obtain the likely number of latent cancer deaths in the wake of such an accident not only for FDI but also Chernobyl.[10] While IAEA and ICRP[11] advocate for planning purposes the assumption of one lethal cancer per 20 Sv (sieverts) population exposure, they are adamant about not using that in the aftermath of an accident, multiplying by the "collective dose" in person-Sv. I judge that good decisions will be made by popula-

---

9 For instance, the expedient at FDI of "long-term sheltering" of population has been abandoned in favor of evacuation.

10 "Expanding Nuclear Power While Managing the Risks of Accident and Proliferation," by R.L. Garwin, presentation for Euronuclear ENA2006 Brussels, March 29, 2006. www.fas.org/rlg/060329-brussels.pdf All presentations formerly (but no longer) at www.ena2006.org

11 International Commission on Radiological Protection.

tions and governments only when the actual expected damage is calculated from exposure to radiation and also from the alternative forced relocation.

For the longer term, the next generation of deployed nuclear power will be dominated by plants expected to be built in China and India. The designs most ready for deployment are evolutionary steps beyond current reactors, which do not yet reflect the lessons from FDI. We assume that they will be incorporated into the designs. For the future, one needs to attend to the assurance of fuel supply, and to the management and disposal of spent fuel.

No better alternative has been proposed to deep geologic disposal of properly encapsulated spent fuel elements or of the waste from reprocessing of LWR spent fuel. Although the eventual deployment of breeder reactors will eliminate any concern about the availability of uranium, the waste disposal problem is not changed by an order of magnitude, since fission products will still result, in the same amount as at present, dominating at least the short and intermediate term heat load, which is the constraining limit on a geological repository. My arguments are given elsewhere, particularly in my testimony and analyses of the Global Nuclear Energy Partnership (GNEP) that burst upon the scene in 2006 during the administration of George W. Bush. I provide this illustrative figure from the Argonne National Laboratory[12]. The baseline is 1.1 metric tonnes of spent fuel per meter of drift (tunnel).

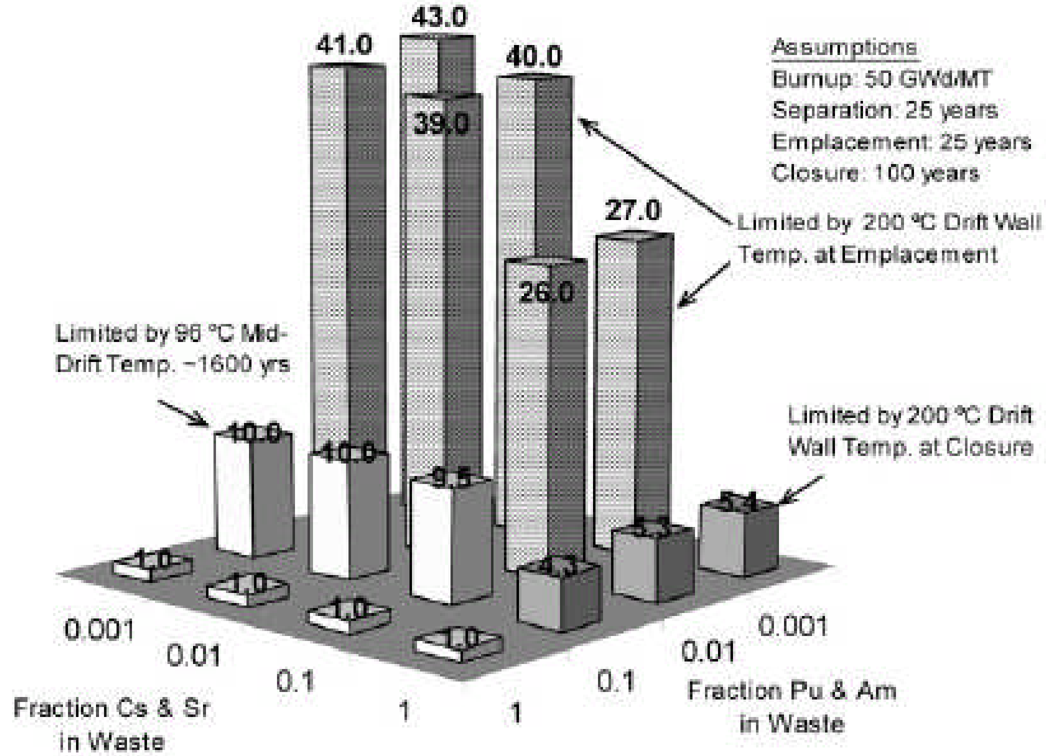


Fig. 7. Potential repository drift loading increase as a function of separation efficiency for plutonium, americium, cesium, and strontium.

12 R&D Priorities for GNEP, by R.L. Garwin, Testimony of April 6, 2006. http://www.fas.org/rlg/060406-gnep.pdf (Figure 7. From Wigeland, et al, Argonne National Laboratory)

I think that President Obama's decision of February 2011 to terminate and to de-fund the Yucca Mountain repository was a serious blow to the U.S. Energy future. Yucca Mountain should never have been made the sole repository for spent fuel or reprocessing wastes, and the arguments for it were, in any case, unwarranted-- that entombment above the water level was safer, and that there was no water flow within YM. But Yucca Mountain is good enough, particularly if one adds additional features, such as granite "tile" roofs above the storage drifts.

But there is far more space available below the water table, and, in any case, the United States should set a priority on an international agreement that permits and encourages competitive, commercial deep geologic repositories under strict control by the IAEA, as I have advocated now for at least 20 years. In this regard, the Council of Europe on 19 July 2011 issued a "Radioactive Waste and Spent Fuel Management Directive"[13] that, in short, from September 2011 permits two or more member states to agree to use a disposal facility in one of them and also to export to coun-

[13] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2011:199:0048:0056:EN:PDF

tries outside the EU under strict conditions: The third country needs to have a final repository in operation when the waste is being shipped, fitting the international definition of a deep geological repository. So I regard this as a helpful step, even revolutionary.

In the meantime, there is consensus between the industry and environmental organizations in the United States, at least, that dry cask storage is far preferable to continued expansion of spent fuel pools, and that dry cask storage is suitable for at least a century of storage of spent fuel, which also eases the initial heat load on the repository.

ASSURANCE OF FUEL SUPPLY

Reactor fuel requires inputs of raw uranium, conversion to UF6, enrichment to a level of 5% U-235, fabrication of UO_2 ceramic pellets, and the assembly of those pellets, perhaps 7 mm diameter, into fuel rods typically some 15-ft long. Of these steps, there is no reason to expect cost increases for any of them except perhaps for raw uranium, and there governments have not done a good job on determining the availability of terrestrial uranium or the feasibility of obtaining uranium from seawater. At present, the world's reactors use about 56,000 tonnes of uranium per year, with about 200 tonnes required annually for each LWR producing 1000 Mwe. If all the world's electrical energy were provided by LWRs, and if that total electrical sector doubled, the annual supply of uranium would need to be increased by about a factor 14, to about 0.8 megatonnes ("MT") per year. The assured reserve of terrestrial uranium is reported as 4 MT, so it would be imprudent to build a reactor with 40-yr lifetime, under these circumstances. Certainly more data is needed, but there have been several analyses as to the increased availability of uranium with increased allowable costs, with these results reported, for instance, in the 2011 MIT Fuel Cycle Study[14]. For instance, 1000 LWRs operating for 100 years at 200 tonnes/yr each of raw uranium could be fueled with terrestrial uranium at a cost that is with 50% probability no more than 30% above 2005 costs. In addition, there is no dispute that there is 4000 MT of uranium in the world's oceans, and that Japanese work has shown that modest amounts can be retrieved at an affordable cost.

---

14 http://web.mit.edu/mitei/research/studies/documents/nuclear-fuel-cycle/The_Nuclear_Fuel_Cycle-all.pdf

What has not been analyzed is the potential environmental effects, broadly understood, of obtaining all or a large fraction of even the current uranium usage from ion-exchange "artificial kelp" in the warm ocean currents.[15] Thus, governments, particularly the U.S. government, but especially the governments of China and India, should support a worldwide effort to assess the amount of uranium available at increasing cost of extraction, which is a lesser problem than that of actually finding high-grade uranium deposits.

Although thorium is several times as abundant as uranium in the Earth's crust, the USGS in 2010 estimated the world total reserves of Th as 1.3-1.7 MT-- about half that of the uranium reserve. Of this total, India has 0.29-0.65 MT. In particular, India has major reserves of monazite sand, about 6-12% Th, which is readily accessible and processible.

Ultimately, the uranium supply problem vanishes with the fielding of breeder reactors that can use essentially all of the U-238, rather than

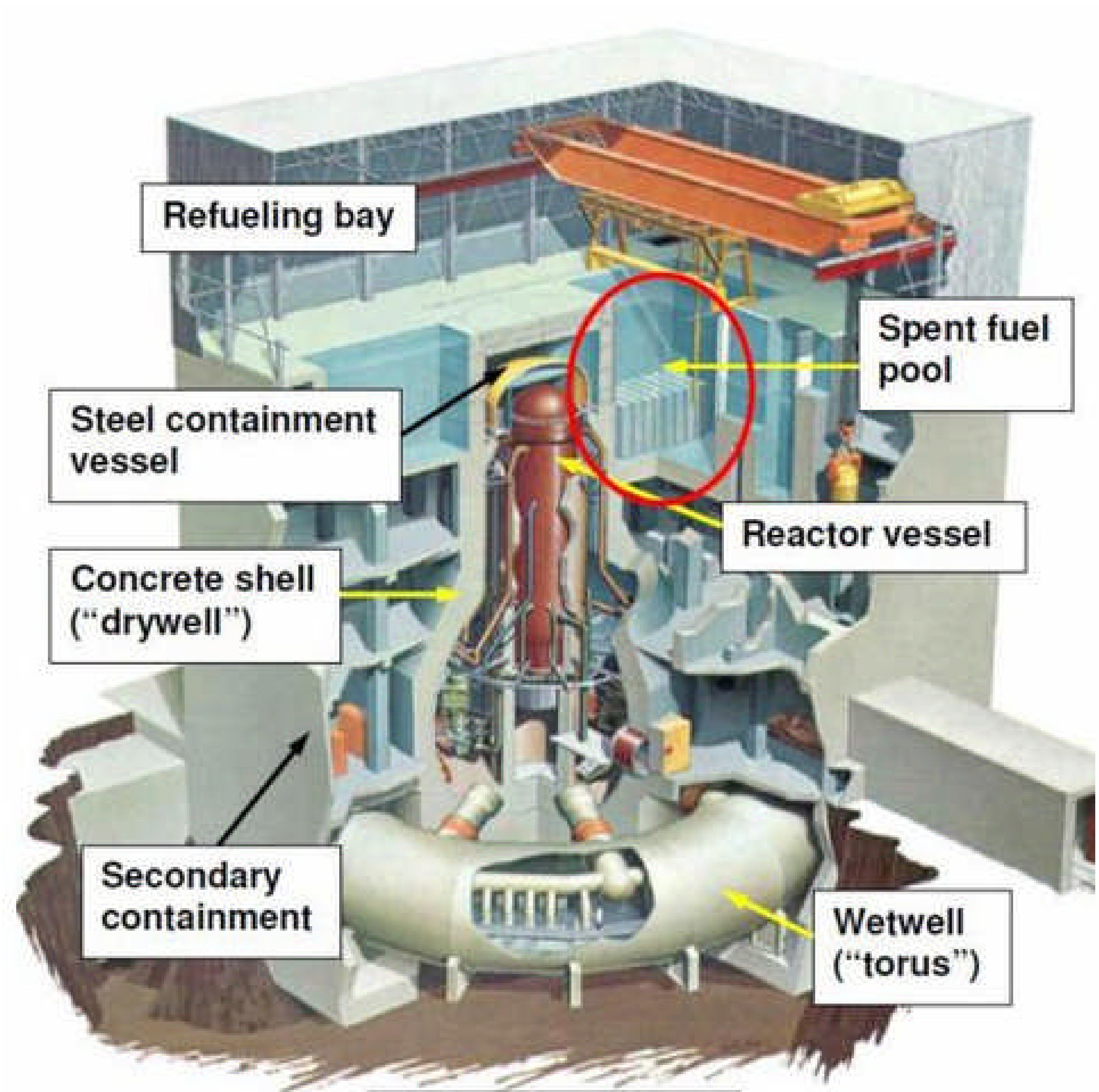
[15] http://www.fas.org/rlg/042209%20R&D_Opportunites_and_Needs2.pdf

roughly half percent of the uranium (0.71% is U-235 that is actually burned in LWRs).

A Th resource of 1 MT would last a mature Th fission economy a long time, because the only way Th can be burned is in a breeder that could consume all of the Th. So with an initial fueling of something like 100 T of Th per reactor, and the fission of about 1 T/yr of U or Th, aside from the initial investment, the present nuclear power capacity could be fueled for 2500 years, and a twenty-fold expansion for 125 yrs. There is surely much more Th available. A comparison of the energy resource in thorium with that of uranium is often muddled by the assumption of LWRs rather than uranium/plutonium breeders, which are more an apples-to-apples comparison.

TWO NEAR-TERM LWRs

As is well known to this audience, LWRs come in two categories; first is boiling-water reactors (BWRs) in which the water actually boils in the re-actor pressure vessel, a steam separator removes the water droplets, and steam issues from the reactor pressure vessel (RPV) to the turbine, which then drives the alternator that provides electrical power to the grid.



Mark I Containment

One of the advantages claimed for the BWR is the economy afforded by a relatively active system for managing design-basis accidents (DBA), specified as a double-ended pipe break that allows reactor coolant to escape the RPV and to enter the primary containment vessel (PCV). As seen in the figure, this steam is supposed to be condensed by allowing it to flow through large ducts to below the surface of ambient-temperature water in a large torus. As demonstrated by FDI, however, the big problem is not handling the steam itself, but ultimately the decay heat from the reactor that in the case of FDI forced venting of the PCV in order to avoid its destruction or leak.

In contrast, the pressurized water reactors (PWR) are provided with a large PCV, so that all of the high-pressure steam and water from the RPV can be allowed to flash into the PCV without exceeding its design pressure.

In both BWR and PWR, however, there is a further very serious problem, and that is the hydrogen produced whenever the zirconium alloy (zircaloy) sheath of the fuel rods overheats in contact with steam. Unlike steam, this hydrogen does not condense, and not only can it overpressure the PCV in the case of the BWR, but it can form an explosive mixture with the air in the PWR containment, as happened in the 1979 Three-Mile Island accident. In that case, fortunately, although the design pressure of the PCV was approached, the containment was not breached. The PCV of a BWR, in contrast, is inerted with nitrogen gas, so that even copious evolution of hydrogen into the PCV would not result in an explosion there. However, destructive hydrogen explosions can and did occur in the reactor building, if the hydrogen is not properly vented under accident conditions, to the ventilation stack.

The Westinghouse AP1000 design is a passive approach to a large PWR. Furthermore by the use of welded steel plate that serves both as a form for the concrete (instead of normal reinforcing rods and forms) and also forms a part of the ultimate structure, construction time may be reduced, and also the "commodities cost" factor. This should not be overstated, since even on current LWRs, the commodity cost amounts only to about 1% of the total capital investment,[16] about $36/kWe capacity of $4000/kWe total.

---

[16] Per F. Peterson, Advanced Reactors for Fuel Cycles, August 5, 2009, http://goneri.nuc.berkeley.edu/pages2009/slides/Peterson.pdf

In our 1977 book, we judged that the Atomic Energy Commission and the Nuclear Regulatory Commission (NRC) were far too optimistic about the core-melt probability of our reactors, and yet, even with a core melt probability given by one not-yet experienced core-melt divided by the number of reactor years of experience, we judged that societal harm to be acceptable and preferable to the continuing illness and mortality from providing a comparable amount of electrical power from coal. This, despite the fact that credible latent cancer deaths could exceed 10,000 from a single uncontained core-melt accident, as I judge is the case with Chernobyl.

Thus, a claimed probability of core melt for modern reactors of 10^{-7} per year produces the expected fatality rate from such an accident, assuming 10,000 fatalities per accident, as 0.001 deaths per year, which at a U.S.-government planning rate of $5 million per fatality would correspond to a cost burden or societal burden of $5,000 per reactor year-- totally negligible in comparison with the $500 million of value for the reactor's electrical energy sold per year. Thus, it is not worth very much to reduce further the assessed probability of core melt, even if it were believable.

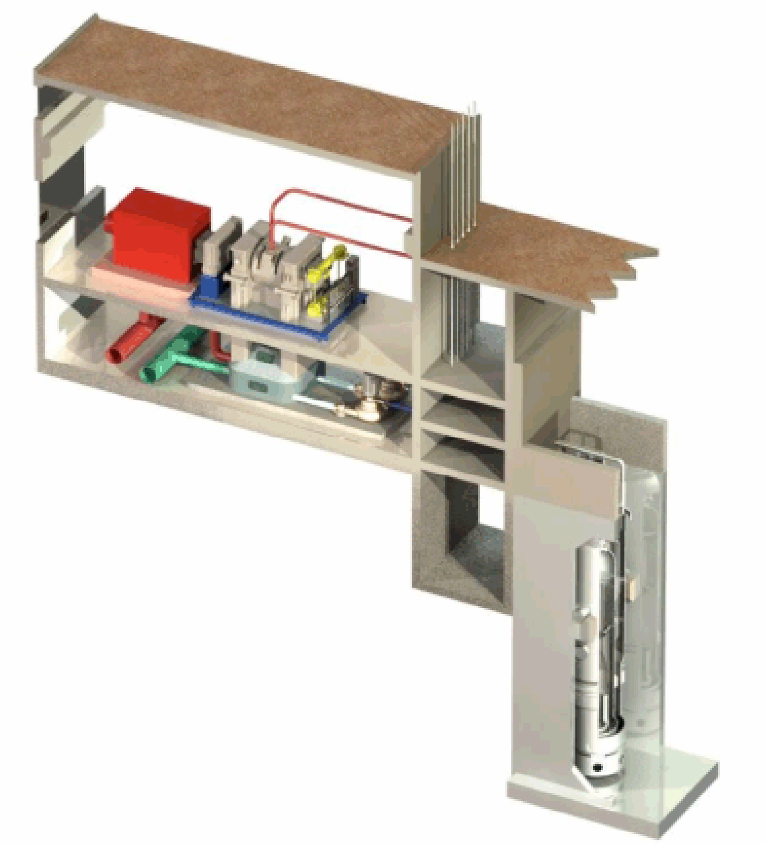
SURETY

What is problematic is not the probabilistic risk assessment but the damage that could be inflicted by a substantial outside terrorist group or such a group in league with a knowledgeable insider. Thus, redundant safety systems that have small probability of both (or even several) being disabled by a single accident, could by the emplacement of small explosive charges be disabled simultaneously. Very different from the 1970s is the evolution of the suicide terrorist mode which makes many approaches more feasible than they were. So one needs to ensure that in a world in which station blackout from accident is nearly impossible, it cannot be provoked by a band of terrorists actively aided by a knowledgeable insider. This is a difficult requirement to meet, and especially to meet all over the world.

SMALL MODULAR REACTORS--SMRs

Although there are designs for SMRs that are not water moderated-- for instance, sodium cooled or helium-cooled-- the regulatory barriers to such designs seem so large that I put them off to the more distant future. One SMR that seems to be gaining favor is that of NuScale Power, an SMR in which the heat exchanger of the small PWR is located within the RPV it-self, which, in turn, is deployed vertically within a water-filled well, below grade level. As indicated in the NSP illustration[17],

[17] http://www.nuscalepower.com/ot-Scalable-Nuclear-Power-Technology.php

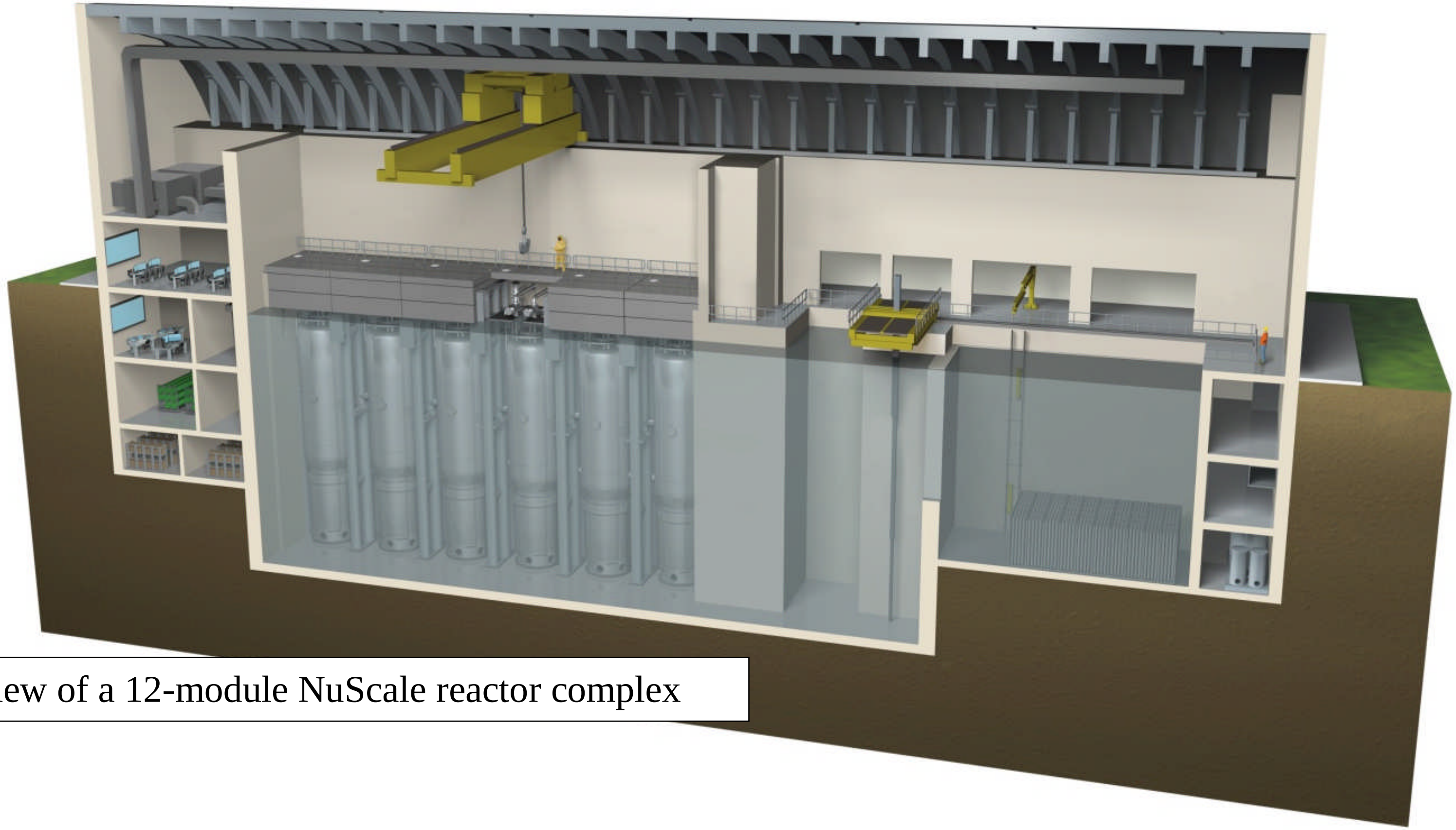


Single-unit side view of the NuScale system design

each 35 Mwe module has its own turbine and alternator. The plan would be to deploy the NSP reactor, 60-ft high by 14-ft diameter, in groups of 12[18]; a core-melt probability target tenfold lower than that of other proposals would make the probability of at least one melt per nominal 1000 Mwe

[18] http://www.nuscalepower.com/ot-Nuclear-Power-Presentations.php (Updated September 2011: NuScale's Passive Safety Approach)

installation about the same with the multiple NSP reactors as with a single reactor.



View of a 12-module NuScale reactor complex

The NSP would be factory built and brought by barge or road to the construction site.

But there are many questions. At FDI there was a strong interaction among the four reactors in separate buildings, coupled closely by shared vent stacks, hydrogen explosions, and the disruption of safety-related facility and activities by the explosions themselves. Is there a "popcorn" effect by which the rather closely-spaced NSP reactors will influence one another and take them offline, even if they aren't damaged permanently? The reactor pressure vessel are to be submerged in 4 million gallons (15,000 m^3) of water that could, by evaporation, remove the decay heat from all 12 SMRs, until natural convection air cooling sufficed to cool the longer lasting 0.4 MWt of decay heat from each reactor

The fuel rods of the NSP are to be deployed in 17 x 17 fuel-element bundles, with the rods only 6-ft long-- about half the length of fuel rods from large power reactors. With a proposed 2-yr refueling cycle, that means the usual replacement of 1/3 or 1/4 of the fuel, with the necessity that a single reactor be refueled while its neighbors continue to operate. The spent fuel pool, at the right in the view, holds the fuel removed from the reactor for a few years to tens of years, until it is transferred to dry-casks for storage or transport.

An NSP reactor that needs refueling would be replaced by a freshly fueled reactor sitting to the right of the pillar in the large water canyon, with the reactor containing spent fuel taking its place, and then over the next few weeks de-fueled with the spent fuel transferred to the spent-fuel pool on the right. Fresh fuel would be loaded into the now empty reactor, which would be ready to replace one of the active reactors when it was scheduled for refueling.

This would all be accomplished by the heavy-lift crane. In the View, there are two rows of six operating reactors in the canyon, separated by a long space for transporting reactors in the shielding water of the canyon. It would be useful to have more details of this operation, and its vulnerability to accident.

THE ROLE OF THE BREEDER

I have frequently published since 1977 my assessment that anyone who believes in the future of breeder reactors cannot possibly believe that their population will grow significantly by the self-generation of plutonium, but must depend upon starting each breeder and its successor by the use of enriched uranium. So I was pleased to read in the MIT Fuel Cycle Study,

"Historically it has been assumed that the pathway to a closed fuel cycle included recovery of plutonium from light water reactor spent nuclear fuel and use of that plutonium to start sodium-cooled fast reactors with high conversion ratios. The conversion ratio is the rate of production of fissile fuel from abundant fertile materials in a reactor divided by the rate of consumption of fissile fuel. Conversion ratios greater than one imply more fissile nuclear fuel is produced than consumed. This future was based on two assumptions: (1) uranium resources are extremely limited and (2) a high conversion ratio is required to meet future needs. *Our assessment is that both assumptions are false.*

> "-- *Our analysis leads to the conclusion that a conversion ratio of one is a viable option for a long-term closed sustainable fuel cycle and has many advantages: (1) it enables use of all fissile and fertile resources, (2) it minimizes fissile fuel flows – including reprocessing plants throughput, (3) there are multiple reactor options rather than a single fast-reactor option, and (4) there is a wider choice of nuclear reactor core designs with desirable features such as omitting blankets for extra plutonium production*

.

"Some of these reactor options may have significantly better economic, nonproliferation, environmental, safety and security, and waste management characteristics. There is time for RD&D to evaluate options before major investment decisions are required. A corollary is that:

"--We must use the available time effectively if real options are to materialize in a few decades.
This conclusion has important ramifications. For example, a future closed fuel cycle could be based on advanced hard-spectrum LWRs rather than the traditional fast-spectrum reactors, possibly with rather different costs and fuel forms, or it could consign current LWR SNF to a geological repository rather than recycling. Such fundamentally different technology pathways underpin the importance attached to preservation of options over the next several decades."

This in fact eliminates a lot of uncertainty in the availability of LWR-derived Pu for the initial fueling of a large population of breeders or near-breeders, in view of the certainty that all but a few early breeders will need to be started with enriched uranium. But this realization does nothing to ensure the cost reduction that would be a prerequisite for early large-scale introduction of breeders.

Among the disparate 4th generation nuclear reactors, the GE-Hitachi PRISM[19] is offered in November 2011 for construction at Sellafield, UK. PRISM is a pool-type liquid sodium fast reactor with metal fuel elements

[19] From : Advanced Nuclear Power Reactors (updated October 2010, World Nuclear Association, at http://www.world-nuclear.org/info/inf08.html

containing Pu and minor actinides from spent LWR fuel. The separation is made by an electrometallurgical process. The fuel remains in the pool for 6 years, one third being replaced each year. A commercial plant under this concept contains an Advanced Recyling Centre and three "power blocks", each of two reactor modules. Each module generates 311MWe, so that the complex generates 1866 Mwe. Each reactor is capable of dissipating decay heat with passive cooling of the fuel and the reactor. GE declined to provide current information for this talk.

The proposal, specifically[20], is to convert all the UK stock of separated plutonium to MOX fuel for PRISM, and to irradiate each of the fuel elements for 45-90 days, in order that the fuel satisfies (barely, and for a short time) the "spent fuel standard" of gamma-ray field that is self-protecting against theft. Then that stock of lightly irradiated fuel would be burned for energy in PRISM, which would take more than a century. In order to carry this out, a high-capacity MOX plant would need to be built, capable of providing a century worth of fuel for PRISM in just a few years. If this

[20] http://www.world-nuclear-news.org/WR-Prism_proposed_for_UK_plutonium_disposal-0112114.html (01 December 2011).

has been thought through by the UK government, no detailed information has been made available.

BETTER OPTIONS FOR DISPOSAL OF THE UK PLUTONIUM

A study by the Committee on International Security of the National Academy of Sciences, funded in part by the U.S. Department of Energy, produced an exhaustive report on the general problem of excess weapon plutonium[21] and an equally complete one[22] on the possible role of reactors in disposition. The conclusions are applicable to excess civil Pu.

A principal option is to "immobilize" the Pu by vitrification along with the fission-product waste that resulted from reprocessing, and to dispose of the stainless-steel-encased glass logs in a mined geologic repository.

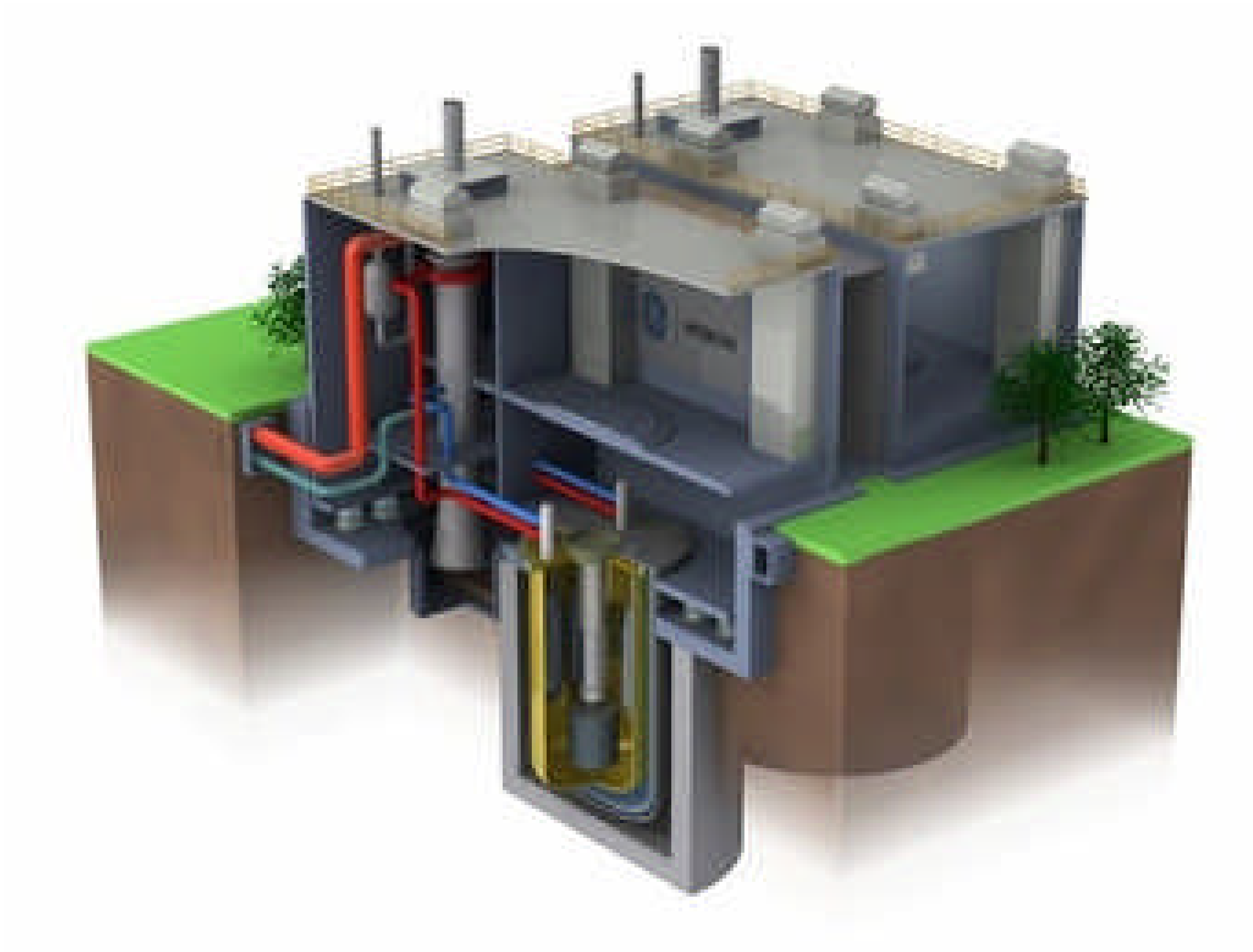
The alternative is to burn or irradiate the Pu as cheaply as possible as mixed-oxide (MOX) fuel in a reactor, to a self-protecting level of gamma-

---

21 Management and Disposition of Excess Weapons Plutonium (1994), National Academies Press, http://www.nap.edu/catalog.php?record_id=2345

22 Management and Disposition of Excess Weapons Plutonium: Reactor-Related Options (1995), http://www.nap.edu/catalog.php?record_id=4754

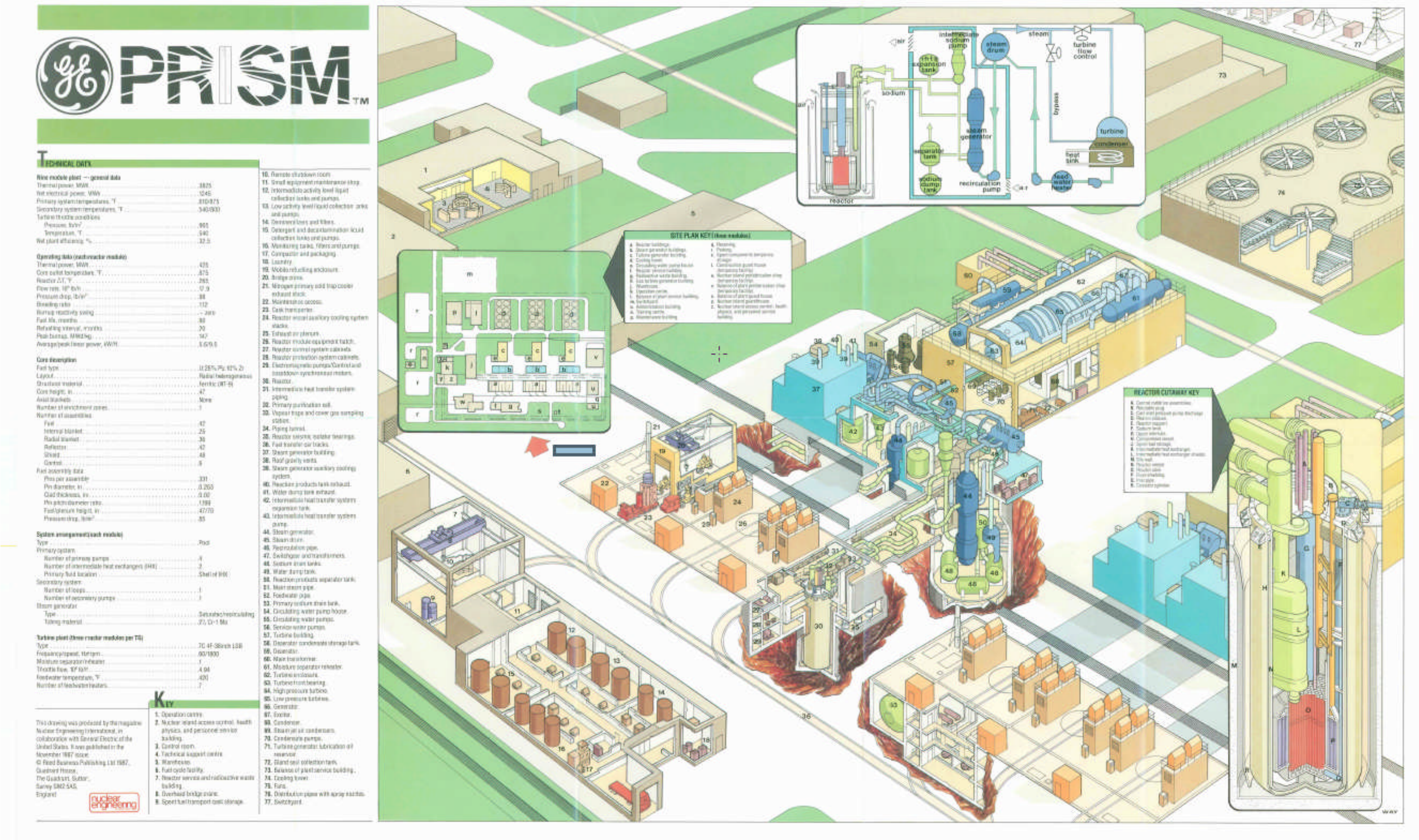
emitting fission products. A new fast-reactor design must demonstrate that it is less costly than the replication of the System-80 PWRs in commercial service at Palos Verdes, California. The report considers also a reactor without high-pressure vessel that produces only waste heat in the process of irradiating high-concentration Pu-bearing MOX. The UK public would be better served if the government prepared a white paper evaluating options for the disposition of its separated Pu.



GE-Hitachi PRISM sodium-cooled fast reactor[23]

[23] http://www.neimagazine.com/story.asp?storyCode=2057914

No detailed drawings seem to be available, but I came across this one from the November 1987 issue Nuclear Engineering International.



This is clearly out of date with respect to the current concept, in power output per module, in lacking the participation of Hitachi, and more. For instance, current statements from GE-Hitachi claim that the pumps are without moving parts, and that the co-location with the Advanced Recycling Center (ARC) reduces the proliferation hazard of the PRISM approach. Even if detailed sketches were available, it would not be possible to evaluate the design, particularly as to its capital cost.

GE-Hitachi, if they have confidence in the approach, have resources sufficient to support the development and first-of-a-kind (FOAK) deployment. In fact, I believe that the best way to keep the first-quality team on the project and to ensure success is to forego government subsidy of both PRISM and the NuScale reactors, but not to preclude the purchase of first-of-a-kind of each.

CONCLUSION

1. The nuclear fission approach to producing electrical power can be very unforgiving, and deficiencies evidenced as core meltdown and release of radioactive materials into the environment resonate around the world.

2. Unless there is a quick and efficient response to Fukushima Dai-ichi, there will be no long-term future for nuclear power. That response

needs to include not only the specific measures against station blackout that have now been proposed by the NRC, but also a tightening of the required response to safety deficiencies that NRC requires to be corrected, but not yet.

3. Greater U.S. government expenditures, preferably in parallel with those of other governments, need to be made on the determination of the supply curve for terrestrial uranium and for evaluation of the environmental problems of obtaining appreciable amounts uranium from seawater.

4. U.S. action in leasing LWR fuel and guaranteeing take back of the spent fuel would be very helpful, but for that to be acceptable there would need to be demonstrated performance toward centralized dry-cask storage and toward competitive, commercial mined geologic repositories under strict IAEA regulation, and their licensing in several countries.

5. Many questions remain about small modular reactors, even about LWRs, and larger ones about the commercial feasibility of sodium-

cooled reactors of any size, even the GE-Hitachi PRISM module of 311 MWe.

6. The conclusion of the 2011 MIT Future of the Nuclear Fuel Cycle Study that a conversion ratio of 1.0 is sufficient to exploit all uranium and thorium in breeder reactors provides much greater flexibility in the choice and design of breeder approaches than does the requirement to maximize breeding ratio. It will be of near-term importance if it enables substantial capital cost reduction, but also in favoring the dry-cask storage of LWR spent fuel in order to defer the reprocessing step until it can be combined with the manufacture of fuel for a specific type of breeder.