

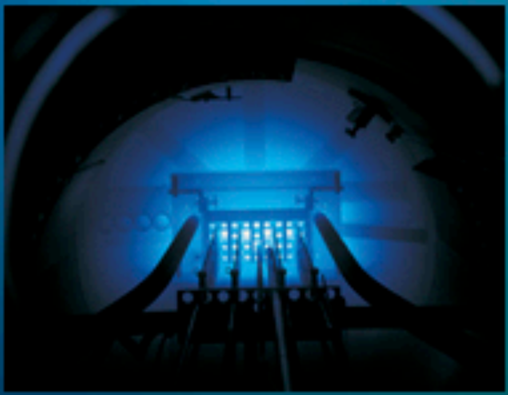


California's Energy Future - Powering California with Nuclear Energy

California Council on Science and Technology
Burton Richter, Robert Budnitz, Jane Long, Per Peterson, and Jan Schori

July 2011

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Letter from CCST

CCST is pleased to present the results of an analysis of the future of nuclear power in California. This study is part of the California's Energy Future (CEF) project, which was undertaken to help inform California state and local governments of the scale and timing of decisions that must be made in order to achieve the state's goals of significantly reducing total greenhouse gas emissions over the next four decades.

California's Global Warming Solutions Act of 2006 (AB32) and Executive Order S-3-05 set strict standards for the state to meet. In order to comply, California needs to reduce its greenhouse gas emissions to 80% below 1990 levels by 2050 while accommodating projected growth in its economy and population. This will likely require a doubling of electricity production with nearly zero emissions. Nuclear power could be an important component in strategies for meeting these standards. This report is a summary of the realistic potential of nuclear power for California and presents an analysis of technological readiness, safety, fuel supply, costs, and siting.

As this report was nearing completion, the nuclear power accidents that resulted from an earthquake and tsunami in Fukushima, Japan were unfolding. Consequently, this report also includes some preliminary observations about Fukushima relevant to California. As the Fukushima events unfold and we learn more about exactly what happened and why, it will be worth revisiting the meaning of Fukushima for California in more depth.

We believe that the CEF nuclear power report presents valuable insights into the possibilities and realities of meeting California's electricity needs and emissions standards over the decades to come, and hope that you will find it useful.

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I. Introduction and Conclusions

This report is aimed at examining the potential of nuclear energy to meet California's electricity demand in the year 2050. The main focus of our analysis is on the CCST Realistic Model (described in detail elsewhere) which assumes that total electricity demand in California in the year 2050 amounts to 510 terawatt-hours per year (TWh/y). Since nuclear electricity is capital intensive, it is most economically used as baseload power where the plants run at their maximum output all of the time and that is what we assume here. We also assume that nuclear plants have a 90% capacity factor and that baseload power represents 67% of total electricity demand (adjusting the baseload fraction up or down does not affect the conclusions reached herein), the rest being supplied by renewables as mandated by California's law AB32. This requires about 44 gigawatts (GW) of nuclear electricity capacity. This scenario and one scenario where nuclear electricity is deployed on a much larger scale (call the Stress Test) are described in section III. We also assume that a large scale growth in nuclear energy in California will be part of a large scale growth worldwide which affects infrastructure and work force requirements as discussed below. Consequently, our analysis assumes that California only gets its fair share of resources needed to scale up, but an expanding nuclear industry results in economies-of-scale which makes nuclear power less expensive for California.[1]

Some of the scenarios used in the full report include use of hydrogen as a fuel. Hydrogen can be produced using nuclear reactors though doing so efficiently requires a new generation of nuclear plants.[2] Requirements for hydrogen production are also briefly discussed in Section III.

While reactor technology is certain to evolve over the period of interest, we are assuming for this study that for electricity production these future reactors will have characteristics similar to the new generation of large, advanced, light-water reactors (LWR), known as GEN III+ that are now under review by the U.S. Nuclear Regulatory Commission for deployment in the next decade. This allows us to say something about costs since these are under construction in Asia and Europe, and a larger number of similar systems have been built in Asia recently. We comment later on the potential of new and improved designs. Our main conclusions on technical issues are as follows:

- There are no technical barriers to large-scale deployment of nuclear power in California. There are, however, legislative barriers and public acceptance barriers that have to be overcome to implement a scenario that includes a large number of new nuclear reactors.
- The cost of electricity from new nuclear power plants is uncertain. No new ones have been built in decades, though 104 generating plants are operating in the U.S. today. Thus, operations, maintenance and fuel costs are known well, but the dominant cost, the amortization of construction costs, is uncertain. Estimates of electricity costs from new plants range from 6 to 8¢ per kilowatt hour (KW-hr) up to 18¢ per KW-hr with most estimates at the lower end of the range. Our conclusion is that 6 to 8¢ per KW-hr is the best estimate today. This is discussed in more detail in section II.

1 The scale-up of nuclear power in California could occur whether or not the world develops an expanded role for nuclear power. Although there are no non-proliferation issues with expanding nuclear power in California, we note that nuclear nonproliferation will be an issue for global scale up and if nuclear power is to fulfill its potential as a global carbon-free energy resource, expansion must be accompanied by dramatic increases in cooperation among national governments to strengthen the Nuclear Nonproliferation Treaty, the IAEA system of safeguards against diversion of civilian nuclear programs to any military purpose, and the physical security of nuclear fuel cycle facilities against attack by terrorist groups and theft of weapon-grade materials by terrorist or other criminal groups.

2 The favored method of hydrogen production requires reactors that operate at much higher temperatures than occur in the present generation of power reactors in order to achieve reasonably high efficiency. These high temperatures raise new materials problems and a major R&D effort will be required to solve them. R&D has begun, but it is not possible as yet to say how long it will take to solve the problems.

- Loan guarantees for nuclear power will be required until the financial sector is convinced that the days of large delays and construction cost overruns are over. Continuation of the Price-Anderson act is assumed.
- Nuclear electricity costs will be much lower than solar for some time. There is insufficient information on wind costs yet to allow a comparison, particularly when costs to back up wind power are included.
- Cooling water availability in California is not a problem. Reactors can be cooled with reclaimed water or with forced air, though air cooling is less efficient and would increase nuclear electricity prices by 5% to 10%.
- There should be no problem with uranium availability for the foreseeable future and even large increases in uranium costs have only a small effect on nuclear power costs. There may be shortages of natural uranium in the long term, but there are ways to get around them.
- While there are manufacturing bottlenecks now, these should disappear over the next 10 to 15 years if nuclear power facilities world-wide grow as expected.
- There are benefits to the localities where nuclear plants are sited. Tax rates in California are set by the State Board of Equalization, typically at 1% of the cost of the plant, and collected locally. By current estimates this would amount to $50 million per year per gigawatt of electrical capacity (GWe). In addition, about 500 permanent jobs are created per GWe.
- The events at Fukushima, Japan where a number of boiling water reactors (BWR) were damaged in a major earthquake and tsunami will trigger review and evalution of safety in design, operation and mangement. The information gained during the Fukushima review and any recommendations made should be factored into decisions about the potential future use of nuclear reactor technologies in California.

Section II of this report looks at costs; section III focuses on the realistic and extreme scenarios; section IV examines fuel availability; section V looks at site issues; section VI discusses the spent fuel problem; and section VII briefly touches on weapons proliferation. Section VIII is a story line; what has to be done on the State, Federal, and industrial levels to make this kind of nuclear expansion possible. Section IX gives some preliminary comments on the nuclear accidents at Fukushima nuclear power plants in Japan which were triggered by a massive earthquake and tsunami. Appendices 1-3 go further into fuel availability, waste disposal, and future options (including fusion).

II. Nuclear Technology and Costs

We focus on reactor types that can be deployed now (none of the new generation has as yet been licensed by the U.S. Nuclear Regulatory Commission, but license approvals are expected soon). Cost estimates for nuclear electricity have been made recently by an MIT group in an update to its 2003 report on nuclear energy,[3] the National Academy of Sciences,[4] and the Energy Information Administration of the DOE.[5] These reports give prices for nuclear electricity in the range from 6¢ to 8¢ per KW-hr in 2007 dollars. These estimates are based on the assumption that loan guarantees are given at the start of construction and that first-of-a-kind costs of a particular reactor type have been recovered in the first few models to be deployed. Without loan guarantees the MIT and NAS reports estimate that higher interest rates on construction loans would lead to an electricity price about 2 to 3¢ per KW-hr higher. The EIA report does not specifically mention the issue (in keeping with the methodology of the California's Energy Futures study, all costs given here are in today's dollars and exclude inflation from now to the year 2050).

The International Energy Agency (IEA) of the Organization of Economic Cooperation and Development (OECD) estimates nuclear electricity costs of 5¢ to 6¢ per KW-hr depending on interest rates.[6] The IEA estimate is based on world costs and is dominated by experience in Asia where many reactors have been built in the last decade in Japan and South Korea.

Seven reactors have been built and put into operation in Japan and South Korea in the period from 1994 to 2005. The average overnight cost of these was $2,100 per KW, and during the period the cost per KW declined by about 30%. Inflating these costs at a rate of 3% per year, leads to a cost of $2,800 per KW in today's dollars. Costs for the first few reactors of any given type will likely be higher in the U.S. because of the lack of recent experience in construction of such facilities.

The Keystone Center in 2007 published a report called "Nuclear Power Joint Fact-Finding"[7] that was produced by a group including members from industry, universities, national laboratories, former government officials, environmental groups, finance experts, etc. Their analysis leads to a levelized cost of electricity of 8.3¢ to 11.1¢ per kilowatt hour without loan guarantees, not inconsistent with the lower estimates above that were made with loan guarantees.

A particularly interesting report commissioned by the German government is "The World Nuclear Industry Status Report 2009".[8] It reviews reactor costs worldwide including the relatively low costs in Japan and Korea, the cost overruns of the AREVA EPR projects in Europe, and summarizes what is known about the costs of reactors proposed for the U.S. Their estimates for U.S. overnight costs range from $2,500 to $4,900 per KW including first of a kind costs. They do not predict the cost of power.

The outlier in electricity costs comes from a report by Energy and Environmental Economics, Inc.[9] Their estimate of electricity costs is about 18¢ per KW-hr of which 6¢ is operations, maintenance,

3 http://web.mit.edu/mitei/docs/nuclearpower-update2009.pdf
4 America's energy Future, National Academy of Sciences, 2009
5 EIA Report #:DOE/EIA-0554(2008)
6 OECD/IEA, World Energy Outlook 2006
7 http://keystone.org/files/file/SPP/energy/NJFF-Final-Report-6_2007.pdf
8 http://www.bmu.de/english/nuclear_safety/downloads/doc/44832.php
9 Energy and environmental Economics, Inc, Meeting California's Long-Term Greenhouse Gas Reduction Goals, November 2009

and fuel; and 12¢ is the levelized capital cost of the plant. There is not much information on how these estimates were arrived at.

Our analysis of all this data leads us to the conclusion that the most reasonable estimate that can be made today of nuclear electricity cost is in the range of 6¢ to 8¢ per KW-hr, with loan guarantees and after first of a kind costs have been recovered. The reader has to choose what to believe. We won't really know what costs are until several reactors have been built. The preponderance of the evidence favors something toward the low end of the estimates.

We expect 20% cost reduction after about ten reactors of a given type have been constructed in the U.S., a further 10% after 30, and, if a large number are built in the U.S., costs should decline by a further 20% by the year 2050. Our assumptions on the learning curve apply separately to reactors from Westinghouse, General Electric and AREVA, among others, and exclude inflation.

Small, modular nuclear reactors are being developed by industry. For example, a Babcock and Wilcox design operates at 125 MWe, a NuScale design at 45 MWe, and others are in the works. Costs of these reactors are claimed by their proponents to be about $4,000 per KW, comparable on a per KW basis with the costs of large LWRs. Small reactors are suited to electrical generation but also may have other applications, for example, desalinization and industrial process heat. We have not included these applications in our estimate of demand though we note that locating reactors near a sea-water supply would allow the waste heat of the reactor to be used for desalinization at little or no cost.

New types of reactors are being studied in the International Generation IV (GEN IV) program and some may turn out to be significantly less costly than the present GEN III+ reactors, and use uranium more efficiently. Considerable time is required to complete the necessary R&D, produce a prototype, and obtain design certification from the Nuclear Regulatory Commission. We expect the earliest possible date for first-of-a-kind deployment of these new reactors could be 2030. We note that one of them, the very-high-temperature gas reactor, is particularly well suited for hydrogen and process heat production (see note 1). If hydrogen and process heat become important, this may increase the demand for nuclear energy. The hydrogen option adds greatly to demand as discussed in Section III.

Studies of uranium availability foresee no problems until the second half of this century at the earliest, even with increased demand. Current estimates of uranium availability at today's prices are enough to fuel 1,300 1-GWe reactors for their full 60 year lifetime (discussed further in Section IV). Uranium prices have been volatile in the past and will probably continue to be volatile in the future. However, the most costly part of reactor fuel fabrication is enrichment, and new players are entering this field while existing enrichment service providers are expanding their facilities. We do not expect enrichment to be a bottleneck. Present fuel contribution to the cost of nuclear generated electricity is only about 0.5¢ per KW-hr[10] so even large increases in uranium costs will have little effect on the price of nuclear electricity. Reference 1 indicates that doubling raw uranium prices would increase nuclear electricity costs by only 0.13¢ per KW-hr. Spent fuel management costs are not likely to increase significantly beyond today's 0.1¢ per KW-hr. Both of these issues are discussed in more detail in section IV and appendix 1.

10 http://www.world-nuclear.org/info/inf02.html

III. Matching Supply with Demand

Introduction

The CCST exercise has several scenarios. Here we look at two including the Realistic Model which has a balanced mix of very low emission energy sources, and an alternate extreme variation (the Stress Test) where nuclear energy supplies nearly all the demand expected in 2050 in a business as usual scenario where total demand is much larger than in the realistic case. The 2050 situation will certainly not be like the extreme version and may not be exactly like the realistic one either but the result presented here can be scaled to whatever realistic scenario is eventually realized based on the mix of supply that is most cost and environmentally effective. Note that in all cases below it is assumed that 33% of electricity is produced from renewables as mandated in state law by 2020.

Balanced Portfolio

As mentioned earlier, the main focus of our analysis is on the CCST Realistic Model which assumes that total electricity demand in California in the year 2050 amounts to 510 terawatt-hours per year (TWh/y). Our assumptions for this case are that nuclear electricity is used as baseload power where the plants run at their maximum output all of the time; that nuclear plants have a 90% capacity factor (it was 92% in 2009) and that baseload power represents 67% of total electricity demand. This requires about 44 Gigawatts (GWe) of nuclear electricity capacity.

California currently has a total of 4.5 GWe of nuclear electricity capacity installed at San Onofre and Diablo Canyon. Even with 20-year life extensions for reactors at both sites, all will have passed 60 years by 2050 so that absent further life extensions the entire 44 GWe will have to come from new reactors.[11] This requires 28 of the AREVA EPR plants or 31 of the Westinghouse AP-1000 plants.

Maximum Electricity

The Stress Test scenario assumes a demand for 1,160 TWh/y and asks that nuclear plants supply it 67% of it. This requires an average output of 99 GWe, but much more in practice because nuclear plants may have to supply the peak demand, not just the base load. This might require a maximum output nearly twice as high as the average requirement giving a total nuclear capacity of as much as 200 GWe. Given the high capital cost of nuclear plants, this would not seem to make much sense and we discuss it no further.

Hydrogen

In the Realistic scenario the hydrogen variant lowers electricity demand to 460 TWh/y requiring 39 GWe of electricity capacity, and adds a requirement for 910 trillion Btus of energy to be supplied in the form of hydrogen. The preferred way today to make hydrogen on a large scale with nuclear electricity relies on high temperature electrolysis which has an efficiency of roughly 50% at temperatures of 800˚C to 900˚. This requires a new type of nuclear reactor which in now being con-

11 Possible life extensions to 80 years are being studied for existing reactors. Since California's nuclear base is small, this would make only a 2% reduction in new nuclear power if it were to come about.

sidered, but is not yet beyond the R&D phase. Even with aggressive promotion such a reactor could not be ready before the year 2030. However, we give the numbers here for completeness. If such a reactor was available, the total nuclear electricity requirement would approximately double.

In the Stress Test case electricity demand is reduced from 1,160 TWh/y to 800 TWh/y while the hydrogen requirement jumps to 2,600 TBtu/y. The total nuclear electricity component would be more than four times the 39 GWe given above.

Infrastructure Issues

At present there is a world-wide infrastructure bottleneck for large reactor construction. The main problem is the forgings required for reactor vessels. We assume that this bottleneck will have been removed by 2025 if world-wide demand is large. There is also a skilled-worker bottleneck in the U.S. and we assume that this too will have gone by 2025 if new reactor demand is as large as expected (enrollment in nuclear engineering majors at colleges is already starting to increase). Operators will also have to be trained.

According to the IEA, the peak of reactor construction world wide occurred in the 1984 when 34 new reactors began operation.[12] Back then, many fewer countries had the industrial capability to build nuclear reactors, and each reactor tended to be different from what had been built before. Today, more countries can and do build nuclear power plants, and the manufacturers are producing more modular designs that have many components factory built and assembled at the site. This simplifies the production and installation of new facilities. We believe that there should be little difficulty in raising this production rate to 70 to 100 per year world-wide if the demand was there.

It will take a while to get up to speed and we assume that from 2020 to 2050, 2,000 to 3,000 new GEN III+ reactors could be turned on world-wide producing from 2,400 to 3,600 GWe if they were the size of the Westinghouse AP-1000 or to 3,200 to 4,800 GWe if they were the size of the AREVA EPR. The U.S. has nearly one-quarter of the world's nuclear power and if that continues there would be no barriers in principle in California having 44 GWe of nuclear power out of a U.S. total that might be as much as ten times larger.

Small, Modular Reactors

The small reactors that might begin to be deployed by 2015 to 2020 offer another road to large scale nuclear power that, because of their lower capital cost per unit, might be more attractive than the large reactors that are now the work-horses of nuclear energy if they also prove to have acceptable costs per kilowatt-hour. For example, the proposed Babcock and Wilcox reactors are to be factory-built and delivered to the site ready for installation. Plans now are for factories capable of producing two to four 125 MWe modules per month which corresponds to 75 to 150 GWe per factory over the 2025 to 2050 period. If this program works out, one such factory could satisfy California's needs. Reactor availability would seem to be of little concern in this scenario.

12 http://www.iaea.org/programmes/a2/index.html

IV. Fuel

The present generation of nuclear power reactors runs on uranium enriched in the fissionable isotope U-235. Natural uranium contains 0.7% U-235, and the enrichment process increases this to something in the range of 4% to 5% for power plant use. It takes about 200 tonnes (1,000 kilograms per tonne) per year of natural uranium fuel for each 1,000 megawatt-years of electricity produced by a reactor. The U.S. fleet of 104 reactors requires about 20,000 tonnes of natural uranium per year, and the entire world collection of power reactors requires 80,000 tonnes per year.

The current estimate of available uranium including both proven and estimated reserves is about 16 million tonnes, a 200 year supply at the current rate of consumption. If nuclear power does expand greatly in the next decades, some worry that a shortage of uranium may develop. However, in contrast to oil and gas, there has been little exploration for new uranium deposits in the last two decades because of relatively low prices. Even so, the world inventory seems to be growing. Many geologists think there is much more available, though perhaps at a higher price.

There are ways to use the 99% of natural uranium that is in the isotope U-238; non-fissionable in today's LWRs. All reactors consume fissile isotopes but also produce new fissile isotopes at the same time by neutron capture in U-238 (or in Th-232 for thorium cycle reactors). The ratio of the amount of fissile material produced to that consumed is called the conversion ratio. It is possible to increase the conversion ratio to values above 1.0 in reactors designed for the purpose, thereby producing more fissionable material than is consumed, by transforming the non-fissionable isotopes into fissionable ones (discussed in detail in appendix 3). Note that the cost estimates given earlier are for the present generation of power reactors that do not use this technology.

Fuel availability for the next 50 to 100 years is discussed further in appendix 1.

V. Sites

At present there are only two sites in California with operating reactors, Diablo Canyon and San Onofre, each with two reactors. Expansion at either of these sites is possible technically, but neither could accommodate a large enough number of additional units to make a major difference in the context of the number needed to achieve the scenarios outlined here. We are not able to offer an opinion on the potential for more coastal sites which would be important for desalinization applications as this involves political and environmental decisions that are beyond the scope of this report.

There are many potential inland sites, and the only technical barrier for these may be the availability of water for cooling. Reactors have no problem using reclaimed water for cooling and, if there is not enough of that, can be air cooled. Air cooling increases the cost of electricity by 5% to 10% because of the need to power the fans in the cooling towers from electricity produced by the plant which decreases the amount of electricity that can be delivered to the grid by the same 5% to 10%.

Because California is "earthquake country", reactors to be deployed in California would, of course, require special design features in order to assure that they are safe in earthquakes. This engineering problem has been solved successfully already. Both the Diablo Canyon and San Onofre reactor plants that are now operating are designed to withstand the ground motion from very large earthquakes, and meet all of the stringent NRC regulatory criteria with adequate margin. There is no reason to believe that earthquake issues should be a barrier to deploying additional reactors in California. In addition, there are potential inland sites with lower seismicity.

The simplest system for California would be a small number of energy parks, each with a large number of reactors. For example, 5 to 10 sites each with 5 to 10 GWe plus the existing coastal sites would be enough to meet the electrical output needs assumed here in the realistic nuclear case. Such reactor parks could each generate over $250 million in local taxes annually and more than 2,500 jobs. We note that California today imports a significant percentage of its power needs and new nuclear plants can be located in other states as well as here. If so, the impact on the grid needs analysis which is beyond the scope of this report.

VI. The Spent Fuel Problem

Appendix 2 discusses the spent fuel issue from both national and California perspectives. We summarize the situation here.

At present, California law requires the licensing of a national repository for spent fuel before any new reactors are built in the state. The Obama administration has said that it will not use Yucca Mountain in Nevada as a geological long-term repository, though it is designated as such by Federal law. It has appointed a "Blue Ribbon Commission" to analyze the issue and recommend alternatives.

The Blue Ribbon Commission is to issue an interim report early in 2011. Any alternative to Yucca Mountain would require that Congress change existing law, a new site be selected, the necessary R&D be conducted to validate the site's technical acceptability, and an NRC license be obtained. It is very unlikely that a new site could be opened to accept fuel in less than 25 years.

What to do with spent reactor fuel in the meantime is an issue of importance. A recent study by the American Physical Society[13] and an older one by a Harvard, University of Tokyo joint group[14] show that storing all of the spent fuel produced over a reactor's lifetime in dry casks at the reactor site is an effective interim solution and is being implemented at all U.S. reactor sites. Centralized interim storage may also be developed. Some experts recommend that it be used to consolidate spent fuel from decommissioned reactor sites, of which two exist in California, while on-site storage be continued for operating reactors.

If California pursues a future with many new reactor sites, state permitting and public acceptance will be issues that could cause major delays in implementing a nuclear route to the state's greenhouse gas reduction goals. As far as land use is concerned, nuclear energy is much more economical than any of the renewables. For example, the entire San Onofe 34 hectare site delivers 2.2 GWe while covering all of it with 10% efficient solar cells would only deliver about 1.5% of that at noon on a bright summer day.

13 "Consolidated Interim Storage of Spent Nuclear Reactor Fuel", February 2007, http://www.aps.org/policy/reports/popa-reports/upload/Energy-2007-Report-InterimStorage.pdf

14 "Interim Storage of Spent Nuclear Fuel", M. Bunn et. al., Harvard University & University of Tokyo (2001); IAEA, http://www.iaea.org/OurWork/ST/NE/NEFW/nfcms_spentfuel_conf2003_res.html

VII. Proliferation of Nuclear Weapons

This is a national, indeed a world issue, rather than a California issue. Yet it is a concern to many that expansion of nuclear energy use will increase the risk of weapons proliferation. The U.S. is a nuclear weapons state so expansion here does not increase proliferation risk. The issue arises with states that use nuclear energy as a road to procuring the material required for weapons. The states that have developed weapons clandestinely include India, Israel, North Korea, and Pakistan. It is worth noting that among these only Pakistan used the enrichment technology required for power reactors to produce the material for their bombs. There is concern about Iran's intentions.

There is an ongoing effort to internationalize the nuclear fuel cycle so that enrichment of uranium and the treatment of spent fuel can be better monitored and controlled. This is a political problem, not a technical one. It is still early in the discussion, but progress is being made. Abu Dhabi which has just contracted with South Korea for the construction of four large reactors has said it will not do its own enrichment or spent fuel treatment. This issue is getting lots of attention and progress is being made, though slowly.

VIII. Story Line

This section outlines what has to happen on the state and national scenes to make a large expansion of nuclear power practical.

- The Nuclear Regulatory Commission has to license more than one new reactor design. Closest is the Westinghouse AP-1000. Next are likely to be the GE ESBWR and the Toshiba ABWR. The AREVA EPR, though under construction in Europe, has to be licensed in the U.S. which will take at least 2 years. The small reactor builders have not yet submitted applications for design certification to the NRC, though the NRC has promised an expedited review when they do arrive.
- Loan guarantees for six to eight new starts nationally will have to be available. DOE now has about $18 Billion for such guarantees, which will only be enough for two to three large facilities. New funding for guarantees will have to be provided, and Secretary of Energy Chu has said that this is an administration priority. These first new builds have to be completed on time and at cost for a large scale nuclear build up to occur. If all goes well, this buildup could start in 2020.
- For small reactors, it is unlikely that design and licensing can be completed in less than 5 years. These too will require loan guarantees and possible federal subsides for the first-of-a-kind plants.
- The interim report of the Blue Ribbon Commission on waste disposal is due in early 2011. This report, and the final report due six months later, will begin a process of review that will determine the road ahead for spent fuel disposition. If it recommends going back to Yucca Mountain (considered a low probability) it will take about 10 more years before the repository could be opened. If it recommends something new, existing law that mandates Yucca Mountain as the repository site will have to be changed, and it will be 25 to 30 years before the cycle of legislation, site selection and characterization, design, licensing, and construction can be completed.
- Interim dry cask storage of spent fuel at reactor sites is the present default system. The courts have determined that the federal government has to pay the reactor owners for it because of present contracts. Since new reactors will have new contracts, the terms and conditions will be different. Recent new contracts require the federal government to take title to spent fuel within 25 years after a new reactor ceases operation.
- By 2020 California will have to repeal its limitation on new nuclear starts which is now based on the licensing of a permanent repository.
- By 2020 California's regulations that now mandate that the large amounts of emission free energy required in the future can only come from wind, solar, geothermal and small hydroelectric systems should be changed to allow all low or zero emission sources to contribute.
- The DOE needs to develop a long term strategic plan for nuclear R&D that supports present reactors, supports advanced fuel cycle R&D that might lead to breeder reactors for the future or fast spectrum burner reactors to ease the waste disposal problem, continue its international collaborations on GEN IV reactors, etc. Such a strategic plan has now been submitted to Congress.[15]

15 http://www.nuclear.gov/pdfFiles/NuclearEnergy_Roadmap_Final.pdf

- Future administrations need to continue what is a long range program and Congress needs to supply the necessary funding.
- Public acceptance needs to continue to grow. Such growth might come about because of relatively low energy costs, efficient land use, etc.

IX. Preliminary Comments on the Nuclear Accidents at Fukushima

On March 11, 2011 a giant earthquake and tsunami struck Japan, severely damaging the cities and towns along the coast near the epicenter of the quake and leading to a still uncertain, but large loss of life, mostly from the effects of the huge tsunami. Four of the six nuclear reactors at the Fukushima nuclear power complex were seriously damaged, along with several of the used-fuel pools, and there is worldwide concern about the effects from the radiation release that is still ongoing.

Damage to the reactors and used fuel storage pools at the complex is heavy though many of the key details are still unclear. While the giant earthquake knocked out all power coming to the nuclear station from the outside the site, all emergency systems started properly, shutting down the nuclear reactions and starting the emergency power and cooling systems. The emergency systems were overwhelmed by the tsunami, now estimated to have exceeded 45 feet in height, which struck the site 55 minutes later. The protective barriers, designed for a maximum tsunami height of 18 feet, were too low to keep water out, and the resultant flooding knocked out the emergency power, destroyed external electrical switch gear, and destroyed infrastructure for delivering fresh water to the site. Subsequently when battery power supplies were exhausted, the backup emergency cooling systems failed. It took two weeks to get electric power back on at the plant.

There was major fuel melting in three of the reactors before fire trucks were used to begin injecting sea water into the reactors to restore cooling, as well as in one of the water filled pools used to store spent fuel. The reactor containment systems retained a large fraction of the radioactive materials released from the damaged fuel, but sufficient radioactive material was released to cause off-site contamination of land. There was also a period of a few hours when workers had to leave the site. Emergency response actions included evacuation of people residing up to 20 kilometers from the plant. At this time the accident has resulted in no cases of radiation illness or fatalities to plant workers, and exposures to the public have remained low. Cleanup will take considerable time, and it is certain that most of the reactors will never operate again. While injuries, deaths, and damage from the radioactive releases will be small compared to the direct effects of the quake and tsunami, they must be taken seriously and are triggering a worldwide review of safety systems at nuclear plants.

In the United States, the Nuclear Regulatory Commission (NRC) has begun a review of nuclear reactor safety which will be comprehensive. Existing power plants utilize what is known in the industry as Generation II technology. In the light of problems at Fukushima the review will certainly include at a minimum the capability of these U.S. plants to function under a prolonged station black out, to rapidly connect external sources of water injection and backup power, to supply water to spent fuel pools from locations remote from the pools, and to control hydrogen accumulation effectively even under station black-out conditions. It will also include reviewing inspection frequency, as well as the ability of plants to come through multiple disasters.

The new generation of nuclear plants now being considered for licensing and construction here in the United States and elsewhere is called Generation III+. While all of the Gen III+ designs being advanced have extensive passive safety systems which require little operator intervention and little or no external power for operation in the event of an emergency, the same questions will be asked. These new designs will also be reviewed by the NRC and others in light of lessons learned from the Fukushima accident. The information gained during the Fukushima review and any recommendations made should be factored into decisions about the potential future use of these Gen III+ nuclear reactor technologies in California.

Appendix 1: Reactor Fuel

Introduction

The standard reference on uranium production and reserves is published every two years as a joint effort of the OECD Nuclear Energy Agency and the International Atomic Energy Agency. The latest volume, "Uranium 2007: Resources Production and Demand" (known as the Red Book), was published in 2008. The estimate of proven reserves is given as 5.5 million metric tonnes, with additional undiscovered reserves an additional 10.5 million tonnes; all at a cost of less than U.S. $130 per kilogram (kg). Reserves have increased from the estimate in the previous volume because of increased exploration induced by rising uranium prices.

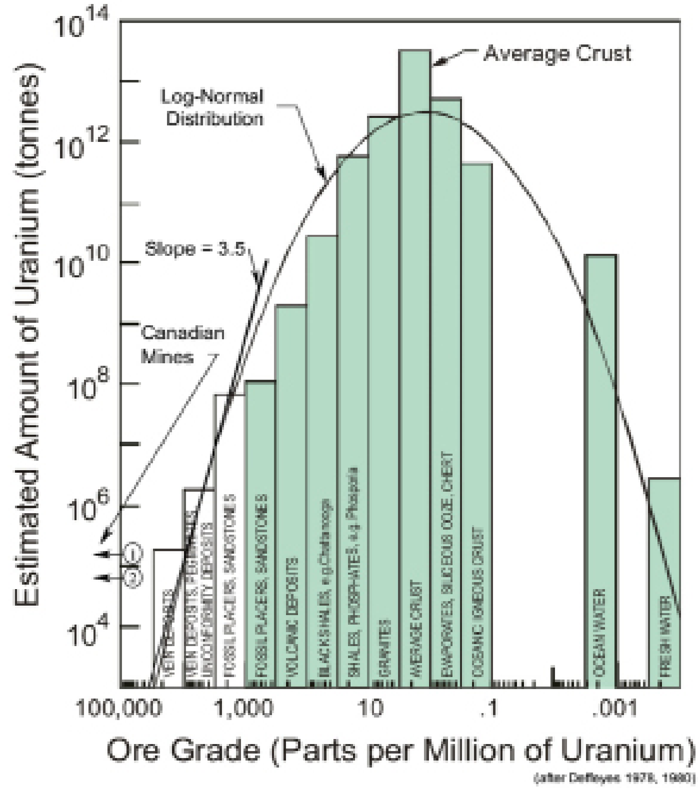
Only the isotope U-235 which makes up 0.7% of natural uranium is fissionable. Fuel for the standard LWR is enriched to 4.5% U-235, mainly in gas centrifuge plants which typically extract about 65% of the natural U-235. A 1-GWe power plant uses about 20 tonnes of enriched fuel per year derived from 200 tonnes of natural uranium. In the U.S., operating licenses for 60 years are becoming the standard, so each new 1 GWe of nuclear power will need 12,000 tonnes of natural uranium to fuel it over its entire 60 year lifetime. The 16 million tonnes given in the Red Book corresponds to lifetime fuel for about 1,300 GWe of new nuclear plants. The current world installed capacity is about 365 GWe

The "Nuclear California" scenario is done in the context of a world that also goes heavily nuclear. Since the 16 million tonnes picture in the Red Book would only be enough lifetime fuel for about 1,300 GWe of new reactors operating in 2050, a faster world-wide expansion would commit the 16 million tonne estimated supply long before 2050. There are three options for solving this problem.

- Find more natural uranium,
- Make reactors operate at higher electrical efficiency so that there is more output for the same amount of fuel,
- Deploy breeder reactors that can turn non-fissionable U-238 and thorium (Th-232) into fissionable fuel, thereby increasing the available amount of potential fissionable material more than 100 fold.

Uranium Availability

There is far more uranium in the earth's crust than the Red Book estimate of what can be recovered at a cost of less than $130 per kg. Figure 1 shows the estimated amount as a function of concentration. The amount of uranium is huge and the issue is extraction from lower concentration ores at a reasonable cost.



Distribution of Uranium in the Earth’s Crust (Deffeyes and Macgregor, Scientific American, 1980)

Fuel is a small part of the cost of nuclear electricity and raw uranium is a small part of the cost of fuel. The World Nuclear Associations gives the cost of reactor fuel as of January 2007 in the table below.

Uranium:	8.9 kg U_3O_8 x \$53	US\$ 472
Conversion:	7.5 kg U x \$12	US\$ 90
Enrichment:	7.3 SWU x \$135	US\$ 985
Fuel fabrication:	per kg	US\$ 240
Total per kg, approx:		**US\$ 1787**

U.S. dollar cost to get 1 kg of 4.5% enriched uranium as UO_2 reactor fuel at likely contract prices: At 45,000 MWd/t (megawatt days per tonne) burn-up this gives 360,000 kWh electrical per kg, hence fuel cost: 0.50 c/kWh.

The cost of uranium is only a small fraction of the cost of fuel and a 5-fold increase in uranium cost would only add another 0.5¢ per KW-h to the cost of nuclear electricity. If other ores are any example, much more uranium will be found when demand rises.

One particular low concentration source deserves special mention. In Japan work has been going on to develop techniques to extract uranium from sea water. In their technology, natural ocean currents move sea water through an absorber that extracts the uranium. Costs now are said to be about \$900 per kg with costs at commercial scale estimated to come down to about \$250 per kg. If this works at the necessary large scale, the supply of uranium becomes effectively unlimited.

Appendix 2: Spent Fuel Disposal

Introduction and Background

The issue of how ultimately to dispose of the high-level radioactive wastes generated by the use of nuclear power, and also generated during the manufacture of nuclear weapons, has been a contentious one for decades. The related issue of how to store this dangerous material in the interim before its ultimate disposal has also been contentious, especially because with no ultimate disposition path on the immediate horizon, interim means at least a decade or two from now, and perhaps longer.

There is very broad agreement that the material at issue should not be disposed of permanently near the surface, such as in shallow land burial, or even in engineered facilities at or near the surface. A large number of careful studies and reviews, both domestically and internationally, and going back a half century or more, have all concluded that for the very long term (meaning for millennia or even millions of years) the only management approach that can provide adequate safety is deep underground disposal. The material simply poses too great a hazard to human health and to the broader environment, to be disposed of on or near the surface, even in the best engineered facility that anyone can imagine deploying today or anytime soon.

The material at issue is mostly used nuclear reactor fuel from LWRs, containing radioactive fission products and actinides. By weight it is about 95% unburned uranium, about 4% fission products, and about 1% long lived actinides, mostly plutonium. There is about 60,000 tons of this used fuel already stored in the U.S., and about 2,000 tons arise annually from the 104 operating reactors. It is mainly still located at the sites where it was generated by the reactors. Its composition varies only slightly from reactor to reactor.

Most of the used reactor fuel comes from commercial power plants (all in the U.S. today are LWRs), but there is also used fuel from naval-propulsion reactors and various research, test, and isotope-production reactors. There is also the waste from the U.S. nuclear-weapons program, much of it still in waste tanks (although much of the tank waste has now been dried out) and other defense waste in various other forms such as glass that have been prepared for ultimate disposal. The only material in California is LWR-generated waste at the two operating reactor sites, San Onofre in San Diego County and Diablo Canyon in San Luis Obispo County, and at two sites where commercial reactors no longer operate, Rancho Seco in Sacramento County and Humboldt Bay in Humboldt County.

Safety and Security During Interim Storage

California nuclear wastes are all stored at the sites where they were generated in storage facilities licensed by the U.S. NRC. When used fuel is initially discharged from a power reactor, it generates so much (thermal) heat that, if not cooled well and continually, the heat would soon melt the fuel rod cladding, thereby releasing the enclosed radioactivity. Therefore, this fuel must be kept in a fuel pool (under water) for three to four years with active cooling to remove the heat from the water, after which the heat generation has decreased enough to allow the used fuel to be removed from pool storage, and to be placed in so-called dry-cask storage. However, this transfer to dry-cask need not take place until later, and some used fuel has remained in pool storage 3 decades.

This fuel storage is controversial with the public, many of whom have strong concerns about whether the storage, especially storage in the pools, is safe and secure. This is in part because a loss of pool cooling, or of pool integrity, would result in loss of the cooling water, and a significant radioactive release could ensue. Thus the integrity and reliability of pool cooling is justifiably a genuine concern. Also, the pools are more vulnerable to sabotage or a terrorist-type attack than if the waste is in dry casks, although the experts believe that such acts would be very difficult to execute.

There is much less safety or security concern with the dry-cask storage, because these are passive systems, they require no active working parts nor active personal intervention to maintain the used fuel intact, and the cask designs are highly resistant to attack.

Despite continuing public concern, the general conclusion of the engineering community is that, if NRC regulations are met, the integrity of the power-reactor pools against radiological releases is very strong. The NRC, for its part, has recently reexamined its regulations and concluded that they are adequate. A number of independent evaluations have confirmed this. This conclusion is even more robust for the dry-cask storage configuration where the consensus is that waste can be kept in these casks for the better part of a century. The total cost of storage for all U.S. power reactors is estimated to be about $500 million annually.

The Current Federal Disposal Scheme

The current scheme in the U.S., embodied in Federal law, policies, and regulations, is to dispose of this used fuel directly, as it is, in an engineered repository located in a volcanic tuff formation deep under Yucca Mountain in southern Nevada. (The current legal framework provides for using Yucca Mountain for disposing of only about half of the reactor fuel ultimately created by our current LWR commercial reactor fleet, after which either a second deep repository site would need to be developed, or the Federal law changed to allow the rest to be disposed of in Nevada too.)

The scheme described above, while embedded in current Federal law and regulation, is not endorsed by the new Obama Administration, which has announced that it wishes to abandon the Yucca Mountain repository and seek an alternative solution for the management of commercial reactor spent fuel. However, the administration has not yet settled on any new policy to replace what is now in law, and has appointed a presidential Blue Ribbon Commission to develop options and advice on this vital matter. This is a situation that is in flux as this is being written in mid-2010.

By current law the site for disposal of the high-level waste will also be used for left over material from the Federal nuclear-weapons program. This waste is composed of materials with generally shorter half lives than spent power reactor fuel. The total amount of the waste in Federal hands requiring disposal, from the nuclear-weapons program, the naval propulsion program, and other sources, is about 10% of the amount of used commercial reactor fuel destined for disposal.

The Federal waste disposal program is financed through a fee, levied on each commercial nuclear power plant, of $1.00 for each thousand kilowatt-hours generated. This "waste fund", which now totals over $20 billion, is judged adequate for the purpose of ultimate disposal at Yucca Mountain. The Federal government assumed responsibility for the disposal of the commercial used fuel in exchange for collecting this fee, and agreed in 1987 to take the used fuel off of the hands of the commercial utilities in 1998, when it was anticipated that the repository would be ready to begin accepting fuel. This 1998 deadline has of course been missed, leading to legal wrangling now in Federal courts about who should pay for the storage costs since then. The current Federal obligation from missing this deadline is judged to be perhaps $10 billion or more, and is increasing at about $500 million annually. Meanwhile, all of the waste is being stored "temporarily" at the reactor sites, and the waste from the Federal government's programs is sitting at Federal reservations too, awaiting resolution of the issues.

There has been controversy about the requirements for safe and secure disposal of spent reactor fuel from the start, but this has been settled by the adoption of an EPA standard and an NRC regulation that a repository design must meet. The basic radiation safety standard is an individual dose standard, under which the repository can obtain an NRC license only if no individual residing in the vicinity receives an annual dose exceeding 15 millirems per year for the first 10,000 years, or 100 millirems per year from then to 1,000,000 years in the future.

The burden of proof is on the repository developer, DOE, to demonstrate the adequacy of the repository design, which can only be done by analysis. The form of the analysis is prescribed by NRC regulations. DOE spent almost two decades and over $12 billion on site characterization, experiments, and analysis, and in mid-2008 it finally submitted a License Application to the NRC, containing its analysis. The DOE analysis, as submitted, seems to demonstrate that the NRC's regulatory criteria are met, and with substantial margin.

The NRC is currently reviewing the application, and in the most optimistic scenario, if sufficient funding is made available by the Congress, could issue its ruling by 2011, or more realistically 2012 or 2013. However, the Obama Administration has notified the NRC that it is withdrawing the application, but several states have said they will sue to prevent this, since U.S. law now designates Yucca Mountain as the repository site. In addition, the State of Nevada has hired a group of consultant experts to challenge the application, and based on their work Nevada has submitted hundreds of individual technical challenges that DOE is studying and that the NRC is now considering too. Today, there is no way to know how this NRC process will play out, but it is fair to say that there is a broad consensus among the community of technical experts in repository science that the DOE work has strong technical quality, is thorough, and will likely stand up well to NRC scrutiny if it ever gets that scrutiny.

Cost of Spent Fuel Management and Disposal

The costs involved in used reactor fuel management and ultimate disposal are not great in the overall scheme of things. While the overall cost of the Yucca Mountain. repository, as now designed, runs to around $100 billion, estimates by DOE and the industry of the total cost to any individual electric utility to dispose of its used nuclear fuel at Yucca Mountain come to between 1% and 2% of the value of the electricity generated. The costs for surface storage, even for decades, are much smaller than this.

If one puts these costs in perspective, one is driven to conclude that while considerable controversy continues about how to manage these radioactive wastes, the cost side of the argument should not be determinative, nor has it been very influential so far.

Chemical Processing of Spent Fuel

It is, of course, feasible to use chemical techniques to treat the spent fuel that is now destined by law for direct disposal at Yucca Mountain, and separate it into components that can be treated differently according to their potential use and potential hazard. This is called reprocessing. Indeed, much of the reactor fuel used to create the material for the U.S. nuclear weapons arsenal has already been reprocessed and put into special waste forms for disposal, and some of the rest will be. Overseas some countries (notably France and Russia) have been reprocessing commercial-reactor fuel for some time, and the Japanese have a plant under construction now to do so too. The purpose of reprocessing as part of nuclear weapons production was to extract the plutonium made in the reactor core for weapons use. The current reprocessing of commercial fuel also seeks to extract the plutonium for re-use as a fuel to be recycled into LWR reactors, which with only modest changes can use such plutonium-laden fuel instead of the more common uranium-laden LWR fuel, and thereby extract about 30% more energy from the original uranium.

If the LWR fuel of today that is destined for disposal at Yucca Mountain were to be reprocessed, the resulting waste material requiring geological disposal would have less radioactive material because of the extraction of the plutonium and other actinides. It would then contain much less of the most dangerous species with very long half-lives, and would also be put into a better physical and chemical form prior to deep disposal. Those who favor such LWR-fuel reprocessing offer several different rationales, which are given different weight by different advocates. Some see reprocessing mainly as a means for reducing the radioactivity and radiotoxicity of the material requiring deep disposal, hence lowering the "burden" on the deep repository. Some mainly wish to extract the plutonium for use as a reactor fuel in today's LWR reactors. Some advocate reprocessing to obtain a stockpile of plutonium and other actinides for use to start up a fleet of reactors of a different design, namely fast-spectrum reactors that can provide both electricity and the destruction of many of the actinides that would otherwise be disposed of deep underground.

Fast-Spectrum Reactors

These reactors operate with neutrons of much higher energy that the LWR power reactors in use today. In some designs, they can actually "breed" more fuel than they consume through neutron capture on the non-fissile uranium isotope U-238, whose latent nuclear energy is otherwise mostly not used to make energy in today's LWRs. Three or four decades ago, the general expectation among advocates of nuclear energy was that the fast-spectrum "breeder" reactors would soon displace LWRs as the major component of nuclear power generation worldwide. This did not happen – there have been a few large reactors of this kind built and run, but none is commercially viable. The reasons are both technical and non-technical. First, the use of such fast-spectrum reactors requires reprocessing to make the scheme attractive, but the costs of the fast-spectrum reactors plus the costs of the reprocessing technology as of now do not allow the scheme to compete economically with LWRs that use direct disposal. (In fact, the reprocessing now underway in France and Russia and planned in Japan, in which LWR fuel is reprocessed for re-use in other LWRs, is also more expensive than the once-through approach, although the cost penalties for this scheme are modest.)

Proliferation concerns are the major reason why some organizations oppose reprocessing. The extraction of plutonium, and its recycle into new reactor fuel, could create vast stores of separated plutonium that might be diverted by a government or stolen by terrorists for use in fabricating nuclear weapons. This concern led the U.S. to change its policy in 1977 to forbid nuclear-fuel reprocessing at home and to try to discourage other nations from moving in that direction (the formal prohibition was dropped in the Reagan Administration, but the policy was never officially repudiated). Opposition is strong among that sector of the public who oppose any use of nuclear power, but it is also present among some who favor expanded use of nuclear power but not expanded reprocessing.

The debate over fast-reactors and reprocessing has been going on for decades, and has been re-energized in recent years by the Bush Administration's proposed Global Nuclear Energy Partnership (GNEP). GNEP was to separate the components of spent reactor fuel that required isolation for hundreds of thousands of years and destroy them in fast spectrum reactors thus solving two problems. Repositories would only require isolation for a thousand years or so, much easier than a million years, and the stocks of weaponizable plutonium would be destroyed as well. The reactors could stretch the world's uranium resources by breeding new fuel, and the proliferation concerns were to be coped with by developing and deploying advanced safeguards technologies for both the reactors and the reprocessing plants. This Bush-era policy is now under reconsideration, and where the US policy will come out in the end cannot be known now.

Nuclear-Waste Policy Status

Nuclear-waste policy is currently is disarray. The President's Blue Ribbon Commission will report in 2011. It is not clear if using Yucca Mountain will be an allowable option in their deliberations. Even if it were to be included, it could not accept spent fuel until 2020 at the earliest. A new repository in a different area and in different geological conditions will require years of R&D and design before it could be opened. Spent fuel will be kept for decades at the sites where it was generated or perhaps at a few consolidated interim-storage sites. This would require Federal legislation. How this will come out is now unknowable.

For California, there are so many options and parameters that no simple conclusion is obvious. However, a few salient points are worth making:

a) The status quo, in which the used fuel at Diablo Canyon and San Onofre is being managed today in pools and ultimately in dry cast storage will continue for many years in any event. This is also true of the fuel at the "orphaned" nuclear-reactor sites in California, Rancho Seco and Humboldt Bay.
b) Even if the Yucca Mountain repository goes ahead on the fastest schedule it could, nothing will change in California vis-à-vis in-state used fuel storage for 10 or 15 years, and probably longer.
c) If a change in Federal policy leads to the search for a new repository instead of Yucca

Mountain, the status quo would be extended another 15-20 years, or more.

d) If Federal policy moves toward significant R&D that ultimately successfully demonstrates that reprocessing technology for LWR fuel to make other LWR fuel makes sense, this technology could be deployed at the earliest in about 20 years. [Here "makes sense" operationally means "is deployed in a commercial marketplace environment", even if not in California.]

e) If Federal policy moves toward significant R&D that ultimately successfully demonstrates that fast-reactor technology and the associated fuel-reprocessing and recycling technologies make sense, this could be deployed at the earliest in 25-30 years.

f) If Federal policy changes leading to the establishment of one or more sites for consolidating all U.S. used nuclear fuel, then California's used fuel could move there. But even if such a decision were taken today, it is unlikely that California's used fuel could move earlier than say a decade or so hence. Since the decision could not be taken today, one must add on whatever extra delay is associated with the timing of such a decision.

Appendix 3: Advanced Systems

Advanced Fission Reactors

In nuclear reactors, neutrons are absorbed in fissile material to cause fission reactions. Each neutron absorbed by a fissile isotope generates an average of 2.1 to 2.9 new neutrons, with the specific value for a given isotope and neutron energy being called *eta*. To sustain criticality, one of these neutrons must go on to be absorbed by another fissile isotope, leaving 1.1 to 1.9 excess neutrons. Some of these neutrons are absorbed by fertile isotopes like U-238 or Th-232 and produce new fissile isotopes. The remaining neutrons are absorbed in materials that do not produce fissile isotopes, or leak from the reactor core.

The number of new fissile atoms created, per fissile atom consumed, is referred to as the reactor *conversion ratio*. Conventional light water reactors (LWRs), which operate with thermal neutrons (neutrons that have been slowed down) and are fueled with low-enriched uranium (LEU), have conversion ratios around 0.6, and are net consumers of fissile material, requiring an external source of fissile material to operate, such as LEU or recycled plutonium or U-233.

Several routes exist to increase reactor conversion ratios, and thus use uranium resources more efficiently. These include measures to reduce neutron leakage (larger cores, use of fertile blankets) and parasitic neutron capture (through careful selection of coolant, structural, and moderating materials, as well as by adjusting the average energy level of neutrons). They also include measures to increase eta.

For U-235, the principal fissionable part of the fuel in thermal-neutron-spectrum LWRs, the number of neutrons released per fission (eta) has a low value of 2.1. Eta takes substantially higher values for high-energy, fast neutrons, typically around 2.9 for Pu-239. Thus, uranium-fueled, fast-spectrum reactors can be readily designed to reach conversion ratios of 1.0 or greater. Above 1.0 more fissionable material is produced in the reactor than is consumed in its operation, hence the name breeder.

Alternatively, when thorium-232 is used in thermal-spectrum reactors, the U-233 produced from Th-232 has an eta of 2.4. This is lower than the fast-spectrum eta for Pu-239, but a variety of approaches exist to use thorium in thermal spectrum reactors that can increase the conversion ratio compared to conventional LEU-fueled LWRs, with some designs achieving a conversion ratio of 1.0 or slightly greater.

In considering how reactor technology might evolve to use uranium more efficiently in the future, an analogy with automobiles and oil is useful. Electric cars consume no oil at all and have significantly lower fuel cost than conventional automobiles, but have been commercially unsuccessful to date because oil prices have remained too low to merit the higher manufacturing cost and inconvenient operational features of electric cars. Likewise, even though fast-spectrum reactors could operate for centuries on depleted uranium already mined, to date they have remained commercially unsuccessful due to high construction costs and reliability problems.

As coal-to-liquids does for oil, the maximum future price for uranium is back-stopped by technology to recover uranium from seawater. But just as coal-to-liquids has never emerged as an economically competitive source of transport fuel, few experts expect that uranium recovery from seawater will ever emerge as a replacement for conventional uranium mining. Most experts instead expect a more gradual and incremental set of evolutionary changes to occur as uranium prices eventually climb.

As with automobile engines, the efficiency of nuclear power plants in converting fuel into power can be expected to improve; with the transition from LWR to high-temperature reactor (HTR) technologies bringing similar benefits for efficiency as has the ongoing transition from gasoline to diesel engines. In analogy to plug-in-hybrid vehicles, which reduce but do not eliminate the consumption of oil, the addition of thorium to LWR and HTR fuels has the potential to boost the reactor conversion ratios and reduce uranium consumption. The use of LEU "seed" and thorium "blanket" fuel pins in LWRs can reduce uranium consumption modestly, while larger reductions are potentially possible in HTRs.

Because discharged reactor fuel will contain fissile material, recycling of spent fuel can further reduce uranium consumption, and can also have beneficial effects in reducing quantities of waste requiring geologic disposal. The fabrication of LWR fuel from recycled plutonium is very expensive, and requires very high uranium prices (potentially exceeding the cost of sea-water uranium recovery) to be economically justified. Conversely, both HTRs and fast-spectrum reactors can use fuel forms that are much more readily fabricated from recycled material. Because HTRs and fast-spectrum reactors can operate with higher conversion ratios than LWRs, the benefits from recycle in reducing uranium consumption are also larger.

Given the number of technology options available to extend uranium resources and the existence of an international market for fuel cycle services and technologies that includes many supplier nations, the question is not so much whether uranium scarcity might constrain a large expansion of nuclear energy by 2050, but instead whether the new technologies that will emerge will be optimized to minimize proliferation and physical security risks.

The United States is actively engaged in efforts to influence this evolutionary process, to encourage continued centralization of sensitive elements of the fuel cycle (enrichment and conventional reprocessing), to strengthen and improve technologies for International Atomic Energy Agency monitoring of civil nuclear energy systems to verify peaceful use and promote non-proliferation, and to develop advanced fuel cycle technologies that handle recycled materials in locations and forms that make them highly unattractive targets for theft.

With the breadth of options available to extend uranium resources, it can be expected that fuel costs will remain a small fraction of total nuclear generation cost, even under substantial world-wide expansion of total nuclear generation capacity by 2050.

Fusion Systems

In principle, bringing together isotopes of the lightest element, hydrogen, to make the heavier element, helium, can release large amounts of energy. There are two attractions that have been driving the program. No uranium or plutonium that can be used in nuclear weapons is involved, and the radioactivity produced in the systems is much less in intensity and of much shorter lifetime than from fission, easing the repository problem. Research has been ongoing for 60 years and the proponents believe that they are close to demonstrating feasibility.

The largest program involves what is called magnetic confinement fusion where strong magnetic fields hold the gases together. An international program has begun to build the International Tokomak Experimental Reactor (ITER) at a site in France to demonstrate fusion energy release on a large scale. Many nations, including the U.S., are partners in the venture. If all goes well initial tests of the device will begin late in this decade, and serious attempts to demonstrate that the system can produce energy will begin in the mid-2020s. If that works, a prototype power plant could be operating about 15 years later and the first commercial power plant might start up around mid-century.

There are smaller magnetic confinement programs going on in a few places that involve systems different from that used in ITER. They are in too early a stage to allow an assessment of promise, but the next decade should get them to the point of a reality check. Some of these systems claim they can get to small power plants faster than ITER can get to large ones.

There is a second program called inertial confinement fusion than is still confined to the laboratory, though several countries are working on systems. In the U.S., the main line is laser-driven compression of a tiny pellet of hydrogen isotopes. If it is compressed far enough and heated high enough, a tiny explosion occurs, releasing energy. A demonstration of the principle is expected in the next few years, but demonstrating commercial viability is still a very long way away.

Appendix 4: Acronyms

OECD	Organization of Economic Cooperation and Development
AB	Assembly Bill
CCST	California Council on Science and Technology
DOE	Department of Energy
EIA	Energy Information Administration
GEN II	Generation II
GEN III+	Generation III
GEN IV	Generation IV
GNEP	Global Nuclear Energy Partnership
GW	Gigawatts
GWe	Gigawatt of electrical capacity
HTR	High-temperature reactor
IEA	International Energy Agency
ITER	International Tokomak Experimental Reactor
KW-hr	Kilowatt hour
LEU	Low-enriched uranium
LWR	Light-water reactors
MIT	Massachusetts Institute of Technology
MWd/t	Megawatt days per tonne
MWe	Megawatt electrical
NAS	National Academy of Sciences
NRC	Nuclear Regulatory Commission
OECD	Organization for Economic Co-operation and Development
R&D	Research and Development
TWh/y	Terawatt-hours per year

Appendix 5: Author Biographies

Burton Richter is the Paul Pigott Professor in the Physical Sciences, Stanford University and Director Emeritus at the Stanford Linear Accelerator Center. His research has centered on experimental particle physics with high-energy electrons and electron-positron colliding beams. He began as a post doc at Stanford University in 1956, became a professor in 1967, and was Director of the Stanford Linear Accelerator Center from 1984 through 1999. Richter received the Nobel Prize in Physics (1976) and the E. O. Lawrence Medal of the Department of Energy (1976).

Robert J. Budnitz is on the Scientific Staff at the University of California's Lawrence Berkeley National Laboratory, where he works on nuclear power safety and security and radioactive-waste management. He has been involved with nuclear-reactor safety and radioactive-waste safety for many years. From 2002 to 2007 he was at UC's Lawrence Livermore National Laboratory, during which period he worked on a two-year special assignment (late 2002 to late 2004) in Washington to assist the Director of DOE's Office of Civilian Radioactive Waste Management to develop a new Science & Technology Program. Prior to joining LLNL in 2002, he ran a one-person consulting practice in Berkeley CA for over two decades.

Jane C.S. Long is currently the Principal Associate Director at Large for Lawrence Livermore National Laboratory and Fellow in the LLNL Center for Global Strategic Research. She works reinvention of the energy system, adaptation and in response to climate change and geoengineering. She is co-chair of both the California's Energy Future Committee and the National Commission on Energy Policy's Task Force on Geoengineering, and a member of the governor's advisory panel on adaptation. She is the former Dean of the Mackay School of Mines at University of Nevada, Reno, Director of the Great Basin Center for Geothermal Energy and Chairman of the Nevada State Taskforce on Energy Efficiency and Renewable Energy. Dr. Long also worked at Lawrence Berkeley National Laboratory where she served as Department Chair for the Energy Resources Technology Department including geothermal and fossil fuel research, and the Environmental Research Department.

Per F. Peterson is Professor and Chair of the Department of Nuclear Engineering at the University of California, Berkeley. He received his BS in Mechanical Engineering at the University of Nevada, Reno, in 1982. After working at Bechtel on high-level radioactive waste processing from 1982 to 1985, he received a MS degree in Mechanical Engineering at the University of California, Berkeley in 1986 and a Ph.D. in 1988. He was a National Science Foundation Presidential Young Investigator from 1990 to 1995. He is past chairman of the Thermal Hydraulics Division (1996-1997) and a Fellow (2002) of the American Nuclear Society. Peterson's work focuses on applications in energy and environmental systems, including passive reactor safety systems, inertial fusion energy, and nuclear materials management. In February 2010, Peterson was appointed by the Obama Administration to the Blue Ribbon Commission on America's Nuclear Future, to provide advice on U.S. policy for the back end of the nuclear fuel cycle.

Jan Schori is the former General Manager and Chief Executive Officer of SMUD, the Sacramento Municipal Utility District--the nation's sixth largest publicly owned electric utility. During her 14 year tenure as CEO, the utility earned a strong reputation for its renewable energy and energy efficiency programs as well as national number one ranking in commercial customer satisfaction by JD Power

& Associates in both 2006-7 and 2007-8. Prior to serving as general manager and CEO, she spent 15 years on the legal staff at SMUD, including five as general counsel. Jan is past chair of the American Public Power Association, the Large Public Power Council, and the California Municipal Utilities Association. She is also past chair of the Business Council for Sustainable Energy and served on the Board of the Alliance to Save Energy. She is of counsel to the law firm Downey, Brand LLP in Sacramento, CA and serves as an independent trustee on the board of the North American Electricity Reliability Corporation (NERC).

Appendix 6: California's Energy Future Full Committee

Jane C.S. Long (Co-chair), CCST Senior Fellow, and Associate Director at Large, and Fellow, Center for Global Security Research Lawrence Livermore National Laboratory

Miriam John (Co-chair), CCST Council Chair and Board Member, and Former Vice President, Sandia National Laboratories

Working Committee

Robert Budnitz, Staff Scientist, Earth Sciences Division, Lawrence Berkeley National Laboratory

Linda Cohen, CCST Senior Fellow and Associate Dean for Research & Graduate Studies and Professor of Economics, University of California, Irvine

Bill Durgin, Professor, Aerospace Engineering, California Polytechnic University San Luis Obispo

Bob Epstein, Founder, E2 Environmental Entrepreneurs

Chris Field, Director, Department of Global Ecology, Carnegie Institution

Jeffery Greenblatt, Project Scientist, Appliance Energy Efficiency Standards, Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory

Bryan Hannegan, CCST Council Member and Vice President, Environment and Renewables for the Electric Power Research Institute

Susan Hackwood, Executive Director, California Council on Science and Technology

Roland Hwang, Transportation Program Director, Natural Resources Defense Council

Nalu Kaahaaina, Deputy Project Director, Energy and Environmental Security, Global Security Principal Directorate, Lawrence Livermore National Lab

Daniel Kammen, Class of 1935 Distinguished Professor of Energy, Energy and Resources Group and Goldman School of Public Policy, University of California, Berkeley (on leave) and Chief Technical Specialist for Renewable Energy and Energy Efficiency, The World Bank

Nathan Lewis, Director, Joint Center for Artificial Photosynthesis, California Institute of Technology

Bill McLean, CCST Senior Fellow and Emeritus Director, Combustion Research Facility, Sandia National Laboratories

James McMahon, Department Head, Energy Analysis, Lawrence Berkeley National Laboratory

Joan Ogden, Professor, Department of Environmental Science and Policy and Director, Sustainable

Transportation Energy Pathways Program, Institute of Transportation Studies, University of California, Davis

Lynn Orr, Director, Global Climate and Energy Project, Stanford University

Larry Papay, CCST Board Member and CEO and Principal of PQR, LLC

Per Peterson, Professor and Chair, Department of Nuclear Engineer, University of California, Berkeley

Burton Richter, CCST Senior Fellow and Paul Pigott Professor in the Physical Sciences Emeritus, Director Emeritus, Stanford Linear Accelerator Center, Stanford University

Maxine Savitz, CCST Senior Fellow and Vice President, National Academy of Engineering; Appointed Member of the President's Council of Advisors on Science and Technology (PCAST), Retired General Manager, Technology Partnerships, Honeywell, Inc.

Jan Schori, Former Director, Sacramento Municipal Utility District

George Schultz, Distinguished Fellow, Hoover Institution, Stanford University

Chris R. Somerville, Director, Energy Biosciences Institute, University of California, Berkeley

Daniel Sperling, Director, Institute of Transportation Studies, University of California, Davis

Jim Sweeney, CCST Senior Fellow and Director of the Precourt Institute for Energy Efficiency, and Professor of Management Science and Engineering, Stanford University

Margaret Taylor, Assistant Professor, Richard and Rhoda Goldman School of Public Policy, University of California, Berkeley

Max Wei, Researcher, Lawrence Berkeley National Laboratory and University of California, Berkeley

Carl Weinberg, CCST Senior Fellow and Principal, Weinberg and Associates

John Weyant, Professor of Management Science and Engineering and Senior Fellow at the Precourt Institute for Energy, Stanford University

Mason Willrich, Board Chair, California Independent System Operator Corporation

Patrick Windham, Consultant

Chris Yang, Research Engineer and Co-leader of Infrastructure System Analysis Research Group, University of California, Davis

Heather Youngs, Bioenergy Analysis Team, Energy Biosciences Institute, University of California, Berkeley

Appendix 7: California Council on Science and Technology Board and Council members

2011 Board Members

Karl S. Pister, **Board Chair**; Chancellor Emeritus, University of California, Santa Cruz; and Dean and Roy W. Carlson Professor of Engineering Emeritus, University of California, Berkeley

Bruce M. Alberts, Editor in Chief, Science Magazine and Professor, Department of Biochemistry & Biophysics, UC San Francisco

Ann Arvin, Vice Provost and Dean of Research, Lucile Salter Packard Professor of Pediatrics and Professor of Microbiology and Immunology, Stanford University

Warren J. Baker, President Emeritus, California Polytechnic State University, San Luis Obispo

Peter Cowhey, Council Vice-Chair and Dean, School of International Relations and Pacific Studies, University of California, San Diego

Bruce B. Darling, Executive Vice President, University of California

Susan Hackwood, Executive Director, California Council on Science and Technology

Randolph Hall, Vice Provost for Research Advancement, University of Southern California

Charles E. Harper, Executive Chairman, Sierra Monolithics, Inc.

Paul Jennings, Professor, Civil Engineering and Applied Mechanics, Emeritus and Former Vice Provost, California Institute of Technology

Miriam E. John, Council Chair and Emeritus Vice President, Sandia National Laboratories, California

Bruce Margon, Vice Chancellor of Research, University of California, Santa Cruz

Tina Nova, President, CEO, and Director, Genoptix, Inc.

Lawrence T. Papay, CEO and Principal, PQR, LLC

Patrick Perry, Vice Chancellor of Technology, Research and Information Systems, California Community Colleges

2011 Council Members

Miriam E. John, Council Chair and Emeritus Vice President, Sandia National Laboratories, California

Peter Cowhey, **Council Vice Chair** and Dean, School of International Relations and Pacific Studies, University of California, San Diego

Wanda Austin, President and CEO, The Aerospace Corporation

Sally Benson, Director, Global Climate and Energy Project, Stanford University

Julian Betts, Professor of Economics, University of California, San Diego

George Blumenthal, Chancellor, University of California, Santa Cruz

Susan Bryant, Former Vice Chancellor for Research, University of California, Irvine

Charles Elachi, Director, Jet Propulsion Laboratory

David Gollaher, President and CEO, California Healthcare Institute

Corey Goodman, Former President, Biotherapeutics and Bioinnovation Center, Pfizer

Susan Hackwood, Executive Director, California Council on Science and Technology

Bryan Hannegan, Vice President of Environment and Renewables, Electric Power Research Institute

Sung-Mo "Steve" Kang, Chancellor, University of California, Merced

Charles Kennedy, Vice President for Health Information Technology, WellPoint, Inc.

Jude Laspa, Former Deputy Chief Operating Officer, Bechtel Group, Inc.

Richard Levy, Chairman of the Board, Varian Medical Systems

William Madia, Former Senior Executive Vice President of Laboratory Operations, Battelle

David W. Martin, Jr., M.D., Chairman & CEO, AvidBiotics Corporation

Fariborz Maseeh, Founder and Managing Principal, Picoco LLC

George H. Miller, Director, Lawrence Livermore National Laboratory

Michael Nacht, Professor, Goldman School of Public Policy, University of California, Berkeley

Stephen D. Rockwood, Former Executive Vice President, Science Applications International Corporation

Jeffrey Rudolph, President and CEO, California Science Center

Shankar Sastry, Dean, College of Engineering, University of California, Berkeley

Soroosh Sorooshian, Distinguished Professor and Director, Center for Hydrometeorology & Remote Sensing (CHRS), University of California, Irvine

James L. Sweeney, Director, Precourt Institute for Energy Efficiency, and Professor of Management Science and Engineering, Stanford University

S. Pete Worden, Director, NASA Ames Research Center

Julie Meier Wright, President and CEO, San Diego Economic Development Corporation

Kathy Yelick, Director, National Energy Research Scientific Computing Center (NERSC), Lawrence Berkeley National Laboratory

Rollin Richmond, President, Humboldt State University

Sam Traina, Vice Chancellor of Research, University of California, Merced

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