# New Nukes For New Niches?

## by R.J. Peterson

Manufacturers of nuclear power plants, professional societies, national governments, and power companies are all proclaiming a renaissance of interest, orders, and installations for nuclear fission electricity. This enthusiasm can be attributed to the search for non-carbon power sources and the growth in demand for the electrical energy they produce. These two issues are being addressed in part by large new nuclear reactors in developed nations, but are equally important for developing nations who need more electrical energy but do not yet have nuclear power reactors. These needs of developing nations can be met with nuclear power stations, but perhaps not in the same way that developed nations are meeting their needs. Technical designs for smaller fission systems are widely proposed, with many advantages from manufacturing all the way to markets, especially smaller markets. This work addresses the questions of whether developing nations, in their quests for clean electricity, will have the licensing and regulatory systems, insurance, and trained manpower to deal with the opportunities offered by nuclear fission, from either the large systems now being manufactured or from newer designs better suited to their markets, but with a different set of start-up issues.

Electricity is the form of energy with the most direct application to human progress and well-being. Electrical energy is easy to distribute, it demonstrates great usefulness even in small amounts, and can be utilized by a wide range of appliances (i.e., lights, laptops, pumps, and other convenient devices). As a result of its convenience and simplicity, global demand for electrical energy is expected to increase in total by 77 percent from 2006 to 2030, outpacing the growth in total energy demand.[1] Many nations already face shortages of electrical energy and frequently experience blackouts and brownouts. Additionally, the demand for greater access to power leads to heavy subsidies, prominently in China and India.[2] These rapidly industrializing nations anticipate particularly strong growth in the demand for electrical power, with long-term growth of 4.4 percent per year.[3]

**THESE NEEDS OF DEVELOPING NATIONS CAN BE MET WITH NUCLEAR POWER STATIONS, BUT PERHAPS NOT IN THE SAME WAY THAT DEVELOPED NATIONS ARE MEETING THEIR NEEDS.**

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This strong increase in demand for electricity could be met by the current leading source of energy, coal, but the advantages of nuclear power will be attractive for many potential customers. While coal is a major source of electrical power for many nations, it is also a major source of pollution and is one of the key culprits behind current atmospheric problems. As the search continues for renewable, less destructive sources of energy, the comparison between coal and nuclear plants will continue to be a source of debate for policymakers worldwide. Both have drawbacks and advantages, and the less familiar nuclear option must be proven to be the more viable alternative to replace coal and its many problems.

**GLOBAL COAL CONSUMPTION IS RESPONSIBLE FOR 20 PERCENT OF THE $CO_2$ EMISSIONS IN THE ATMOSPHERE EACH YEAR, AND THERE IS MUCH CONCERN ABOUT THE EFFECTS OF THAT GAS.**

Coal is a base line fuel for electricity, with steady outputs not dependent upon winds or sunshine. Coal power plants are often centrally located near their markets, and are thoroughly integrated into power distribution systems. Overall, coal now provides 41 percent of global electrical energy,[4] with large fractions in China (80 percent) and India (75 percent).[5] Coal consumption continues to grow rapidly each year, with the strongest growth of any energy source in 2008 for the sixth year in a row.[6] However, coal consumption has considerable drawbacks. Coal is intrinsically dirty, and its combustion can only be partially cleaned up. Mining is dangerous, and there are no realistic prospects for dealing with the climate-changing emissions of carbon dioxide.[7] Furthermore, because it is a nonrenewable resource, coal resources are declining. By dividing known reserves by annual consumption there is only a 48-year horizon in China.[8] Global coal consumption is responsible for 20 percent of the $CO_2$ emissions in the atmosphere each year, and there is much concern about the effects of that gas.[9]

## EMBRACING THE NUCLEAR RENAISSANCE

In an effort to curb the widespread negative effects of coal usage, states worldwide are scrambling to develop alternative resources. Renewable sources such as wind and sunshine are often dilute and distant from their markets, and will continue to have only a minor impact on power needs. As discussed above, coal power plants are often centrally located near their markets, and are thoroughly integrated into power distribution systems, making them more attractive than alternative sources of power. Similar siting opportunities would be appropriate for nuclear plants, with power outputs similar to many coal-burning facilities.

Currently, about 50 large nuclear power plants are under construction or have been contracted and about 130 more being planned around the world,[10] and several nations are building new nuclear fission power plants about as fast as they can. China has 17 plants under construction and up to 50 more planned,[11] but even this large effort will still meet only 5 percent of the expected electrical demand in 2030.[12] All of these nuclear reactors under construction or under contract are in nations that already have one or more operating nuclear power plants. These nations alone have the regulatory framework, licensing, insurance, workforce, and local support systems able to deal with new construction. In many, if not most cases, the new reactors are on the same grounds as existing facilities, with shared access to existing power grids.

The progressions of these designs within the nuclear renaissance have reached Generation III+ advanced light water reactors (LWR), which are very similar to the 439 power reactors now operating around the world, mostly classified as Generation II, with a few at the Generation III level.[13] The differences for the new Generation III+ systems include better reliability, stability (safety), and efficiency.

There are two major classes of operating and proposed nuclear reactors. The first are boiling water reactors (BWR), which use the heat from fission to boil water into steam. This steam runs electrical turbogenerators, just as would steam from a coal heat source. The second are pressurized water reactors (PWR), which use a two-step process, with heat carried off from the fission core by one water loop being used to heat water to steam in a second loop. The first loop operates at such a high pressure that it is liquid water, not steam, in circulation. Orders and plans for both types have been announced, indicating that both technologies are known to be reliable and economic options. Descriptions of the options offered have been summarized in *The Economist*.[14]

**THE AVERAGE OPERATING NUCLEAR POWER STATION PRODUCES ABOUT ONE GWE (GIGA OR BILLION WATTS ELECTRIC) OF SALABLE POWER; THAT IS ENOUGH ENERGY TO PROVIDE FOR THE NEEDS OF ABOUT 650,000 AMERICANS, 1.1 MILLION FRENCH CITIZENS, OR 5.5 MILLION CHINESE.**

The average operating nuclear power station produces about one GWe (Giga or billion Watts electric) of salable power; that is enough energy to provide for the needs of about 650,000 Americans, 1.1 million French citizens, or 5.5 million Chinese.[15] New orders of Generation III+ systems range from 1 to 1.4 GWe, and each is larger than almost all plants currently in operation. This very size presents problems; for instance, the largest components can be made in only a few facilities. Large Generation III+ plants require about twice the weight of heavy forgings than is found in operating plants today. For the largest pressure vessels, heat exchangers, and steam generators weighing up to 600 tons, there is only one facility in the world, operated by Japan Steel Works in Muroran, Hokkaido.[16] This one facility provides 80 percent of the large forgings for nuclear power plants, with a throughput of only about four pressure vessels per year.[17] Other large facilities are in China (China First Heavy Industries and China Erzhong) and Russia (OMZ Izhora). New capacity is also being added by Japan Steel Works, as well as in China and the Republic of Korea, with further plans for India and the UK.[18]

No such expansions of heavy forgings are planned for the US, which will force US firms to rely on foreign partners for large reactor systems.

Several global manufacturers are competing for these new reactor orders, and many of the new orders are in the hands of firms with a strong history of exports. Areva, a state-owned French firm, has been the world's largest producer of nuclear power plants.[19] Their new model is the EPR, a Generation III+ pressurized water reactor, and there are currently three under construction, in China, Finland and France. These large systems can provide up to 1.65 GWe.[20] Atomstroyexport is the nuclear export arm of Rosatom (a Russian state corporation) and is another integrated supplier of nuclear reactor systems. Fourteen of their standard export model VVER pressurized water reactors, each producing 1 to 1.2 GWe, have been ordered.[21] The March 2010 visit of Russian leadership to India announced plans for up to sixteen new reactor orders.[22] Westinghouse, now controlled by Toshiba, is currently building four AP1000 reactors in China.[23] The fourth major supplier, GE Hitachi Nuclear Energy, is building three ABWR advanced boiling water reactors in Japan and Taiwan.[24]

Canada's Atomic Energy Canada Ltd. (AECL) has marketed the CANDU power reactor, with 29 now operating in seven nations.[25] This heavy-water technology requires no very large forgings and is thus free of a major manufacturing hurdle, and does not rely upon enriched uranium. The design, however, is seen as a proliferation threat because of its efficiency for breeding plutonium.[26] No CANDU plants are currently under construction or on order, although India continues to build knockoffs.

Partnerships and joint ventures among the aforementioned manufacturing giants, including buy-ins for uranium mining resources, are in a state of chaos as adjustments are made to meet what is expected to be a huge demand for large reactors.[27] State backing of some firms is an important ingredient in the bidding processes, and the eventual structure of the business in large reactors is very much unknown.

These large reactor plants require significant investments in several stages. The financing of a new nuclear power plant is the first barrier, with a much different profile from that of a fossil-fuel plant. Nuclear plants carry large construction costs, including a large cost in paperwork (estimated to be up to half the total in the US[28]), with an initial cost more than twice the capital cost of a coal plant.[29] However, once a nuclear plant is in operation, the fuel costs are much less than the fuel costs for a coal plant. A coal plant may count on a cash flow, selling electricity while purchasing coal fuel. In contrast, the costs of maintaining a nuclear plant largely entail keeping up mortgage payments, relying on demonstrated safe operation and public acceptance for their forty year operating lifetime to meet the initial financial obligation.

While coal faces a short horizon in some areas such as China, the uranium fuel for a nuclear reactor is more abundant. A global system for uranium fuel has emerged with mining, purification, enrichment and fuel rod construction.[30]

Estimates of global uranium at current prices (a small part of the operating cost of a reactor) are near 70 years.[31] If the price goes up to twice the current value, it would even pay to extract uranium from sea water.[32] As briefly described below, there are nuclear science methods that could extend our fission fuel reserves by large factors. No such technical extensions can be possible for coal.

Both coal and uranium generate waste. Although the $CO_2$ emissions from burning coal dominate the climate change debate, this gas is not the only concern for environmentalists. The inorganic solid waste (fly ash) from coal can reach enormous volumes. The largest waste cleanup in recent US history is that of the coal waste that flooded in Tennessee, with a cleanup cost estimated at $825M.[33] On the other hand, a recent study found that nuclear reactor waste (spent nuclear fuel) can continue to be stored on the sites of the power stations for decades, awaiting eventual burial.[34] Eventual permanent burial of used nuclear fuel is likely, but has not yet been carried out by any nation, and seems not to be a short-term issue, even when considering the strong expansion of nuclear power.

**THERE ARE NUCLEAR SCIENCE METHODS THAT COULD EXTEND OUR FISSION FUEL RESERVES BY LARGE FACTORS. NO SUCH TECHNICAL EXTENSIONS CAN BE POSSIBLE FOR COAL.**

## BRINGING THE RENAISSANCE TO NEW NATIONS

The best example of a nation new to nuclear power and now planning construction can be found in the United Arab Emirates (UAE), where an order has just been placed for four plants, totaling 5.5 GWe. The Emirates are experiencing a 9 percent annual increase in demand for electricity, with 98 percent of its electricity now produced from local gas.[35] To meet growing demands for both domestic electricity and for expanded gas exports, nuclear power has been the choice. A new agency, the Federal Authority of Nuclear Regulation, has been established in the UAE as the regulatory agency for this nuclear future,[36] and the Emirates are signatories to all relevant international nuclear agreements.[37] The winner of the power plant contract is a consortium of Korean firms, who will install four APR-1400 reactors, with the first to commence operation in 2017 at Braka, on the west coast of Abu Dhabi.[38] If this fast-track approach of using assets from energy sales today to invest in future energy succeeds, one can readily envisage other wealthy nations without nuclear facilities following this path and joining the nuclear renaissance with large systems.

Yet, what still must be considered is the rapidly rising demand for clean electrical energy, even in modest amounts, in nations that do not have operating nuclear power plants and may lack strong domestic fossil fuel resources. Their per capita electrical demands are often much lower than those in the developed world, and the impact of more electricity would be significant. However, these nations lack the financial resources to invest in a large 1 GWe nuclear plant; the infrastructure to license, monitor, and control the technology; an electrical grid to handle a lot of power; and the professional workforce to manage nuclear power responsibly. For example, Jordan is an energy-starved nation without nuclear experience. Recently, the European Union began a project to help the Jordan Nuclear Regulatory Commission draw up a suitable regulatory framework as a necessary first step to begin plans for fission power.[39]

However, the large plants currently supporting the nuclear renaissance are not suitable for small nations such as Jordan. Does this mean that these small nations are doomed to continue burning imported fossil fuels? By the end of this decade, 80 percent of the world's middle-income consumers will be living in nations not currently considered developed.[40] Many of those nations will not have the complex infrastructure to build or operate a large power plant, and their electrical systems will not be adequate to distribute the vast amounts of electricity from currently ordered plants. This indicates a demand for small (below 1/3 GWe) or medium (1/3 to 2/3 GWe) plants, which are better suited to meet these intermediate-level needs. In recognition of this,the American Nuclear Society, the US professional association of reactor operators and engineers, has become active in promoting such 'right sized' reactors, as in a presentation by the current president.[41] The June 2010 meeting of the American Nuclear Society is to be dedicated to deliberation of small to medium reactors.[42]

All of these small to medium reactors (SMR) would operate on the same principle as larger systems, with enriched uranium fuel creating heat from fission, and their cooling systems creating steam for turbogenerators. Use of uranium enriched to as much as 20 percent (which is below the grade needed for a weapon) allows for a more compact system. The decades of experience with large systems have contributed to the development of the science and engineering to design, build, and operate smaller systems, particularly in the use of computer simulations for designs and to compute the responses to problems.

There are a number of strong reasons to develop and deploy smaller 'right sized' nuclear power systems. One advantage of these small systems is that they could be built in factories and shipped to their markets, rather than be built on site; this is akin to the advantages of manufactured homes. These smaller systems also require smaller individual parts, greatly enlarging the pool of subcontract suppliers. Additionally, they could have a lower cost per electrical watt, because of the possibilities of mass production and standardization, lowering the main barrier and objection to large power plants. Babcock and Wilcox, a major US firm, claims to have all the facilities and plant space needed to make a line of new small reactors.[43]

An array of smaller reactors could also provide flexibility to a power station, with up to ten identical units creating steam. If an emergency, or a need to refuel, shuts one reactor off, the market demand will still be met. Training of engineers and operators could become standardized, as could procedures and regulations.

Most of the world's experience with small nuclear reactor systems has been gained from naval systems –submarines, surface combatants, and icebreakers. Russia has recently launched a barge-mounted fission power source, with two KLT-40S 35 MWe (megawatts of electricity) reactors.[44] This is meant to be the first of a fleet of power sources suited to needs in remote Arctic or Pacific markets. This first system is destined for the Russian Far East in 2012, and several more are planned.[45] If this method is successful, Rosatom could find quite a large market, since these systems are portable, standardized, controllable (with Russian ownership retained) and returnable.

Similarly, an example of a specific plan to install and operate a small reactor for a remote area is found in the plans of reactor supplier Toshiba and the village of Galena, Alaska. Toshiba has offered Galena (for free, valued at $20M) its 4-S (Super-Safe, Small, and Simple) design, weighing 60 tons and placed 30 meters underground.[46] Water goes down, and steam comes up to generate electricity, with a only a small workforce needed to operate the electrical system. This 10 MWe system would replace the annual need to ship in 4000 gallons of diesel fuel per person in Galena.[47] The great regulatory hurdle to overcome before such a system can be installed has barely been approached, but if such systems become acceptable, Toshiba envisions a large market designed around building the sealed reactor steam sources in Japan and shipping them all around the globe. These sealed systems would later be returned to Japan after a 30 year life.[48] The initial plan was to provide nuclear electricity to Galena in 2012, but the plan has been in regulatory limbo.

## BENEFITS AND CONSTRAINTS

Toshiba's 4-S reactors, and many of the other small systems, would rely on liquid metal to remove the heat from the fission core. The hot metal then flashes water to steam in a secondary loop, much as in larger pressurized water reactors. Although this sounds complicated, there has been much experience with such systems, including submarine reactors. The liquid metal does not require high pressure water, and is more efficient with the neutrons driving the chain reaction, allowing a smaller core and providing greater intrinsic stability. Some of the designs for small reactors would use uranium enriched to nearly 20 percent, instead of the 3-5 percent standard for large systems.[49] The advantage is again a smaller system. Some submarine reactors operate with highly enriched (bomb grade) fuel, but fuel enriched to 20 percent or less is not suitable for the production of nuclear weapons.[50]

**EVEN SO, 20 PERCENT ENRICHED URANIUM IS AN IMPORTANT STEP TOWARDS WEAPONS-SUITABLE ENRICHMENT, AND REACTORS OF ANY SIZE WILL BE BREEDING PLUTONIUM; THIS MEANS THAT PROLIFERATION CONCERNS WILL STILL NEED TO BE ADDRESSED.**

Even so, 20 percent enriched uranium is an important step towards weapons-suitable enrichment, and reactors of any size will be breeding plutonium; this means that proliferation concerns will still need to be addressed. The proposed small sealed reactors would be shipped under suitable protection and then installed in underground vaults, secure from theft or attack. After a few weeks of operation, the fuel assemblies would be so radioactive as to be self-protecting, fatal to anyone attempting to handle them. The weight of the sealed system would be too great for any handling machinery available at the remote sites, save for the installation and removal efforts with special equipment. Return of the sealed system could then be under adequate security. A secure global shipping system for large volumes of enriched fuel, radioactive spent fuel, and even plutonium-based fuel has been a successful operation for decades.[51]

Another advantage of SMR systems is that they do not need to rely on the very few firms able to make the large components of large power stations. A new entity, B7W Modular Nuclear Energy LLC will market the 'mPower' modular reactor, which can be produced from components the parent company (Babcock and Wilcox) already has the capacity to produce. These modular underground reactors could be used alone or be adjoined to larger facilities, with a five-year cycle time for refueling.[52]

The ability to construct medium to large-scale nuclear facilities in stages, adjusting for demand and financial resources at each stage, is a great benefit to utilities seeking nuclear power. As more reactors are constructed and integrated into the regional power grid, trouble with a single reactor will not be so worrisome and the likelihood of power outages will be reduced. Therefore, the manufacturer and the utility customer would be facing a smaller risk of participating in nuclear power production and consumption.

The fuel requirements for a future array of small to medium sized reactors would not be much more than what is currently available and marketed. Several designs are planning to use enrichments of 20 percent, instead of the 3.5 percent typical of current large reactors.[53] A feature of uranium enrichment that many find surprising is that the enrichment is easier the further it is enriched. The step from 3.5 percent to 20 percent will not require new equipment, only an adjustment of current practices. For instance, Iran recently announced use of its centrifuge enrichment facilities to enrich fuel to 20 percent for use in a reactor used for the production of radioactive medical isotopes.[54] Conversion from the enrichment uranium gas to fuel is also a known step, although not one yet achieved in Iran. Other than a slightly increased market for uranium and its processing, the proposed smaller reactors would have only a small impact on global uranium fuel supplies.

**DECENTRALIZED SMR SYSTEMS FOR DESALINATION PROJECTS ALONG THIRSTY SEA COASTS PRESENT ANOTHER ATTRACTIVE PROSPECT. WITH ELECTRICITY AND FRESH WATER, NEW POCKETS OF STRONG PRODUCTIVITY COULD BE CREATED.**

It is not just small, remote, or underdeveloped populations that could benefit from SMR. The new discoveries of valuable minerals tend to be of low grade, requiring large energy inputs, and are usually in remote locations, but mines tend to have roads and heavy equipment to bring in and install an SMR. An SMR system for power and possibly heat for a mining campaign of several decades can be very practical. Remote oil and gas fields could be another SMR market, with the waste heat and steam providing the means to liquefy and expel the underground fluids. The US Idaho National Laboratory is developing a plan that uses a fission reactor for use in the Canadian tar sands deposits, providing electricity and using the waste heat to enable extraction of the hydrocarbons.[55] Some of the electricity would be used to make hydrogen, the necessary ingredient to engineer heavy oils into products we can use.

In many parts of the world, the most lacking resource for humans is fresh water. Desalination of seawater is a process intensive in energy, and fresh water can be expensive to move. Therefore, decentralized SMR systems for desalination projects along thirsty sea coasts present another attractive prospect. With electricity and fresh water, new pockets of strong productivity could be created. The International Atomic Energy Agency (IAEA) has recognized this niche for SMR in its 2007 General Resolution, Section 5.[56]

**GIVEN THE FRAGILITY OF PUBLIC OPINION ABOUT NUCLEAR POWER, RELIABLE AND RESPONSIBLE OPERATORS AND MANAGERS ARE VITAL. ONE INCIDENT OR ACCIDENT ANYWHERE WOULD BE A GREAT SETBACK TO PROGRAMS THROUGHOUT THE WORLD.**

Nuclear power plants require a staff of highly trained and specialized professionals. In the United States, much of this work force has been derived from the US Navy nuclear power program, but a strong increase in new plants will require a new generation of expertise. University programs in nuclear engineering are ramping up to meet this need and the industries themselves are sponsoring crafts training for the special skills needed to construct reliable nuclear power systems. Work force development in nations new to nuclear power will be a great need, and there are few such programs available. Given the fragility of public opinion about nuclear power, reliable and responsible operators and managers are vital. One incident or accident anywhere would be a great setback to programs throughout the world.

All of the current construction and orders for nuclear power plants are for large, 1 GWe or greater, and the national regulatory agencies have been gearing up to deal with the expected license applications. This involves hiring and training staff, and furthermore, constructing the computer codes to assess the operation, reliability, and safety of these systems. The US Nuclear Regulatory Commission has just begun to consider pre-applications for SMR systems.[57] The IAEA has published guidelines for regulations in general, and maintains a registry of proposed designs, with about fifty such SMR designs,[58] and a very recent compilation of plans and progress for small nuclear reactors has been prepared by the World Nuclear Association.[59] Without some degree of experience and standardization, the regulatory barrier for SMRs might be very high. If such reactors were built for export it is likely that more than one national regulatory approval would be required.

The transport of a complete reactor, either within national jurisdictions or internationally, is also a very new idea, and suitable regulations will need to be developed. Many of the SMR modular sealed designs are meant to be returned to the manufacturers after their life cycle, in order to solve problems of possible proliferation and radioactive waste disposal. Return of such a package will require very careful new regulatory conditions which will need to be developed for this step, since even a small reactor holds a vast radioactive burden of fission products and long-lived radioactive transuranics. The IAEA has begun a study of the needed steps.[60] Nonetheless, the advantages of new SMRs are so diverse that manufacturers, professional societies, and the IAEA are sponsoring enthusiastic presentations and conferences. This momentum will surely have an effect, but can the world deal with a significant increase in nuclear power?

Uranium is now mined in many countries, with a spot price of about $93 per kilogram of yellow-cake, the marketed oxide obtained from local milling and separation.[61] Global uranium (reasonably assured reserves plus inferred resources) at a higher price of $130/kg of uranium are estimated at 5,468,900 tons, and with 2007 consumption of 69,110 tons per year, these sources would last about 79 years.[62] A successful nuclear renaissance would consume more uranium to shorten this resource horizon. New technologies, poorer resources, and higher prices would extend this horizon, but, even so, one could not expect societies to rely on nuclear fission power, as it is currently produced, for a great time into the future. However, the nuclear industry operates on the rare (0.71 percent) 235U isotope alone. The other 99.3 percent is 238U, and we know how to use this as feed stock to breed another fissionable fuel (239Pu) in fission reactors, a process known and employed since 1945. The plutonium may be separated from the uranium and other products in the spent (now better called 'used') fuel by chemical methods, under the general name of 'reprocessing.' It is thus possible to envision a much longer nuclear fission future, based upon bred plutonium. Nations poor in both fossil fuels and uranium, but rich in technology and nuclear skills, can be expected to lead the way to develop an electrical energy system based upon plutonium. Japan is leading the way in these efforts.[63] A global plan to develop and operate reactor systems, with designs efficient at power and others at breeding new fuel, has been proposed.[64] These Generation IV systems and the Global Nuclear Energy Partnership (GNEP) to develop them lost US support and funding because the Obama administration is no longer pursuing domestic commercial reprocessing, which is a cornerstone of the GNEP plan.[65] If the science, engineering, financial, regulatory and security aspects of this plan to produce new fissionable fuel from the abundant isotope of uranium could be met, the technology also includes opportunities to consume the most long-lived waste from power generation, greatly reducing the volume and the long-term toxicity of nuclear waste to be buried. With investment funds and interest low, the prospects for such a long term increment to global nuclear energy seem dim for now

Nuclear fission also can provide transportation fuel, not just electricity. Hydrogen is emphasized as a fuel that can be burned without the emission of $CO_2$, but if the hydrogen is produced from fossil fuels, the $CO_2$ problem has only been moved elsewhere. Nuclear fission has two attributes that offer an alternative source for hydrogen fuel production. The steam from a high temperature reactor is so hot that it is already partway to dissociation, becoming hydrogen and oxygen. This steam requires less electrolysis than liquid water would to continue to the gases, using the cheap power available from that same reactor to make hydrogen as a potential transportation fuel.[66] In another method, engineers point out that the most effective way to make fuel from hydrogen is to use it as an ingredient in cracking heavy oils into lighter liquid fuels, as familiar today. There is a proposal to build such a high temperature reactor atop the Canadian tar sands, using the reactor heat to soften and separate the heavy tarlike hydrocarbons.[67] The electrical energy from the system is used to run the operations and make hydrogen, and the hydrogen to crack the semi-solid tar into gasoline.[68] The remote location, limited project life and small size of each project would seem very suitable to new designs of small, semiportable, high temperature reactors, as considered by a collaboration of the Alberta Research Council and the Idaho National Laboratory. Environmental and water supply issues are also considered in this report.[69]

India is a nation with special needs and strengths in the arena of small to medium reactors. The nation is poor in uranium resources, and partially still under an embargo as a non-signatory to the Nuclear Nonproliferation Treaty.[70] The size of the country and the rural nature of the society create special problems in the distribution of electrical power, making smaller systems more attractive. Almost since independence, India has been pursuing a three-stage program that will enable a future based on smaller reactors with fuel founded upon India's abundant supplies of thorium.[71] Thorium is the second heaviest element we can dig from the earth, and the US holds the greatest known reserves.[72] Thorium holds no fissionable isotope analogous to 235U, but can be used as fertile stock for breeding, much as in the transformation of abundant 238U into fissionable 239Pu. India's plan is to begin with 235U-fueled reactors, with designs to conserve neutrons, allowing thosereactors to breed plutonium as well as generate power.[73] Then a second set of reactors burning that plutonium fuel would have enough extra neutrons to convert 232Th into 233U, an isotope that would in turn be suited to fuel a third generation of reactors, with excess neutrons to breed replacement 233U from thorium. India is currently stuck on the first phase, without sufficient uranium to even fuel its existing fleet of first generation reactors.[74] If India is able to master the thorium cycle, it can be expected that they will seek export markets for their reactors and their thorium.

There are those who are willing to accept nuclear fission power only as a bridge to the day when societies can thrive on renewable sources. A more extreme view is that mankind can someday use energy derived from the nuclear fusion of deuterium, the heavy isotope of hydrogen, 0.015 percent of all the hydrogen in the seas. Although the large ITER experiment (originally called the International Thermonuclear Experimental Reactor) will attempt to demonstrate this is feasible in principle, the cost and complexity of the machinery needed to convert sea-water into electricity is extravagant, and the start of construction is delayed.[75] Thus, this eternal fusion path is not a reasonable hope.

## CONCLUSION

For the near-to medium-term, the spate of orders, contracts, and discussions for large nuclear power reactors in the established nations will continue, while new facilities for construction of the major component are likely to increase. Some nations have very ambitious plans, and issues will surely arise, but it seems likely that nuclear power will hold its own current position at providing about 16 percent of global electricity. The major vendors will both compete and collaborate in search of business. Uranium supplies, including all the technical steps that lead to fuel, are adequate to sustain this growth. Issues of proliferation, safety and spent fuel disposal will not change, since adequate means exist to avoid or defer these problems. The treaty structure, with the crack in the Non Proliferation Treaty provided by the US-India 123 agreement will not need adjustment.

**THE ADVANTAGES OF SMR ARE SO STRONG THAT THERE WILL BE A MARKET FOR THEM, BUT THE EARLY STAGES WILL SURELY BE PAINFUL.**

When SMRs gain more traction, mass production is likely to lead to an increase in new nations investing in fission systems. The technical and engineering issues seem to be under control, uranium fuel will be available at a reasonable cost, and a host of potential new suppliers will arise in prospect of new markets. Issues of safety, proliferation, and spent fuel disposal will not be greatly different than they are today. The greatest challenge will be the need for a completely new regulatory regime, including the financing and insurance instruments that must accompany the expansion of nuclear power to nations not now operating power reactor systems. Large nations with well-established regulatory systems will face an overload of unfamiliar designs, while nations new to nuclear power will have to start from scratch, with little mentorship. The IAEA has recognized this issue, and has begun steps to lead and mentor the changes needed.[76] The advantages of SMR are so strong that there will be a market for them, but the early stages will surely be painful. SMR systems may be built quickly, but large-scale production will likely not be implemented for several decades. The International Project on Innovative Nuclear Reactors and Fuel Cycles, under the IAEA, held a conference in October of 2009 with an interim report on just these issues, Legal and Institutional Issues of Transportable Nuclear Installations, laying out the many issues to be addressed.[77]

Overall, the future of nuclear power is on a steady path of growth in nations now enjoying this carbon-free source of power, with large reactors of a few designs. One current limitation to growth is the manufacturing of very large components, but several nations are building new or enlarged facilities to meet those needs. Nations new to nuclear power may choose large systems, as The United Arab Emirates have done, or they may be able to select from an array of new smaller designs, better suited to their markets. There is rapid growth in designs for SMRs,[78] and their smaller size could permit rapid deployment. The major obstacle will be the international and national legal, financing, regulatory, and monitoring systems which must be in place before orders are placed. We will surely see the wider deployment of nuclear power, in a wider variety of power levels, around the globe within decades, but not until daunting non-technical issues are settled.

## Notes

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