RESTARTING THE STALLED USA NUCLEAR RENAISSANCE

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"Thinking is the hardest work there is which is probably why so few people engage in it."
Henry Ford

"No one can whistle a symphony. It takes a whole orchestra to play it."
H. E. Luccock

"One man with courage is a majority."
Thomas Jefferson

INTRODUCTION

The Nuclear Renaissance in the USA is described as having retreated back to the Dark Ages. Its revival as a base-load, non-polluting and carbon-free source can only be achieved by adopting a new paradigm based on visionary innovation. It is suggested that existing plants sites need to be refurbished initially using Gen3+ and Gen4+ reactor core designs, with a crash program in introducing the superior Thorium fuel cycle. New Gen3+ plants have reactor core accident risk of once in a million years, as opposed to once per ten thousand years for the aged Fukushima BWR4 and BWR5 designs.

Nuclear energy production is increasingly considered as a base load and carbon-free component of a sustainable energy mix of conventional and renewables sources with energy storage and spinning capabilities associated with conservation and Smart-Metering as part of a "Smart Grid" that is supervised by a visionary Internet of Things (IoT). Quoting the inventor of the geodesic dome concept, Bucky Fuller: "You never change anything by fighting the existing reality. To change something, build a new model and make the existing model obsolete."

The hoped-for Nuclear Renaissance has been thwarted by several developments: the earthquake and tsunami and the ensuing Station Blackout accident at Fukushima, Japan, an oversupply of cheap natural gas from the Hydraulic Fracturing and horizontal drilling of shale deposits; exorbitant capital costs, wind power production growth, and regulatory delays caused by excessively demanding environmental activism.

In a low natural gas price environment, nuclear operators are faced with slimmer margins and high maintenance capital investments requirements. However nuclear power plants benefit from a low variable cost of $12 / Mw.hr of energy compared with $24 / Mw.hr for the most efficient gas turbine plants. Nuclear power plants do not have carbon emissions, unlike coal power plants which are faced with greenhouse and pollution regulations that could cause plant closures.

Nuclear power plants complete life-cycle CO_2 emissions including construction, which represents 90 percent of the cost, uranium fuel extraction and manufacturing, fuel transportation, and decommissioning, are about 20 – 80 gms / kW.hr of energy produced. Wind energy has the same carbon footprint. Solar Photo-Voltaic (PV), in comparison is 100 gms / kW.hr.

Nuclear power plants are ideal for base power generation. Wind power and solar need to have energy storage facilities developed to surmount their intermittence nature. Until then, wind capacity is currently supplemented with concurrent natural gas turbines plants. Hydroelectric and gas turbine plants sources have high ramp-up rates to follow the load and satisfy demand that is several thousand times faster than nuclear plants. Some General Electric (GE) gas turbines have ramp-up times of minutes from running idle and full throttle power. Nuclear power plants ramp-up times are hours for Pressurized Water Reactors (PWRs) and days for Boiling Water Reactors (BWRs). Containment failure is small in PWRs, an order of magnitude less likely than at a BWR. The only recorded failures at USA PWRs involved minor xenon (an inert noble gas) or iodine gases releases from failed fuel elements when the system pressure needs to be reduced. The largest pollution source that nuclear power plants has been fuel oil used for the backup diesel generators.

NUCLEAR PLANTS EARLY RETIREMENTS

The nuclear merchant utilities are not expanding their nuclear fleets, instead, they are shrinking them. The Entergy utility has no plans to build any more nuclear facilities, noting that the construction costs are exorbitant. It is retiring its Vermont Yankee's 600-MWe facility, but still maintaining its 4,400 MWe of nuclear generating capacity. Other retrenching nuclear utilities include Exelon Corporation, NextEra Energy and PSE&G Corporation.

Exelon has been vocal in advocating the granting of federal loan guarantees for the nuclear utilities while calling for the discontinuance of the Production Tax Credit (PTC) allocated to wind energy and other renewable sources of electricity, suggesting that it creates market inequities. Exelon's 28 percent electrical production from natural gas to supplement production in areas with higher concentration of wind power may be the real reason for the complaint. The installation and idling of standby gas turbine plants when the wind is blowing providing zero cost and even negative electricity cost, and their restart when it stops blowing, is costly in term of capital cost, lost revenue and tax obligations.

Five nuclear units, including Entergy's Vermont Yankee, have announced closures and nine uprates to increase the plants power output were cancelled or placed on hold in 2013 because of the competition from cheap natural gas. Duke Energy and Southern California Edison closed their Florida and Southern California facilities, respectively, citing persistent technical issues. Dominion Resources has closed its Wisconsin unit and Exelon is expected to shut down a New Jersey plant because neither one is able to compete with natural gas.

In 23 states, 38 reactors are at risk of early retirement. Twelve of these face the risk of being shut down. These include Exelon's Clinton plant in Illinois, Entergy's Indian Point in New York, Tennessee Valley authority (TVA)'s Browns Ferry in Alabama and FirstEnergy's Davis-Besse plant in Ohio, and Constellation Energy Group Nine Mile Point in New York [38].

Increased regulatory review and scrutiny is a factor in these retirements, particularly after the Fukushima earthquake and tsunami. This has untimely emerged when the world is emphasizing the use of carbon-free, reliable base-load operation, which nuclear energy provides. With the added uncertainty about federal loan guarantees for nuclear projects, the nuclear renaissance was forced to retreat back into the dark ages.

The Chicago-based electrical utility Exelon, parent of Commonwealth Edison, and the nation's largest operator of 22 nuclear power plants, said in February 2015, that unless market conditions improve, it will announce plant closings by the end of 2015. Exelon's six nuclear power plants in Illinois have failed to turn a profit over the 2010-2015 period. The 27-year-old plant in Clinton, Illinois west of Champaign-Urbana is the most vulnerable for closing. Exelon's six nuclear power plants in Illinois have failed to turn a profit over the last five years, and the 27-year-old Clinton plant is the most vulnerable for closing [39].

Nuclear power plants were at some point in time the most profitable form of generated power. Cheap natural gas from hydraulic fracturing and horizontal drilling in tight formations and a boom in wind power generation have driven down electricity prices, eroding nuclear power's profits. By mid-2008, competing sources of generation had very high costs relative to nuclear plants. As the fossil fuel costs came down substantially from those peaks starting 2010, nuclear has lost a lot of its cost advantage when considering its capital-intensive characteristic. The Chicago Tribune analyzed hourly power prices that Exelon's reactors in Illinois received over six years and determined that the plants have not made enough money to cover operating and ongoing capital costs since 2008. Among the newspaper's findings [39]:

> "Exelon's plant in Clinton, the only one without a second reactor, is in the worst financial shape of the company's Illinois nuclear installations. The plant's power prices plummeted from $42 per megawatt-hour in 2008 to $22 in 2009 and have held below $29 on average each year since. Single-reactor plants like Clinton cost between $45 and $55 per megawatt-hour to operate, according to the NorthBridge Group.
>
> Exelon's Dresden plant is faring the best of the Illinois plants, but it still is not profitable. In 2010 and 2011, the plant eked out $33 per megawatt-hour in sales, offset by operating costs ranging between $35 and $40 per megawatt-hour.
>
> Quad Cities and Byron have been hit the hardest by "negative" price conditions, meaning Exelon paid the operator of the electric grid to take its power. Because nuclear plants operate around the clock, they are continually producing power, and in 2012, the Quad Cities plant was paying the grid operator to take its power 8 percent of the time. In 2010, the Byron plant was paying out 7 percent of the time.
>
> Clinton's operating costs are the highest per megawatt-hour compared with its sister plants. Clinton, which supplies electricity to 1 million homes, also is vulnerable because it sells electricity to a less lucrative market than its sister plants, one that's flush with cheap electricity generated by wind turbines.
>
> In 2013, power prices at Clinton fell below zero 1.7 percent of the time. That means Exelon paid to have Clinton's power taken away during those hours. The average cost to Exelon when prices were negative: $53 per megawatt-hour.
>
> Exelon has other tools to help offset losses. Its plants receive "capacity" payments, a reservation fee paid by the grid operator for power. For all of Exelon's Illinois plants other than Clinton, such payments have

> boosted revenue by $1 to $8 per megawatt-hour, depending on the year. Clinton's capacity payments last year were just pennies. Exelon can also hedge against a decline in power prices through fixed price contracts."

Exelon officials, in a conference call in February 2015, detailed some of the company's challenges: "Despite our best-ever year in generation, some of our nuclear units are unprofitable at this point in the current environment, due to the low prices and the bad energy policy that we're living with," said Chief Executive Chris Crane. "A better tax policy and energy policy would be the clear answer, but if we do not see a path to sustainable profits, we will be obligated to shut units down to avoid the long-term losses. [39]"

The Clinton plant is the most likely candidate for closing, along with plants in Byron and Quad Cities. Exelon's other plants are in Dresden, Braidwood and LaSalle. Exelon also operates two nuclear plants in other states. The Clinton plant, with its 650 employees, is DeWitt County in Illinois largest employer. It is also the county's largest taxpayer. Exelon helps pay for roads, parks, the library and schools. "Good neighbor" is how residents refer to the plant.

Closing the three Illinois nuclear plants at greatest risk of early retirement would have a significant negative economic impact on the state, including $1.8 billion in annual lost economic activity and more than 7,800 job losses, and the resulting increase in carbon emissions would have a societal cost of more than $18 billion. The closures would increase wholesale electricity costs in the northern Illinois region served by ComEd by up to 9.9 percent, or $437 million, in the first year.

Exelon would not have to close a nuclear plant or two if electricity prices dramatically rose or if it got legislative or regulatory relief. If the state legislature imposed a tax on carbon emissions. That would aid nuclear power producers because the plants emit zero carbon emissions as opposed to coal-fired or natural-gas-fired plants. Eliminating the $22-per-megawatt-hour production federal tax credit to wind generators would also help by reducing their pricing advantage. Though Exelon has said the government should stop the subsidies, wind power supporters have noted that Illinois' nuclear plants never would have been built if it had not been for utility customers paying for their construction through their electric bills. Insurance costs for those plants also have been subsidized by the rate payers [39].

The Quad Cities and Byron plants are hurting because they are in the path of wind power that flows in from the Iowa border into Illinois. Though wind is a minor part of the energy supply mix and fails to produce energy 86 percent of the time when Exelon's customers need it, its effect on electricity prices is substantial. "Wind generators keep supplying power even when profits would be zero. More important, prices are set based on the lowest cost provider needed to keep electricity flowing. In the middle of the night, when the only two power producers running are wind and Exelon, wind sets the price. With subsidies that pay wind producers even when power prices are below zero, that means wind power gets paid while Exelon pays out" [39].

The state of Illinois has passed laws that support "clean coal," wind, hydro, solar and biomass energy. Nuclear energy is the only energy source not recognized for the carbon-free energy and the base-load power generation that it provides and deserves to be included as part of an overall energy strategy.

In addition to plants already closed or scheduled for closure, like Exelon's Oyster Creek plant in New Jersey, Vermont Yankee, Vermont, San Onofre, California, Kewaunee, Wisconsin, Crystal River, Florida, Oyster Creek, New Jersey, and temporary disabled plants, like Fort Calhoun in Nebraska, affected by flooding, the following plants face the possibility of early retirement due to the pressure of cost competition with natural gas and wind power [40]:

1. Indian Point: Less than 50 miles north of Manhattan, New York, the reactors at Entergy's Indian Point Energy Center face a tough political fight for relicensing.
2. Ginna Nuclear Generating Station: On the south shore of Lake Ontario near Rochester, New York, Ginna is a single-reactor plant that faces fresh competition from wind turbines, falling power prices, and, like Indian Point, a political climate hostile to nuclear reactors. Ginna is owned jointly by Exelon and Électricité de France.
3. James A. Fitzpatrick Nuclear Power Plant: A plant on the south shore of Lake Ontario in New York. FitzPatrick faces the same challenges as Ginna, but it is also an older boiling-water reactor that may need upgrades.
4. Three Mile Island: Most of the shale gas boom in America is happening in the Marcellus region of Western Pennsylvania, which means Exelon's Three Mile Island plant now has to compete with an abundance of gas not been seen in its lifetime. Several large, high-efficiency gas power plants are planned for the region.
5. Davis Besse Nuclear Power Station: FirstEnergy's plant near Toledo is not far from the Marcellus Shale formation and all that cheap natural gas. After Indian Point, it is the next power plant up for license renewal in 2017. It has an unfavorable reputation after an extended outage in 2002-2004 due to corrosion in the reactor vessel.
6. Pilgrim Nuclear Generating Station: Entergy's Pilgrim plant in Plymouth, Massachusetts, survived a contentious license renewal process and was granted a new lease on life through 2032. But it may not survive the energy economy in which it now must compete. The old boiling water reactor is more expensive to operate than newer designs.

Most other existing nuclear plants will survive because of their base-load operation and they provide power without producing carbon emissions. Coal power will suffer with greenhouse gas regulations, and because power prices should recover from their current trough. But most of all, because of nuclear's low variable cost at about $12/MWhr, compared with $24 for the most efficient gas plants.

RENAISSANCE GLIMMERS OF HOPE

In the 2005 Energy Policy Act, the USA Congress signaled its interest in nuclear power by including $13 billion in incentives for the industry. New spending in the act included risk insurance and loan guarantees for the construction of new plants. It included tax credits of 1.8 cents/kW.hr of energy generated in a plant's first eight years of operation. And the law lowered from 35 percent to 20 percent the tax rate on investment gains utilities make in funds they must set aside to decommission plants.

Another glimmer of hope appeared in February 2012. For the first time since the Three Mile Island accident in 1979, the USA Nuclear Regulatory Commission (USNRC) approved the construction of two new Toshiba-Westinghouse 1,000 MWe plants at a cost of $14 billion which are scheduled to go online in 2016. The new reactors are part of an expansion of the Vogtle Electric Generating Plant operated by the energy supplier Southern Company near the city of Augusta, Georgia.

Table 1. New Reactors commitments, USA, 2012.

Reactor Type	Reactor units	Location
PWR, AP 1000 Toshiba-Westinghouse	2 units: Vogtle units 3 and 4.	Near Waynesboro, Georgia. Southern (SO) subsidiary of Georgia Power and partners.
PWR, AP 1000 Toshiba-Westinghouse	2 units, V. C. Summer station.	South Carolina, 40 miles North-West of Columbia, South Carolina

Figure 1. Georgia Power Vogtle plants units 3 and 4 under construction, 2013.

Figure 2. Georgia Power Vogtle 3 PWR unit 900 tons bottom of pressure vessel installation, Georgia, USA, 2013.

The USA Department of Energy (DOE) projects a 45 percent growth in electricity demand by 2030, suggesting 35 to 50 new nuclear plants will be needed by then just to maintain the nuclear energy share of the electricity market at 20 percent. The 2005 energy bill passed by Congress provides subsidies for the first six plants, which the industry sees as a one-time “jump start.”

If the USA nuclear industry is to continue supplying 19 percent of its electrical energy supply, there is no way to avoid building new plants. The fact is that many of the 102 nuclear reactors currently in service in the USA are well aged, and most of them have already been operating for over 30 years. To buy time, since 2000, the USNRC has extended the operational life span of 71 reactors to 60 years. Of concern are 23 aged BWR units, constructed by the General Electric (GE) Company which are of the same design as the Fukushima reactors.

The USA Department of Energy has allocated $18.5 billion in federal guarantees available for building new nuclear power plants. Approval will soon be in the works for two reactor blocks in South Carolina. The USNRC, has received applications for some 30 additional reactor blocks. Not all of the planned facilities will actually be built, even under the best of conditions, a single nuclear power plant capital costs per megawatt of installed capacity are almost twice as much as a coal-fired power plant and almost four times as much as a gas-fired one

Hurdles exist. In the USA, the NRG utility had filed in 2006 the first licensing application for a new nuclear power plants since the Three Mile Accident in 1979. The project depended on financing from the Tokyo Electric Power Company, Tepco utility that operates the Fukushima Daiichi plant and cannot provide the promised capital anymore. The San Antonio, Texas utility CPS Energy followed by announcing that it was “indefinitely suspending all discussions with NRG,” about purchasing power from the proposed units.

Acquisitions and mergers are leading to consolidation in the utility industry. In April 2011, Chicago-based Exelon and Baltimore-based Constellation proposed a merger that would combine the nation's largest operator of nuclear power plants with a large marketer of electricity along the East Coast. Exelon operates the utilities Commonwealth Edison in Illinois and PECO in Pennsylvania. Exelon and Constellation have significant assets in the mid-Atlantic region and throughout the PJM Interconnection regional market. PJM operates electricity markets stretching from Illinois, across northeastern Rust Belt states, to the mid-Atlantic states and as far south as North Carolina. The deal envisions shedding a significant slice of coal-fired power in Constellation's energy mix, and it would create a $52 billion company dominated by "clean energy" in the form of nuclear power, natural gas and renewable energy.

In January 2011, Duke Energy Corp. proposed a $13 billion merger with Progress Energy Inc., both based in North Carolina. Northeast Utilities proposed a deal to buy Boston's NStar. Wholesale power giant AES Corp., based in Arlington, Virginia., has offered to buy out Dayton Power and Light in central Ohio.

The need for base-load electrical power production and the unavailability of capital as a result of the 2008 financial crisis forced the aging USA’s nuclear power reactors fleet to have its life extended through license renewals even though they need to be replaced by a new fleet benefiting from the advent of inherently safe new technologies.

However, aging equipment has to be replaced with new equipment in all fields of engineering to avoid unforeseen serious accidents. For instance, new Boeing 767 tankers are planned to replace the aging Boeing KC-135 which first entered service in 1957 by a new aircraft designated as the KC-46A. The first 18 aircraft, out of a fleet of 179 tankers, are to be deployed by 2017. About 100 of the oldest Stratotanker models have been grounded since 2006 due to age. Originally needed to keep B-52 nuclear bombers in the air for long periods of time, the Stratotankers found new missions enabling small fighter bombers to revolutionize the use of air power. In much the same way, the aging fleet of nuclear reactors have served their admirably served their mission and it is time to promptly replace them with modern safer versions.

By 2011, according to IAEA data [1], 67 new nuclear power plants are under construction worldwide. However, according to the same source, 125 reactors are in the shutdown state. This suggests that the new construction is replacing about half the number of those units that are retired with a net addition of 58 units.

Considering the new added capacity of 62.9 GWe; this exceeds the shutdown capacity of 37.794 GWe for a net addition of 25.106 GWe. The new added capacity by China, Russian Federation, Republic of Korea and India is countered by retirement of units by the USA, UK, Germany and France.

The restarting of the stalled USA Nuclear Renaissance is described along different time frames.

On the immediate time frame, plants licenses renewals and extensions are considered as unsustainable because of the aging and obsolescence of the current nuclear reactors fleet.

In the short term, the reviving of earlier abandoned projects such as the Bellefonte reactors is being pursued. In the intermediate term, Next Generation designs such as the AP1000 are being considered.

On an intermediate time frame, the adoption of small reactor designs such as the Modular Integral Compact Reactor concept as a remedy to the dearth of available capital is a promising alternative. The Tennessee Valley Authority, TVA plans to be the first utility in the USA to build a set of small reactors of the integral type initially developed for naval propulsion applications. TVA is studying the feasibility of beginning construction of up to 6 mPower Babcock &Wilcox, B&W, modules of 125MWe reactors at its Clinch River site in 2020. Small nuclear units can potentially replace TVA's fossil fuel plants where the existing transmission lines and water use rights could accommodate the transition. Given that small reactors need less upfront capital to build, TVA could purchase certain number of units without federal loan guarantees. By comparison, it is inconceivable to spend 10-14 billion dollars at a time for new nuclear generation capacity based on large reactor units at the 1,000 MWe of installed capacity. B&W plans to submit an application for the USA Nuclear Regulatory Commission, USNRC to license its mPower integral reactor design aims to build the first unit by 2020. The modular design would enable the reactor to be built and assembled in a factory and transported by rail, truck or bargeto the construction site. Such a concept, he said, would slash construction time and provide cost certainty. The TVA is in talks with the USA Department of Energy, USDOE to power the Oak Ridge National Laboratory, ORNL with the small units to meet a mandate to the USDOE to reduce its greenhouse gas emissions by 2020 to 28 percent below its 2008 level on all its facilities, including national laboratories, under an executive order issued by President Barack Obama in 2010.

Small reactor offers an advantage in that they can use existing power-transmission lines without overloading them and can function as a “drop-in replacement” for ageing coal and nuclear power plants without the need for costly refurbishment.

For a sustainable long term nuclear energy future, the Thorium-U^{233} breeding fuel cycle is proposed as a solution to the long term resource availability, waste generation and nonproliferation concerns.

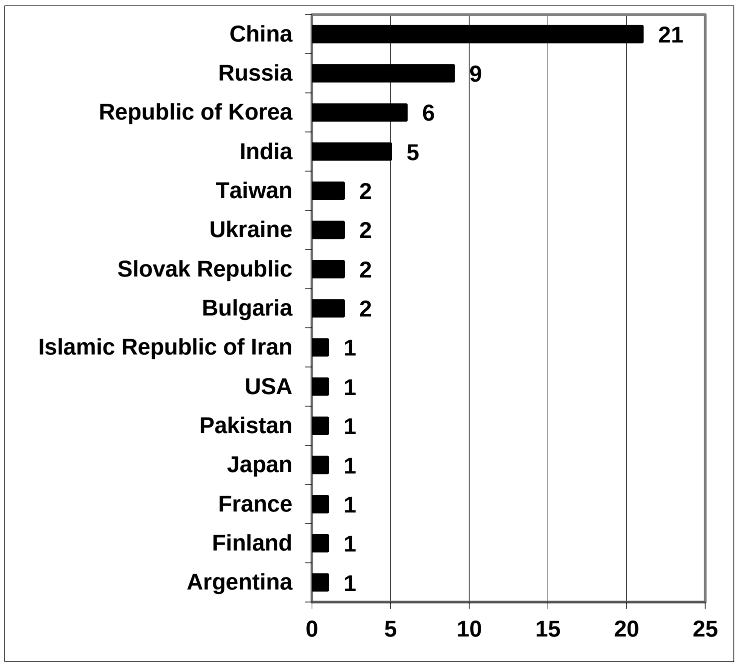

Figure 3. Number of power reactors under construction worldwide. Total: 67. Net electrical capacity: 62.9 GWe. Source: IAEA, 2011.

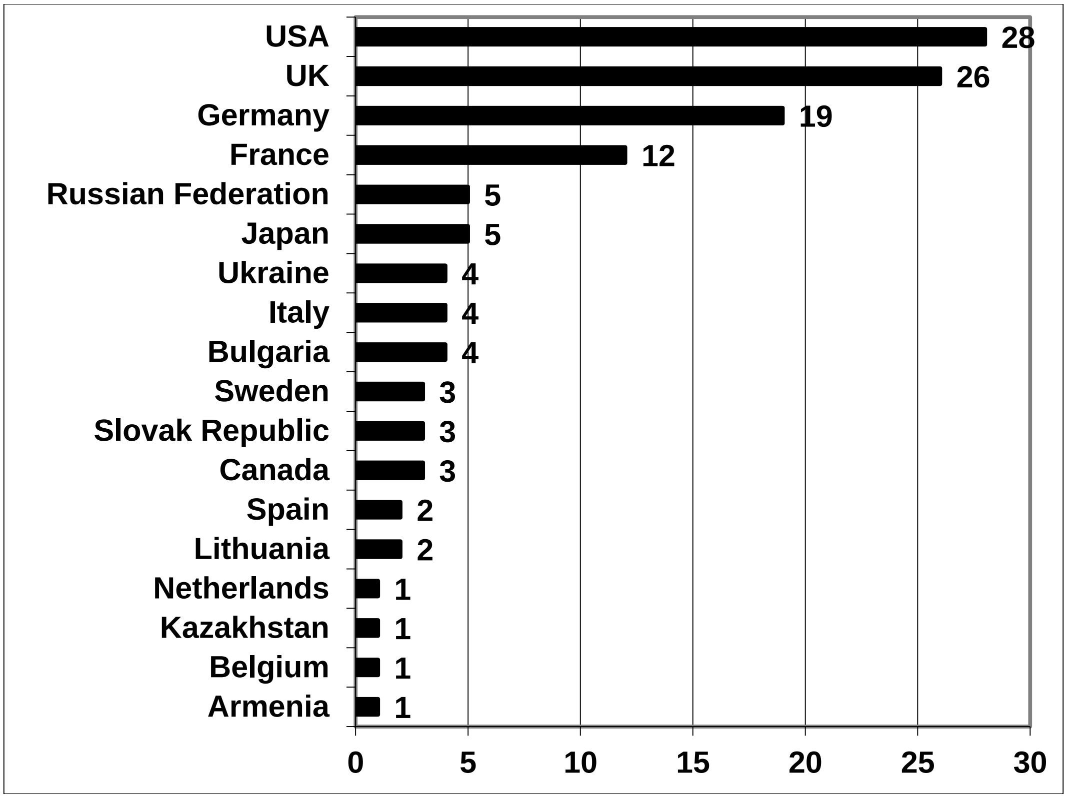

Figure 4. Number of shutdown reactors. Total: 125. Total capacity: 37.794 GWe. Data: IAEA, 2011.

POWER PLANTS CLOSURES

San Onofre Plant, Southern California

Southern California Edison's San Onofre plant south of San Clemente, California unit 3 plant was closed by ongoing maintenance issues. Three steam generator tubes in unit 3 of the nuclear reaction facility failed pressure stress tests by Southern California Edison (SCE), prompting the USA Nuclear Regulatory Commission to assemble a team of nuclear energy inspection experts to try to determine why the level of wear on the tubes is unusually high. The unit has been shut down since the detection of a leak in one of the steam generator tubes on January 31, 2013. Unit 2 is also off-line for routine inspections, and unit 1 has been decommissioned. The two mothballed unit 1 and unit 2 reactors had provided 17 percent of the region's electricity to be replaced using imported natural gas. The Breakthrough Institute points out that the state's carbon emissions will rise by 8 million metric tonnes per year.

Indian Point Plant, New York

About 50 miles north of Manhattan, the reactors at Entergy's Indian Point Energy Center face a political fight for relicensing. One license has expired, and that reactor operated under an allowance from the USA Nuclear Regulatory Commission (USNRC). Another license is due to expire in 2015. New York Governor Andrew Cuomo opposes relicensing. Outgoing New York Mayor Michael Bloomberg has defended the plant, based on the impact closure could have on New Yorkers' electric bills. Mayor-elect Bill DeBlasio has called for a gradual decommissioning as alternative power sources come online. The decision rests not with local officials, but with the USNRC.

The Indian Point plants need a water discharge permit, which can be obtained from the state if a closed cycle cooling system is built. The USNRC cannot give the plants an operating license unless it has its state permits. The plants need to meet the prerequisites of the state's Coastal Management Plan and its approval is uncertain. An adverse decision cannot be appealed in the courts system, and the USNRC has no say in the court process.

Indian Point provides about 5 percent of the electricity used daily in New York City and Westchester County. The electrical delivery contracts with municipal entities was taken over by the competing natural gas generators. However, Entergy sells the rest of the produced electricity through the Independent System Operators (ISOs) NYISO, ISO New England, and the PJM-Interconnect serving 13 Mid-Atlantic States. During Hurricane Sandy, the one of the major plants that kept New York City lit was Indian Point 2. The reactors in the area that were brought off-line because of shoddy power facilities going offline elsewhere.

Ginna Nuclear Generating Station, New York

On the south shore of Lake Ontario near Rochester, New York, the Ginna plant is a single-reactor plant that is owned jointly by Exelon and Électricité de France (EDF).

It faces fresh competition from wind turbines, falling power prices, and, like Indian Point, a political climate hostile to nuclear reactors. Upstate New York off-peak power prices have fallen to $32 per MW.hour as of mid-2013 from $55 /MW.hr in 2008.

James A. Fitzpatrick Nuclear Power Plant, New York

On the south shore of Lake Ontario in New York, the FitzPatrick plant faces the same challenges from wind power generation, falling power prices, and a hostile political environment as the Ginna plant, but it is also an older BWR that may need upgrades. Its operating license expires in 2034, but its revenue-sharing agreement with the New York Power Authority expires in December 2014, and unfavorable contract renewal negotiations could lead Entergy to shut the plant.

Three Mile Island, Pennsylvania

Most of the shale gas boom in America is happening in the Marcellus region of Western Pennsylvania, according to the Energy Information Agency, suggesting that Exelon's Three Mile Island plant has to compete with an abundance of natural gas. Several large, high-efficiency natural gas turbines power plants are planned for the region.

Davis Besse Nuclear Power Station, Ohio

FirstEnergy's plant near Toledo, Ohio is not far from the Marcellus Shale formation and its cheap natural gas. After Indian Point, it is the next power plant up for license renewal in 2017. Strong political opposition is expected considering an extended outage in 2002-2004 due to corrosion in the reactor vessel head.

Pilgrim Nuclear Generating Station, Massachusetts

Entergy's Pilgrim plant in Plymouth, Massachusetts, survived a contentious license renewal process and was granted a new lease on life through 2032. However it may not survive the wind and natural gas energy economy in which it competes. The old BWR is more expensive to operate than newer designs.

A minor unknown incident of a spike in tritium, possibly from tertiary fission, around 2012 which was 20 percent above the limit for one measurement, was exploited by environmental activists which also suggest that the plant is generating a thermal plume that is warming out Cape Cod Bay affecting fish eggs larvae and plankton. Since then, there was no recorded leaks.

Fort Calhoun Plant, Nebraska

Damaged by a backup batteries fire in June 2011 in the aftermath of the Mississippi River flooding. An earth mover was mistakenly driven into an 8 foot high flood protective levee and drove a hole into it. The levee barrier protects the plant up to a 35 foot crest, and worked just fine in the dozen other flooding high water events that reached up to the barrier. The plant did in fact flood in June 2011, water went right up to the reactor containment building. However, there was no meltdown, and no trace of radiation leakage. The plant safely switched to backup power generation without a problem. Its spent fuel pool is about 45 feet high inside the reactor structure, and in an impossible flood of this flood of this magnitude, the entire USA Midwest region would be lost to the flooding.

Crystal River Plant, Florida

Duke Energy plant was closed due to ongoing maintenance issues.

Kewaunee Plant, Wisconsin

Dominion Resources plant was caused by lower competing natural gas price.

Oyster Creek, New Jersey

Scheduled for closing by Exelon.

Vermont Yankee, Vermont

ENVIRONMENTAL CONCERNS

In November 2013, James Hansen, formerly head of NASA's Goddard Institute for Space Studies, and the doyen of the climate science movement, published an open letter, with three colleagues, addressed "to those influencing environmental policy but opposed to nuclear power":

> "As climate and energy scientists concerned with global climate change, we are writing to urge you to advocate the development and deployment of safer nuclear energy systems.
>
> In the real world there is no credible path to climate stabilization that does not include a substantial role for nuclear power.
>
> Continued opposition to nuclear power threatens humanity's ability to avoid dangerous climate change."

While acknowledging the risks associated with nuclear power, including accidents and the possibility of weapons proliferation, the scientists said these are dwarfed by the risks associated with pumping vast quantities of carbon dioxide into the atmosphere as a result of burning fossil fuels.

Echoing Hubbert King, they assert that: "We understand that today's nuclear plants are far from perfect. Fortunately, passive safety systems and other advances can make new plants much safer. And modern nuclear technology can reduce proliferation risks and solve the waste disposal problem."

Hansen and his colleagues argued that wind, solar and biomass simply cannot scale up fast enough to provide cheap and reliable energy on the scale required, so anyone concerned about global warming cannot afford to rule out nuclear as a way to displace substantial amounts of fossil fuel combustion.

OPPOSING VIEWS

A substantial part of nuclear's high capital costs has been caused by regulatory and construction delays, most of which stem from a dogged campaign waged by environmentalists to tie up projects in administrative and legal delays to make them uneconomic and force their sponsors to abandon them.

However, the industry is not blameless. For 60 years, nuclear engineers and operators have been promising safer and cheaper designs. By the early 2000s, the industry had recovered from memories of Chernobyl and was promising a fourth generation of standardized reactor designs with more passive safety features. Then Fukushima revealed a host of design flaws and unsafe operating practices, damaging public confidence.

The USA Natural Resources Defense Council (NRDC) and other environmental groups, many of which have campaigned against nuclear power for more than three decades on safety grounds and wants policymakers to focus on energy efficiency and renewable sources of energy such as wind and solar: "A USA nuclear renaissance has failed to materialize, despite targeted federal subsidies, because of nuclear power's high capital cost, long construction times, the lower demand for electricity due largely to improvements in energy efficiency, and competition from renewables."

EXTENDING LICENCES

Commercial reactors licenses in the USA were extended by the Atomic Energy Act for 40 years with a renewability period of another 20 years for a total of 60 years. The US

Nuclear regulatory Commission, USNRC bases those licenses on whether the plants meet current safety requirements; not on technical considerations.

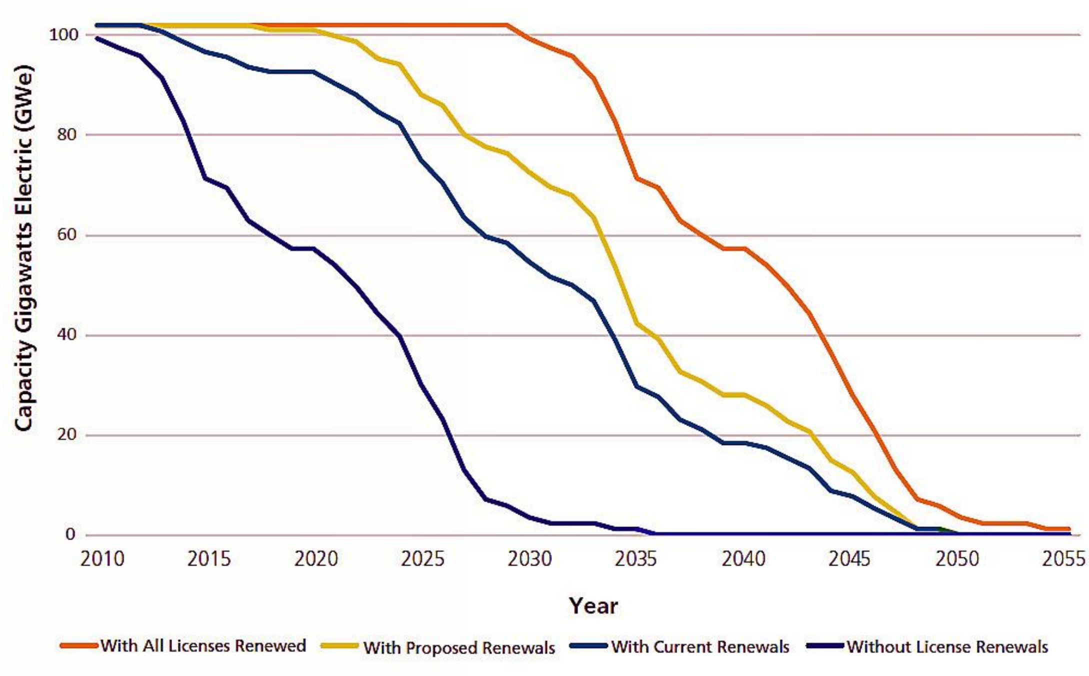

Figure 5. USA nuclear electrical capacity in GWe for different license renewal strategies. Source: USNRC.

Constellation Energy Calvert Cliffs plant received the first license renewal from the USNRC in March 2000. Its two reactors had come online in 1975 and 1977. They are now licensed to operate through 2034 and 2036.

Plant owners are evaluating what it would take to extend the life of the existing units possibly to 80-100 years operational lifetime.

This raises aging issues and identifies the need for research in several critical areas:

1. Online monitoring
2. Materials degradation.
3. Concrete degradation.
4. Life-cycle management.
5. Risk-Informed Safety Margins.

CLEAN ENERGY STANDARD

Nuclear power is included in a proposed “clean energy standard” moving the electrical system away from CO_2 emitting conventional coal and gas. Building 100 reactors in the next 20 years is advanced as a national priority both for energy security as well as to limit climate change emissions. The US Nuclear Regulatory Commission has been working for more than 15 years on streamlining the reactor licensing process to cut construction time and reduce financial risk. The 2005 Energy Policy Act provides loan guarantees for the first new reactors and insurance against regulatory delays.

By 2008, the USA Nuclear Regulatory Commission, NRC had 15 applications for new reactors and expected 15 more. Across from the NRC's headquarters in Rockville, Maryland a 14 stories office building costing $131 million is constructed to accommodate 1,500 new employees for the anticipated flood of applications.

Yet, this hoped-for nuclear revival is stalled: out of 4 power reactors projects considered by the US Department of Energy, USDOE in 2009 as candidates for $18.5 billion of government loan guarantees, only two are moving forward.

All forms of clean energy, including wind and solar, are undercut by a cheap price of natural gas and a surplus of generating capacity linked to the so-called "Great Recession" or "Credit Crisis" of 2008-2010.

Factors specific to the nuclear industry are the ballooning costs of construction of large units taking advantage of the economies of scale and the unavailability of investment capital. Nuclear projects require about a 10-year period involving a Federal Licensing process, whereas Wind Power projects require only a local licensing process for a project time of about 2-3 years before production starts.

The world moves forward in the use of nuclear energy, whilst the USA is in retreat. It is "renaissance" of the nuclear industry across the world; in the USA it is in a state of "stall," mired in a "Dark Age."

USA AND GLOBAL NUCLEAR ENERGY PRODUCTION

The USA has 66 nuclear power plant sites with a fleet of 104 reactors producing 20.2 percent of its electricity. If all the proposed projects were approved, the USA reactors fleet would grow by about 25 percent. According to the USA Energy Information Administration (EIA) most recent Annual Energy Outlook, total USA energy consumption is estimated to increase from 3,873 billion kWh in 2008 to 5,021 billion kWh in 2035, an increase of 30 percent. Nuclear power is expected to increase in plant capacity from 100.6 GWe to 112.9 by 2035.

Globally, energy consumption is forecast to increase by 100 percent. The World Nuclear Association (WNA) expects nuclear capacity to double from the present 373 GWe to 746 GWe within 40 years.

Table 2. Share of the USA electric power generation as of October 2009. Data: Energy Information Administration, EIA.

Source	Share of electrical production [percent]
Coal	44.4
Natural Gas	23.7
Nuclear	20.2
Hydroelectric	6.8
Other, wind, solar, biomass	4.9
Total	100.0

Out of 33 initial projects, eleven applications for new nuclear power plants are under consideration for licenses by the USA Nuclear Regulatory Commission (NRC), with four reactors, as expansions of existing plants, targeted for government support loan guarantees and financing. The 2011 USA federal budget slashes the subsidies for fossil-fuel companies and triples loan guarantees for building new nuclear reactors, raising the total available from $18 billion to $54.5 billion.

Paradoxically, the Yucca Mountain spent fuel repository in the USA is placed on hold by being removed from the federal budget, turning the existing reactor sites in the USA into de-facto spent fuel repositories. With five miles of tunnels, it cost $11 billion since 1983, to seal fission waste for an arbitrary Machiavellian determined period of 10,000 years, double the length of human civilization of 5,000 years.

Nuclear electricity users paid $33 billion in fees and interest since 1983 for its construction. The DOE yielded to the will of the opponents of nuclear energy, suggesting that storing the spent fuel onsite at nuclear plants can continue for another 50 years.

No discernible progress in recycling of the nuclear fuel so as to reduce its volume and burn the minor actinides produced in the once-through U^{235}-Pu^{239} fuel cycle is apparent. Other disposal sites and methods are proposed including recycling at a Yucca Mountain facility.

France is the only country in the world that recycles its own fuel with Belgium, Germany, the Netherlands, Switzerland and Japan sending their fuel to be recycled at the La Hague facility.

Regardless, the USA Department of Energy in June 2009, ceased preparation for a nuclear recycling program under the Global Nuclear Energy Partnership meant to deny nuclear energy as a dual use technology to unfavored nations while looking the other way on the activities of friendly ones, and formed a 15-member “blue ribbon commission” composed of primarily nuclear energy opponents to study the management of nuclear waste stalling progress for another 2 years.

Although uranium provides the USA with about 20 percent of its electricity, the US continues to depend on imports for almost 90 percent of the fuel. To extend the fuel burnup, it is suggested that the uranium pellets would have a BeO core that can sustain a temperature of 4,500 degrees F.

CREDIT CRISIS EFFECT

The credit crisis of 2008-2011, decrease in business activity, cost overruns, redirection of the available capital to wasteful security uses and military expeditions, deflation and debt retirement, and higher costs for materials and labor have burdened some of the early reactors being built this century.

One Progress Energy Florida plant's reactors cost doubled past its original $3.5 billion estimate to $7 billion. Florida Power and Light could have spent $9-12 billion for each of two reactors. Being refused a requested electricity rate hike, it shelved the project. In spite of a streamlined licensing process and standardized plant designs, 10-12 years are needed for project completion. In Europe and other parts of the world, the cost of a nuclear power plant is in the $5 billion range with a 5 year completion time.

The situation calls for the consideration of sustainable alternative that address the existing stalled state of the envisioned nuclear renaissance.

Yet, the expansion by these countries is starting from a low fraction of nuclear electricity contribution to their energy mix and is trying to catch up with the other industrialized nations.

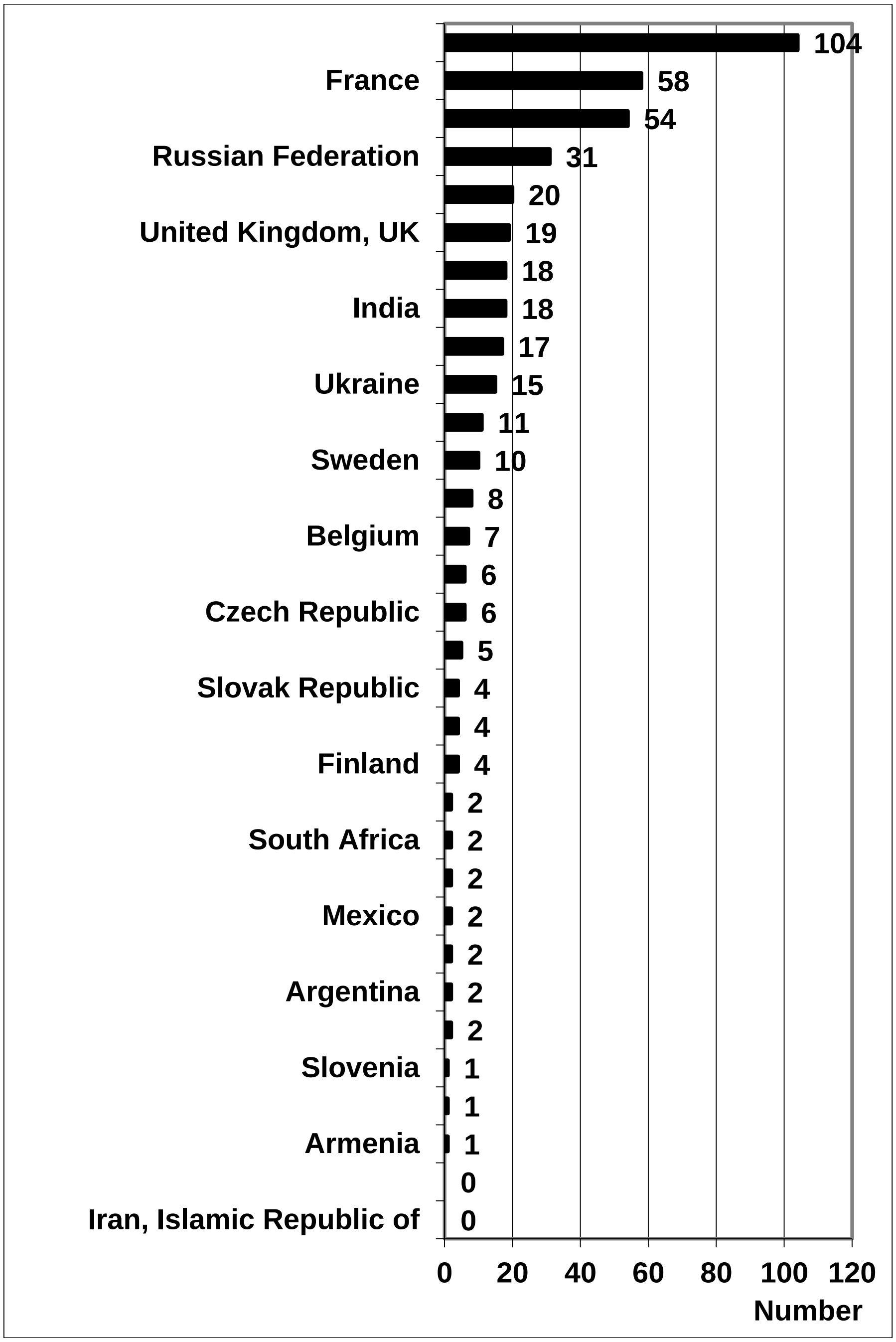

Figure 6. Number of power reactors in operation worldwide. Total: 448. Source: IAEA, 2011.

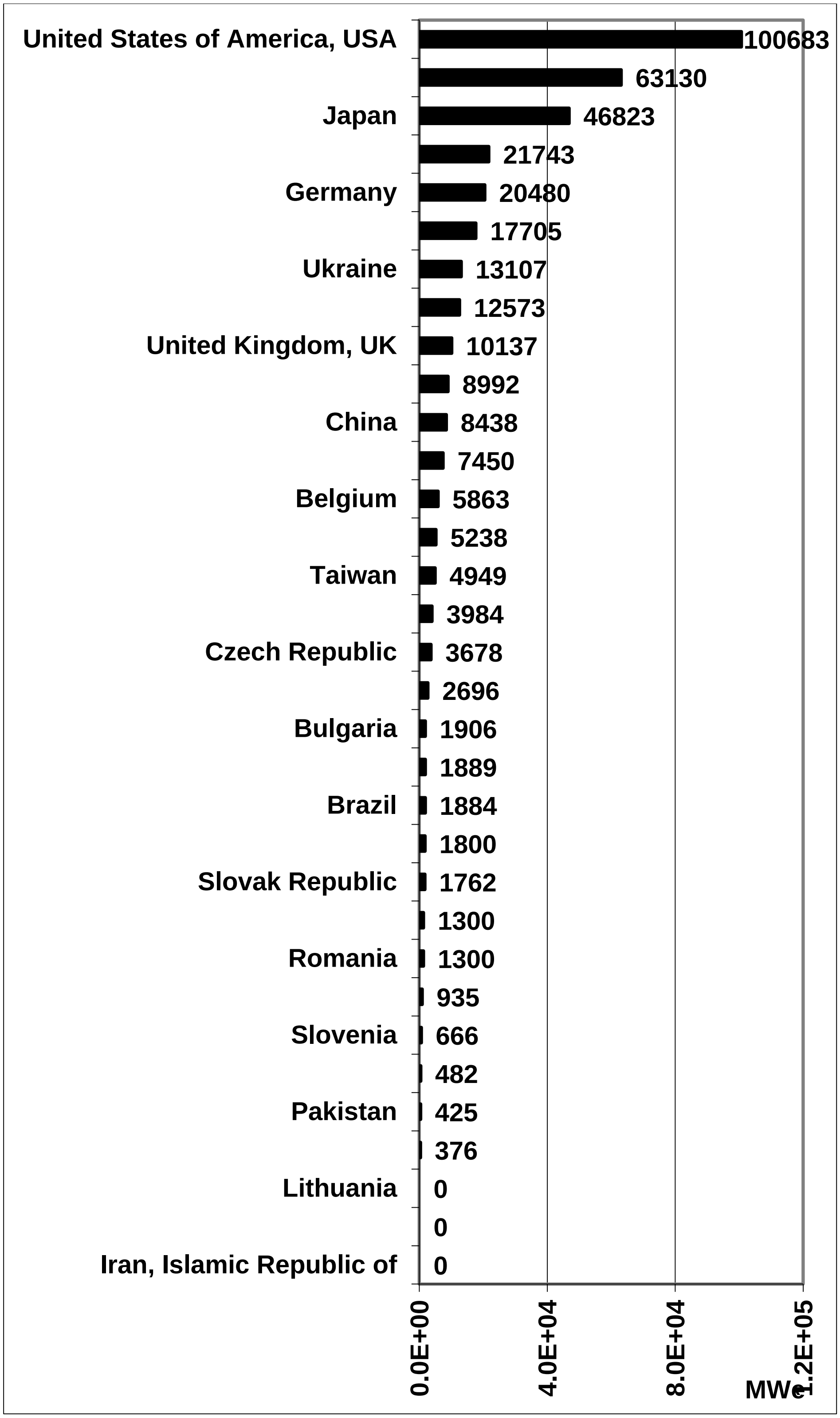

Figure 7. Nuclear power installed capacity worldwide. Total installed capacity: 375.343 GWe.. Data: IAEA, 2011.

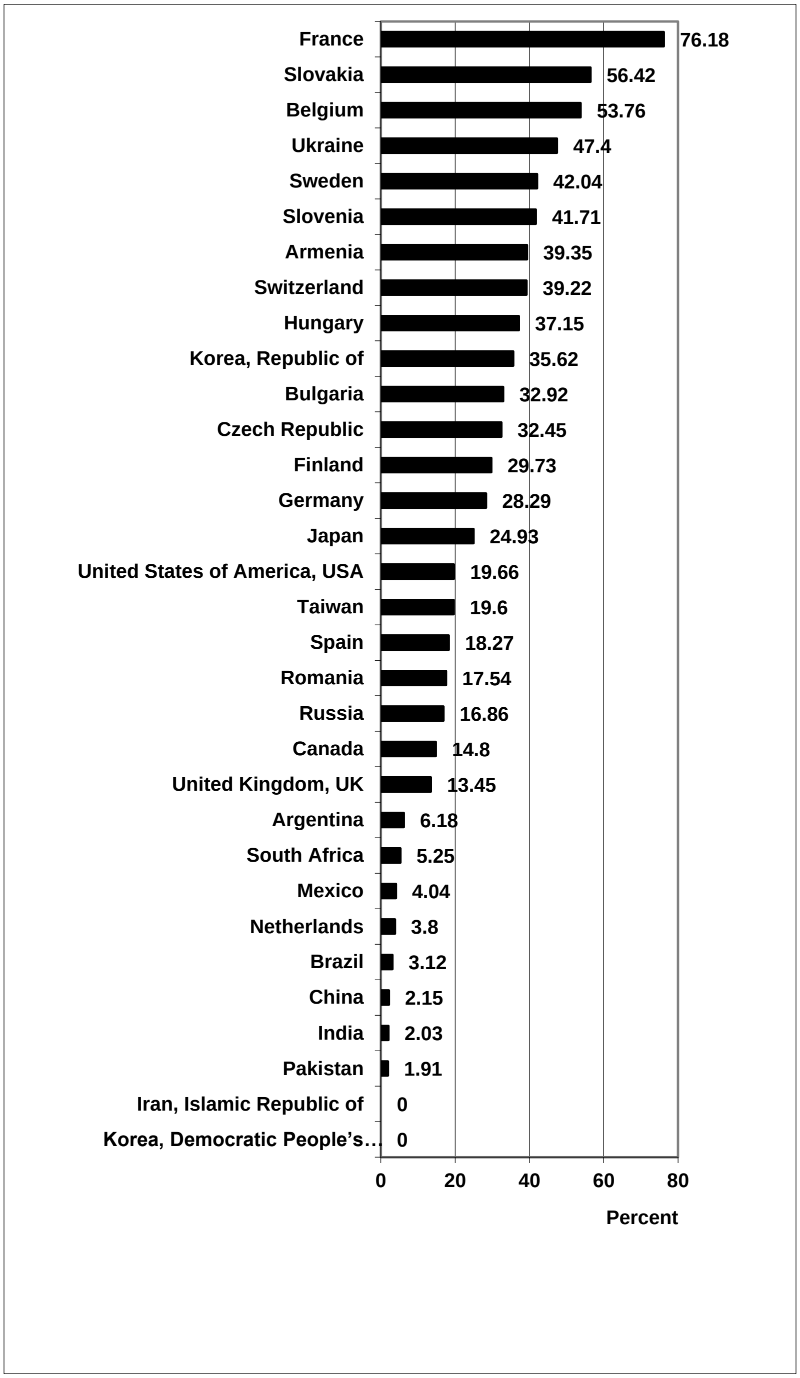

Figure 8. Nuclear share of electricity generation in different countries. Data: IAEA, 2011.

SPENT FUEL REPOSITORY

The Nuclear Waste Policy Act designates the Yucca Mountain site as the USA's SNF long term repository, requiring the DOE to pursue the licensing of the facility.

The Yucca Mountain spent fuel repository is placed on hold with the Department of Energy, DOE withdrawing its permit application, turning the existing reactor sites in the USA into de-facto 66 spent nuclear fuel repositories.

A panel of NRC judges, in June 2010, ruled that the DOE has no authority to withdraw the Yucca Mountain permit application. In a strange turn of events, the NRC has asked the DOE to overrule its own judges' decision.

No discernible action in recycling of the spent nuclear fuel so as to reduce its volume and burn the minor actinides produced in the once-through fuel cycle, is apparent.

Under new USNRC regulations casks storage of Spent Nuclear Fuel, SNF at nuclear power plant sites can be used for 60 years and perhaps up to 120 years, after the reactors are decommissioned.

According to the NRC:

> "If necessary, spent nuclear fuel generated in any reactor can be stored safely and without significant environmental impacts for at least 60 years beyond the licensed life for operation (which may include the term of a revised or renewed license) of that reactor in a combination of storage in its spent fuel storage basin and at either onsite or offsite independent spent fuel storage installations."

The NRC directed its staff to draft rules that allow onsite storage for more than 120 years.

The impasse calls for alternative fuel cycles such as the thorium fuel cycle that address the existing stalled state of the envisioned nuclear renaissance.

Figure 9. Yucca Mountain disposal site. Source: USDOE.

Figure 10. Onsite storage of Spent Nuclear Fuel in concrete silos at reactors sites.

NUCLEAR RENAISSANCE VISION

By 2006, no new nuclear plants have been built in the USA in more than 30 years, but that needs to change because of several trends:

1. Global energy demand is expected to keep growing by more than 50 percent over the next 20 years, according to the USA Energy Information Administration estimate.
2. Fossil fuels such as natural gas and petroleum are getting increasingly expensive.
3. Public support for nuclear power seems to be reborn. Polls conducted by the Nuclear Energy Institute in May 2005, found that 70 percent of the 1,000 people surveyed supported nuclear power.
4. The passage of a federal energy bill, signed into law on August 8, 2005, offering financial incentives, liability protections and research funding to the nuclear industry.
5. Some prominent and respected environmentalists, considering the threat of global warming, are accepting nuclear power as part of the future energy mix. The mainstream environmental community still remains opposed, but the defections mark a significant departure for a movement that was once fully united in opposition to nuclear power.

ENERGY BILL OF 2005

The 2005 energy bill includes provisions that should advance nuclear power in the next decades: a new test reactor for hydrogen production at the Idaho National Engineering and Environmental Laboratory (INEEL), an extension of industry funded liability protection for nuclear facilities and incentives to jump-start construction of some advanced design reactors.

This federal energy bill is expected to help jump start the nuclear power industry through four key provisions:

1. A 20 year extension of the Price Anderson Act, which provides liability insurance that indemnifies companies that design and build nuclear power plants.
2. An allocation of $1.2 billion to fund research on next generation nuclear power plants, including designs that would produce hydrogen as an energy carrier for transportation uses with fuel cell technology.
3. Up to $2 billion to offset the costs of regulatory or legal delays in the licensing and construction of new nuclear power plants. This includes up to $500 million each for the first two new plants, and up to $250 million for the third, fourth, fifth and sixth new plants to be built.
4. A production tax credit of 1.8 cents/kWh of energy produced for the first eight years of a new nuclear power plant's operations.

In his 2011 State of the Union address, President Barack Obama called for major investments in clean energy and set a goal of 80 percent of USA electricity to come from clean sources by 2035.

FORMATION OF NUCLEAR POWER CONSORTIA

The nuclear industry can point to several advances: existing plants are more efficient and cost effective, designs for the next generation of reactors makes them reliable and safe, standardized construction plans and a streamlined licensing process should help make nuclear power an attractive investment.

A consortium designated as NuStart Energy was organized in response to the 2005 USA Energy Bill and announced locations in 6 states as possible sites for new nuclear power plants. Four of the six states already house operating nuclear power plants. The sites, by location, are:

1. Scottsboro, Alabama:
The Bellefonte Nuclear Power Plant, an unfinished site owned by the USA government owned utility Tennessee Valley Authority.
2. Port Gibson, Mississipi: The Grand Gulf Nuclear Power Station, owned by the Entergy utility.
3. St. Francisville, Louisiana: The River Bend Nuclear Power Station, owned by Entergy.
4. Aiken, South Carolina: The Savannah River Site, a USA Department of Energy nuclear weapons laboratory.
5. Lusby, Maryland: The Calvert Cliffs Nuclear Plant, owned by Constellation Energy.
6. Oswego, New York: The Nine Mile Point Plant, owned by Constellation Energy.

The six sites chosen by NuStart are owned either by a consortium member or by the USA Department of Energy.

The consortium, hopes to work on two advanced plant designs. The four sites with operating power plants have the most comprehensive licensing basis, and the five sites housing power plants have the benefit of established transmission systems.

The consortium will evaluate the sites on 75 factors including seismic activity, availability of water and emergency preparedness issues. It is sending letters to state and local politicians and development leaders to determine what incentives they might offer to attract the two proposed plants.

The NuStart consortium does not appears to be worried about protests from environmental activists at the local level, but does expect some resistance from environmentalists at the national level.

The NuStart consortium consists of nine utilities, including Exelon, Entergy, and Duke Energy, as well as nuclear reactor manufacturers GE Energy, a unit of the General Electric-Hitashi Company, and the Westinghouse-Toshiba Electric Company, a unit of the British government-owned British Nuclear Fuel Limited (BNFL) Plc. GE is a parent in the joint venture that owns Microsoft-National Broad Casting system (MSNBC). In 2006 both GE and the Toshiba companies have presented bids to purchase the Westinghouse Company with Toshiba winning the bid.

Under the USA Department of Energy's Nuclear 2010 program, half of the estimated $520 million cost of the project would be shouldered by the Department of Energy and half will be paid by the consortium members.

The consortium expected to apply for licenses in 2008. Construction could then have begin in 2010 with completion in 2014.

LOAN GUARANTEES

In his $3.8 trillion budget plan for 2011, President Barack Obama called for boosting loan guarantees to triple from $18 billion during President George W. Bush administration to $55 billion to help jump-start construction of USA nuclear plants. This is similar to $60 billion devoted to renewable energy projects which are more favored to be without paying fees along the way for the loan guarantee.

In his January 26, 2010 State of the Union address, President Barack Obama urged the "building a new generation of safe, clean nuclear power plants in this country." His words marked a shift toward more public support for an industry that has brought just one new USA nuclear power plant online in 20 years.

Administered and pushed by the Department of Energy, the financing scheme would cover as much as 80 percent of the likely $7-10 billion-plus cost of designing, licensing and building each new USA nuclear reactor that receives a loan guarantee. The guarantees would extend up to 30 years.

In February 2010, President Barack Obama announced $8.3 billion in federal loan guarantees to help build 2 nuclear power plants in the state of Georgia to be built by Southern Company.

At President George Bush's behest, the Energy Policy Act of 2005 provided $13 billion in subsidies to the nuclear power industry for research, construction, operations and site cleanup, and it authorized the loan guarantees. The Department of Energy selected recipients for an initial round of $18.5 billion in guarantees.

Four projects at the top of the DOE's list for a first round, culled from 19 applications, all are facing squabbling among partners, cost overruns and reactor design difficulties.

COMPLETION OF UNFINISHED NUCLEAR POWER PLANTS

BELLEFONTE UNIT 1, ALABAMA

The Tennessee Valley Authority, TVA the nation's largest publicly owned utility, is spending $248 million in 2011 on next steps to complete the Bellefonte Nuclear Power Plant, some 36 years after work began at the Hollywood, Alabama, site.

Work began in 1974 on two 1,260 MWe Babcock & Wilcox Pressurized Water Reactors , PWRs Units 1 and 2 at Bellefonte, but construction was halted in 1988. An estimated $2.5 billion had been spent on the projects.

Work was suspended when the construction of Unit 1 was 88 percent completed and Unit 2 was 58 percent complete in response to decreased electricity power demand.

An estimated $2.5 billion had been spent on the projects. If Unit 1 is approved and built as planned, it would go online in 2018.

Figure 11. Tennessee Valley Authority, TVA Bellefonte Unit 1. Source: TVA

A 1,600-acre site encloses the Bellefonte 1,260 MWe Unit 1 reactor. The TVA determined that completing one of the two unfinished units at Bellefonte would be preferred over building a new Toshiba-Westinghouse AP1000 reactor there, or taking no action.

In a recently issued Final Supplemental Environmental Impact Statement on the generation options associated with Bellefonte, the utility will commit to spend up to $4.7 billion on the reactor.

Even though construction was halted several years ago, studies show new generation capacity will be needed by 2020, and nuclear energy provides power generation with no carbon emissions.

TVA has considered an option for Bellefonte including two AP1000 reactors, the first in the USA, as part of a NuStart Energy Development Consortium application for a new combined construction and operating license from the Nuclear Regulatory Commission, NRC.

In 2009, the NRC granted TVA's request to reinstate Bellefonte's original construction permits so TVA could better evaluate the engineering and economic feasibility of completing Units 1 and 2. Both units are now being maintained in construction-deferred status.

The reversal of a 2006 decision by TVA was complicated by rising material and construction costs and considerations of delays in certification of the AP1000. The project is about $1 billion less to finish the existing unit versus the AP-1000 and there is about a 12-month earlier completion with the existing reactor.

WATTS BAR 2 NUCLEAR PLANT

Along with designating $900 million for development of nuclear energy in 2011, TVA said it would spend $635 million toward completion of the Watts Bar 2 nuclear reactor, which is on schedule for completion by late 2012.

The utility proposes to replace 1,000 MWe of coal-fired power generation, representing 3 percent of its combined capacity, with generation from nuclear and natural gas plants.

Figure 12. Shoreham, finished but not started nuclear power plant, on Long Island, New York.

SHOREHAM POWER PLANT

The Long Island Lighting Company, LILCO Shoreham reactor on Long Island, New York was commissioned after its fuel was loaded, and the plant operated for only a few hours. The local authorities would not allow its operation and forced its shutdown, multiplying the decommissioning cost several times.

Figure 13. Satsop Washington Public Power Supply System, WPPSS utility unfinished Nuclear Power Plants, Gray Harbor County, Washington State.

Figure 14. Seabrook, New Hampshire unfinished unit to the left.

SEABROOK UNFINISHED UNIT

The construction and licensing of the Seabrook's power plant, was subject to an onslaught of objections both in the courts and demonstrations. Seabrook survived the attacks and received an operating license in October 1986.

Commercial operation was delayed until August 1990, and one of two reactor units was canceled and remains as an empty steel and concrete shell.

The host community is torn between the unappealing appearance of Unit 2 along New Hampshire's of initial marshland in its 17 miles coastline, and the energy production and tax benefits accruing from Unit 1.

SASTOP WASHIGTON PUBLIC UTILITY PLANTS

In the 1950s, the Washington Public Power Supply System (WPPSS), since renamed Energy Northwest, started a massive statewide nuclear power-plant construction project. Construction was halted mid-project as a result of design issues and cost changes. Four of the five plants were never finished. The fifth was the Columbia Generating Station, which is still in operation as of 2014.

The WPPSS Board of Directors stopped construction in 1982 because the projected cost for all the plants was going to be more than $24 billion instead of the original $16 billion estimate. This caused the agency to default on $2.25 billion in bonds, money that had already been spent on the scrapped power plants. At the time, it was the largest municipal debt default in USA history.

The total debt for the project is currently $5.4 billion, which includes the Columbia Generating Station, according to Energy Northwest. The debt is owned by Bonneville Power Administration, a Government Agency, because they were the original backers on the bonds. That debt is being paid by ratepayers through their electricity bills.

The Satsop, Washington Public Power Supply System, WPPSS Nuclear Power Plants units 4 and 5 were voted down on July 12, 1976 by the Seattle city council, on the basis of costs and a non-existing need of additional power production.

WPPSS, is an agency made up of publicly owned utilities in the Northwest region. It launched the construction of two nuclear power plants in Hanford and Satsop, Washington. The member utilities were invited to sign up for portions of the power generated in exchange for shares of the cost.

Planners expected that the demand for electricity would continue to double every 10 years as it had done in the past, hence the need for nuclear power. WPPSS cancelled construction of all the plants because of cost overruns and because the projected load growth did not materialize. The agency defaulted on $2.25 billion in bonds sold for the units 4 and 5.

NEXT GENERATION POWER PLANTS PROJECTS

Figure 15. Calvert Cliffs Nuclear Power Plant in Lusby, Maryland, south of Washington DC. Photo: Constellation Energy.

As of 2010, these projects were under serious consideration in the USA:

1. Southern Nuclear Company's Plant Vogtle Units 3 and 4 Reactors, Augusta, Georgia

This an expansion plan at the Vogtle site in Waynesboro, 45 Minutes south of Augusta, Georgia, which currently operates two reactors with a total of 2,430 MWe of capacity. The plant's owners want to nearly double that by adding a pair of the Westinghouse-Toshiba AP-1000s. In addition to the hurdles faced by the reactors, the project is the subject of a lawsuit over its financing. Southern Company was awarded an $8.3 billion loan guarantee from the Department of Energy.

The "Next Generation" of nuclear plants, represented by these two units, includes two major improvements: the use of passive safety systems and a reliance on digital control systems. The latter represents a gigantic leap in modernization and a fundamental change in control of the plant.

About 1,500 employees are constructing the foundations and building a modular assembly building is in progress.

The USA NRC is expected to issue a license for the building and operation of these two plants in 2011.

Figure 16. Preliminary construction at the Southern Company Vogtle 3 and 4 reactors site. Two holes in the ground as large as 5 football fields have already been excavated. Source: Southern Nuclear Company.

Figure 17. Active construction at the Vogtle units 3 and 4 reactors. Source: Southern Nuclear Company.

Figure 18. Foundations for the Vogtle units 3 and 4. Source: Southern Nuclear Company.

Figure 19. Toshiba-Westinghouse Next Generation first AP1000 reactor under construction since March 2009 at Sanmen 1, China by Shandong Nuclear Power Company. Reactor is slated for operation in 2013. Photo: Westinghouse Electric.

2. Virgil C. Summer 2 and 3 Station, Scana Corporation, South Carolina Electric and Gas

Preliminary work has begun at this site although one of the partners, municipal Santee Cooper is looking for selling part of its share.

The Virgil C. Summer Station nuclear power plant proposal aims at adding two 1,117 MWe reactor units to its Fairfield County, South Carolina site which currently operates a single reactor. The new reactors would be Westinghouse-Toshiba AP-1000s, not in operation anywhere yet and under new scrutiny from the USA Nuclear Regulatory Commission over the design of the shield building and other issues. The station's owner warned that the projected cost of the reactors could be $500 million higher than expected.

3. Calvert Cliffs 3, Maryland Project

This project is on hold as the lead partner for this project withdrew in October 2010 and the other partner is seeking a replacement. Negotiations broke down over a dispute about what fee the builders should pay to the Federal Government to compensate the Treasury Department for the risk it is undertaking in providing loan guarantees. One of the partners, Constellation Energy of Baltimore gave up. The other partner, Electricité de France has not located another investor.

A plan to add a 1,600 MWe reactor at the Calvert Cliffs Nuclear Power Plant, which operates two reactors near Lusby, Maryland., with a combined output of 1,750 MWe. The plant's owner has chosen France's Areva Evolutionary Power Reactor, EPR design. The design has not yet received certification from the USA Nuclear Regulatory Commission, NRC.

The first installation of that reactor in Okiluoto, Finland By Areva is running two to three years behind schedule, with cost overruns raising the price from $4.4 billion to $6.5 billion.

The Calvert Cliffs plant is one of six sites being considered for a new advanced reactor by the NuStart consortium. When built, it would be the USA's first new commercial reactor since the 1979 Three Mile Island accident.

It will cost $520 million to develop a new reactor design and submit the first two plants licensing applications. A new plant would start operations in 10 years at the earliest.

At the local level in Calvert County, leaders are supportive of an expansion of the plant. The county's economic development department anticipates that a new reactor at Calvert Cliffs could bring in 250 to 400 permanent jobs as well as more than 2,000 construction jobs. The existing plant pays more than $15 million in annual property taxes to the county.

4. South Texas Project, STP 3 and 4, Texas

The developer is attempting to find a purchaser of its future production of electricity before the start of construction. A market for the power is not found because of natural gas being currently cheaper as an alternative and the availability of excess generating capacity.

A partner in the project, CPS Energy, a municipal utility serving San Antonio, Texas, inspired by rising costs, decided to withdraw from the project. It settled with the other partner, NRG of Princeton for 7.6 percent ownership in exchange for its investment. NRG looked for partners to replace CPS. The Tokyo Electric Power Company, Tepco, would take a 10 percent stake if the project gets a loan guarantee from the DOE. Before the project could move forward, it needed to identify more investors or utilities that would sign contracts to purchase the power for 10-20 years or more beginning in 2017.

The Japanese Tepco utility that operated the Fukushima Daiichi plant could not provide the promised capital anymore. Uncertainty about federal loan guarantees for the project suggests a delay and even a cancellation

The South Texas Project, STP bid to become the nation's largest nuclear power plant by adding a pair of reactors to its Matagorda County facility for a total generating capacity of more than 5,000 MWe or enough electricity to supply the needs of about 2 x 10^6 homes and businesses. The STP's plans are threatened by a courtroom squabble among its partners over the estimated cost of the expansion, which has skyrocketed from $6 billion to $17 billion. The Texas project is the only proposal on the loan guarantee list that calls for using the General Electric-Hitachi's Advanced Boiling Water Reactor, ABWR currently in operation.

Other projects include:

Burke County, Georgia Project

An amount of $8.3 billion was earmarked for the construction of two units in Burke County, Georgia. This would be an expansion of an existing facility near Augusta, Georgia operated by Atlanta-based Southern Company.

Callaway Plant, Missouri Ameren UE

This would be a unit adjacent to the existing Callaway plant operated by Ameren UE. It would be identical to the Constellation Energy Calvert Cliffs unit 3 in Maryland.

The project is on hold after the Missouri legislature did not allow the company to collect funds for the project from users before the plant is finished.

SMALL IS BEAUTIFUL INTEGRAL PWR DESIGNS

MODULAR INTEGRAL COMPACT UNDERGROUND REACTOR, BABCOCK AND WILCOX

INTRODUCTION

Babcock & Wilcox's, B&W mPower design is a 125 MWe design, that was introduced in 2009. The Tennessee Valley Authority, TVA is partnering with B&W on the mPower project. Designed to be installed underground, the plant incorporates many features of Naval reactors. B&W has long been a major contractor for naval reactors.

The coolant outlet temperature is 330 ^{o}C.

B&W plans a 2012 design application at the NRC. The engineering and construction company Bechtel Corporation recently signed on to partner with B&W on the mPower project. The alliance is designated as “Generation mPower.”

DESCRIPTION

An integral compact nuclear reactor that is smaller in size than a rail car and that costs one tenth the cost of a conventional plant is emerging as a contender in the resurgent global nuclear power industry [1]. These small power reactors designs benefit from the accumulated experience in the design and operation of naval propulsion reactors with which they share the integral and small power features.

Because they could be water-cooled or air-cooled, such compact reactors would not have to be located near large sources of water, voiding a limitation on the use of large reactors that require millions of gallons of water each day for cooling purposes.

This opens up parts of the arid USA West and other arid regions of the world for nuclear development. Underground brackish water supplies that are otherwise unusable, could be desalinated into fresh water for agricultural and municipal use [2].

An attractive feature of the prospect is that utilities could start with a few reactors and add more units as needed. By contrast, with large reactor units, utilities have what is called in the industry a "single-shaft risk," where billions of dollars are tied up in a single plant.

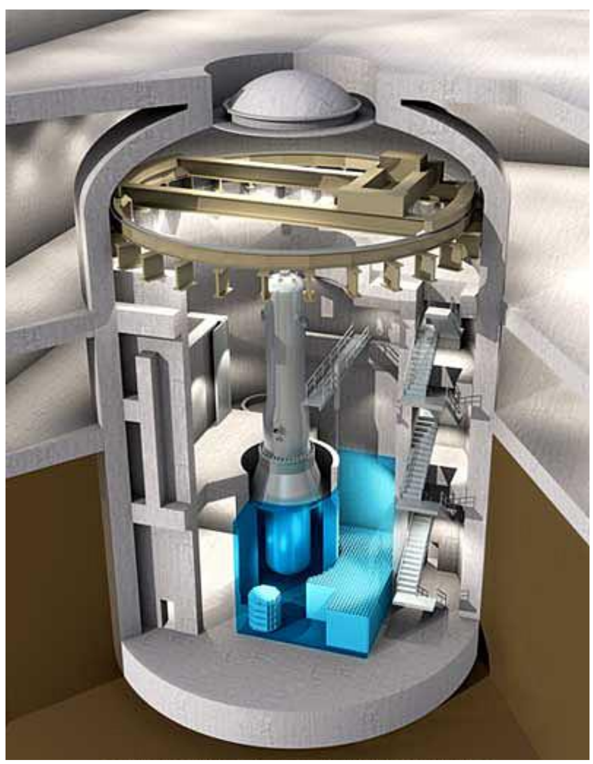

Figure 20. Schematic of modular mPower compact underground reactor. Source: Babcock & Wilcox.

Yet, another advantage is that these reactors will store all of their waste on each site for the estimated 60-year life of each reactor. Once on site, each reactor would be housed in a two-story containment structure that would be buried beneath the ground for added security. They would remain on-line round the clock, stopping to refuel every 5 years instead of every 18 - 24 months, like existing reactors.

Three large utilities, the Tennessee Valley Authority, First Energy Corp. and Oglethorpe Power Corp., signed an agreement with Babcock & Wilcox a subsidiary of the construction and Engineering Company: McDermott International Inc., committing to get the new reactor approved for commercial use in the USA.

The reactor design possesses the following main characteristics:

1. An Integral nuclear system design,
2. The use of Passive Safety systems,
3. It operates on a 4 ½ year refueling interval,
4. It uses a 5 percent U^{235} enriched fuel,
5. It is housed in a secure underground containment system,
6. It incorporates a spent fuel pool capacity for the 60 years expected lifetime of the facility.

The Babcock & Wilcox Company (B&W) plans to deploy its B&W mPower reactor as a scalable, modular, passively safe, advanced light water reactor system. The design, with its scalable, modular feature, has the capacity to provide 125 - 750 MWe or more for a 5 year operating cycle without refueling, and is designed to produce near-zero emission operation.

A newly formed entity, B&W Modular Nuclear Energy, LLC, leads the development, licensing and delivery of B&W mPower reactor projects.

The Babcock & Wilcox's Company roots go back to 1867 and it has been making equipment for utilities since the advent of electrification, furnishing boilers to Thomas Edison's Pearl Street generating stations that brought street lighting to New York City in 1882. Based in Lynchburg, Virginia, the company has been building small propulsion reactors since the 1950s. In addition to reactors for the USA Navy submarines and aircraft carriers, it built a reactor for the USS NS Savannah, a civilian commercial vessel. It is now moored as a floating museum in the Baltimore harbor. It also built eight large reactors, , including one for the two units Three Mile Island plant.

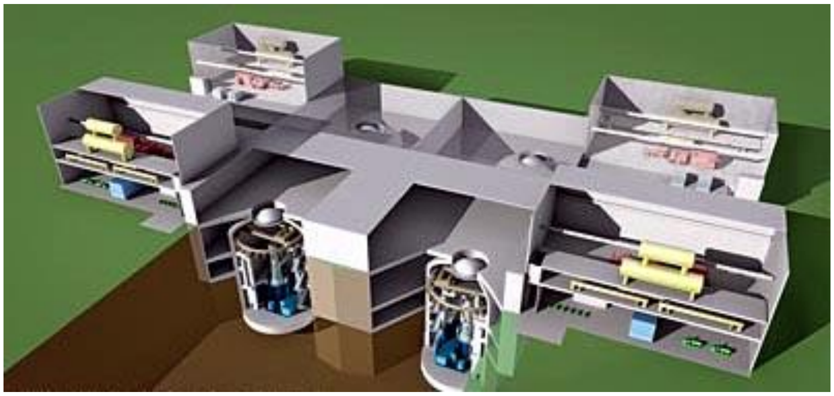

Figure 21. Compact Underground Reactor in a 4 units 500 MWe configuration of 125 MWe each. Source: Babcock & Wilcox.

Figure 22. Integral configuration of core and steam generator within the reactor vessel of the modular reactor. Source Babcock & Wilcox.

MAIN FEATURES

The compact modular Babcock & Wilcox reactor can generate only 125 - 140 MWe of power. This is about 1/10 the standard capacity of the larger 1,000 MWe capacity.

The USA utilities are betting that these smaller, simpler reactors can be manufactured quickly and installed at potentially dozens of existing nuclear sites or replace coal-fired plants that may become obsolete with looming emissions restrictions.

The emerging interest in small reactors illustrates a growing unease with the route that nuclear power has taken for half a century. The first commercial reactor built in the

USA in 1957 at Shippingport, Pennsylvania, had only a 60 MWe capacity. Three decades later, invoking the economies of size, reactors had grown progressively bigger, ending up at about at the 1,000 MWe of capacity.

A standard modular reactor unit generates 125 MWe of power. It is 75 feet in height and 15 feet in diameter.

The core assembly consists of 69 fuel assemblies to be replaced as a whole after 4-5 years. It is surrounded by an underground containment dome that encloses the nuclear reactor and steam generator.

The Steam Generator uses an integral technology adopted from naval reactors technology. It is not a separate component like in conventional reactor designs. It is instead incorporated into the reactor's core.

A crane is used to replace the core assembly during refueling or move any heavy components that need replacement. A water pool surrounds the reactor vessel to store the unused as well as the spent fuel assemblies for the 60 years lifespan of the plant.

The scalable design offers flexibility so that multiple reactor modules can be aggregated to support a local utility requirements and infrastructure constraints.

TECHNICAL DESCRIPTION

The optimized Advanced Light Water Reactor (ALWR) of the Pressurized Water Reactor (PWR) type, is presented as a Generation III++ nuclear technology that can be certified, manufactured and operated within the existing USA regulatory domestic industrial supply chain and utility operational infrastructure.

The modular and scalable design of the B&W mPower reactor allows B&W to match the generation needs with the proven performance of existing light water reactor technology. Each B&W mPower reactor that is brought online will contribute to the reduction of approximately 57 million metric tons of CO_2 emissions over the life of the reactor. Its technical specifications encompass:

1. Flexibility and scalability to local power needs with 1-10 multi units plants,
2. Integrated design reactor modules,
3. Accepted ALWR, PWR concepts,
4. The use of a Passive safety system,
5. Shop manufactured with no on-site Nuclear Steam Supply System (NSSS) construction,
6. A short 3-year construction cycle,

The Integral simplified NSSS includes:

1. An internal steam generator,
2. No need for safety-grade backup power,
3. No need for an external pressurizer,
4. The use of conventional core and standard fuel,
5. No credible large pipe break Loss of Coolant Accident (LOCA),

Its offers simplified operations and maintenance through:

1 A 4 ½ year replacement core design,
2. Sequential partial-plant outages providing a high capacity factor,
3. A standardized balance of plant.

INNOVATIVE AND SECURE REACTOR, IRIS, WESTINHOUSE

The Westinghouse Innovative and Secure Reactor, IRIS design was originally conceived in 2006 as a 325 MWe power plant but subsequently was resized to 100 MWe.

The containment is a conventional above-ground steel vessel. The plant is designed to be refueled every four years and uses conventional enriched uranium fuel.

The steam temperature at outlet is 330 ^oC. The developers, an international consortium, are expected to apply for design certification at the NRC in 2012.

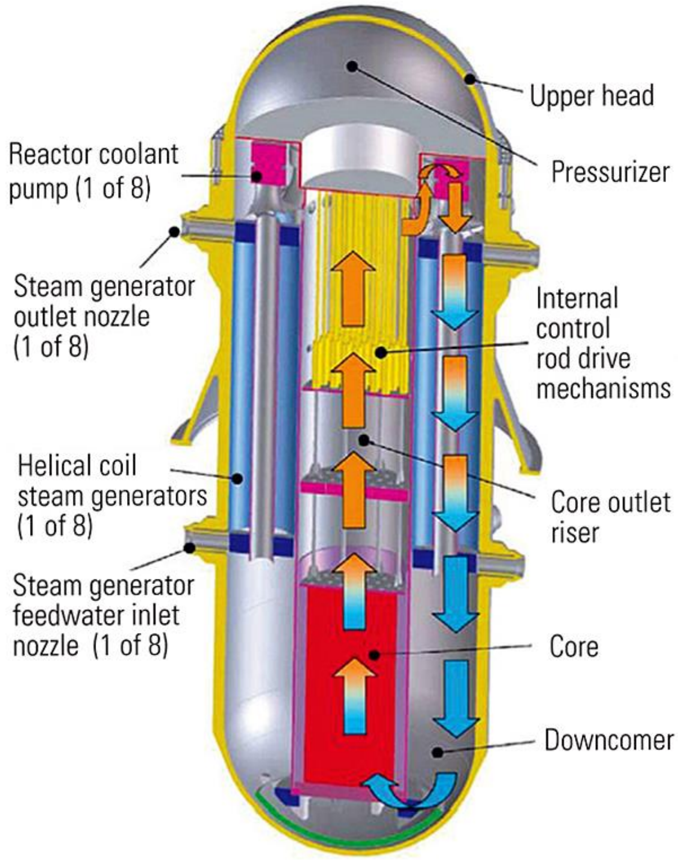

Figure 23. Innovative and Secure Reactor Integral reactor design.

NUSCALE POWER SMALL REACTOR DESIGN

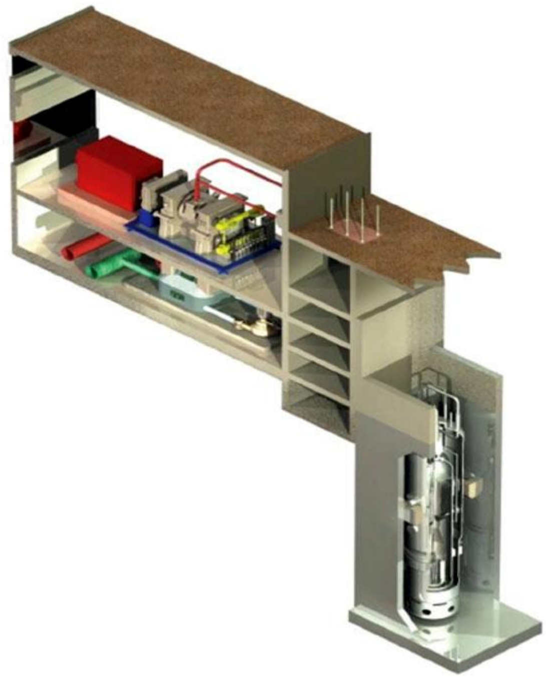

Figure 24. NuScale small 45 MWe reactor design.

The NuScale Power company has a 45 MWe design based on work done by Oregon State University for the Idaho National Laboratory, INL early in this century. The NuScale reactor operates using natural circulation. No pumps are needed to circulate water through the reactor.

Kiewit Power Constructors of Omaha, Nebrasca, is a NuScale partner. NuScale Power is a 2007 startup company.

The integral reactor vessel would be installed in a water-filled underground pool, constituting the reactor containment. The coolant outlet temperature is 300 ^{o}C. NuScale expects to submit the design certification documents to the NRC in 2012.

POWER REACTOR INNOVATIVE SMALL MODULAR, PRISM, GE-HITACHI

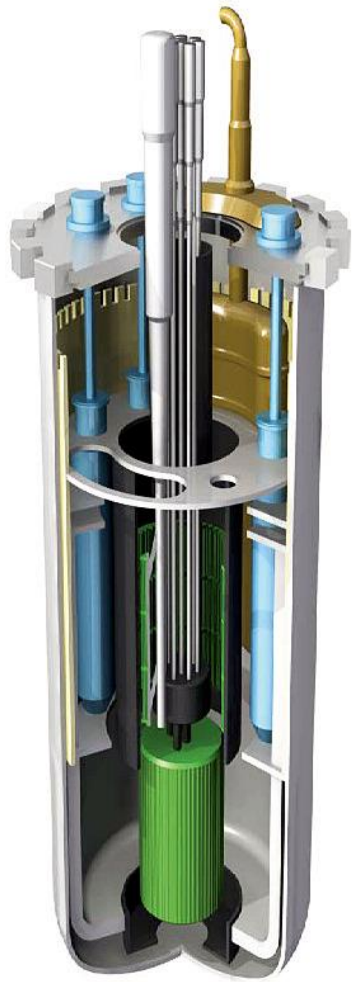

Figure 25. GE-Hitachi Power Reactor Innovative Small Modular, PRISM small Na cooled Fast reactor concept. Source: GE-Hitachi.

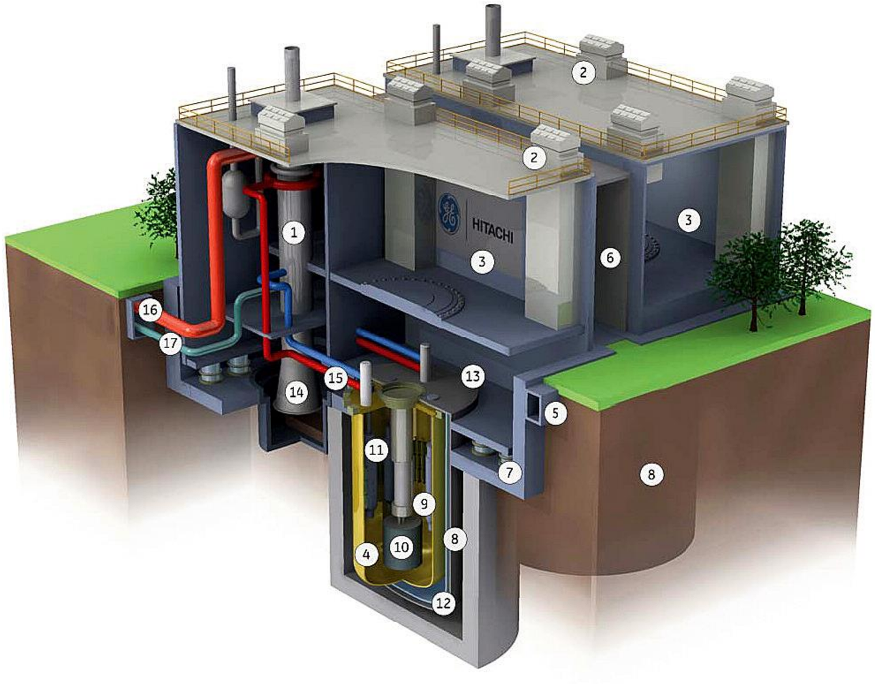

Figure 26. GE-Hitachi PRISM power block. Source: Ge-Hitachi.
1. Steam generator, 2.Reactor Vessel Auxiliary Cooling System, RVCAS stacks (8), 3. Refueling Enclosure building, 4. Vessel liner, 5. Reactor protection system modules, 6. Electrical equipment modules, 7. Seismic isolation bearing, 8. Reactor modules (2) 311 MWe each, 9. Primary electromagnetic pump (4 per module), 10. Reactor core, 11. Intermediate heat exchangers (2), 12. Lower containment vessel, 13. Upper containment building, 14. Sodium dump tank, 15. Intermediate heat transfer system, 16. Steam outlet piping to turbine, 17. Feedwater return piping.

GE Hitachi Nuclear Energy, GEH next evolution of the Na cooled reactor technology is the Power Reactor Innovative Small Modular, PRISM reactor concept.

The use of Na as a coolant allows for a fast neutrons spectrum in the core allowing breeding; hence a long time between refuellings.

In addition, the hard neutron spectrum fissions the transuranic elements produced in the U-Pu fuel cycle, converting them into shorter lived fission products. This produces useful energy as well as reduces the volume and complexity of the U-Pu cycle waste disposal problem.

The concept can also be used for consuming the transuranics in used nuclear fuel from water cooled reactors.

Sodium-cooled reactors enjoy a safety aspect of operating at low pressure compared with light water cooled reactors.

The PRISM reactor employs passive safety design features. Its simple design, allows factory fabrication with modular construction and ultimately lower costs.

Passive core cooling is used enhancing the reactor’s safety. The residual or decay heat is passively released to the atmosphere with the elimination of active safety systems.

Electromagnetic pumps without moving parts are used, eliminating valves and motors used in other nuclear island designs.

The standardized modular design allows for an expedited construction schedule due to pre-licensed design, and factory fabrication. PRISM has a referenced construction schedule of 36 months.

A single PRISM power block generating 622 MWe the same amount of electricity generated in the USA through conventional sources would reduce greenhouse gas emissions by an amount equivalent to taking 700,000 cars off the road while at the same time offering the possibility of acting as an actinides burner consuming LWRs used nuclear fuel.

SUPER SAFE, SMALL AND SIMPLE: 4S REACTOR

The 4S reactor would be installed underground, and in case of cooling system failure, heat would be dissipated to the earth as a heat sink. There are no complicated control rods to move through the core. Reflector panels around the edge of the core control the number of reflected neutrons and hence the power level, startup and shutdown.

The modular reactor would be factory constructed and delivered to the site on barge. Its components are small enough to be delivered by truck or helicopter. The 10 MWe would cost 2,000 $/kWe or $20 million. The reactor would require minimal maintenance over its 30 years lifetime. The electrical power plant would require the same number of employees as diesel powered plant.

The design is described as inherently safe. It uses liquid sodium at atmospheric pressure, not highly pressurized water, to extract the heat away from the core.

Sodium allows the reactor to operate about 200 degrees hotter than most power reactors increasing its thermal efficiency, but still keep the coolant depressurized. Light water reactors operating at high pressure could lose their pressurized coolant through flashing if suddenly depressurized as a result of a pipe rupture or leak.

The design uses uranium enriched to 20 percent in U^{235} and would generate power for 30 years before decommissioning.

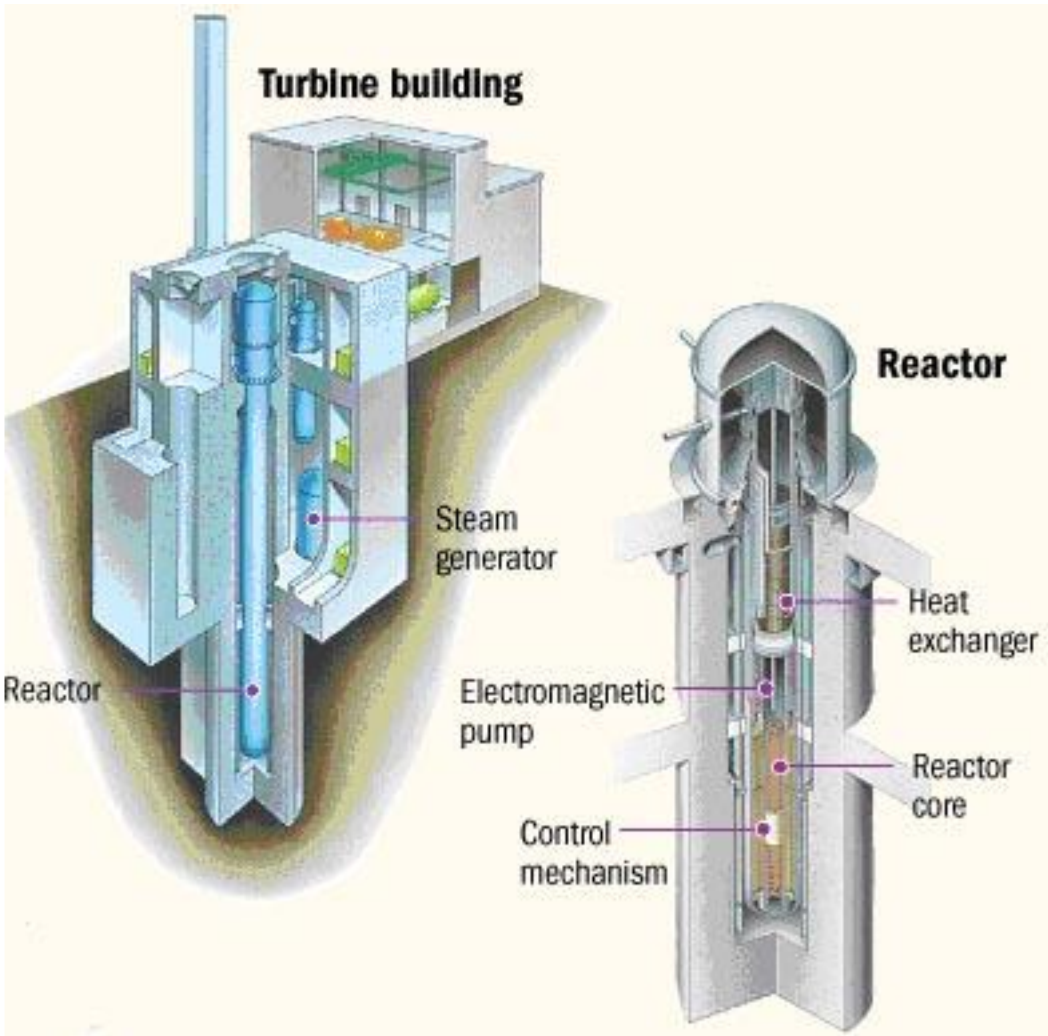

Figure 27. 4S Toshiba reactor configuration.

The 4S is designated as a nuclear battery. The power comes from a core of non-weapons-grade uranium about 30 inches in diameter and 6 feet tall. It would put out a steady stream of 932 degree Fahrenheit heat for three decades but can be removed and replaced like a flashlight battery when the power is depleted.

The reactor core would be constructed and sealed at a factory, then shipped to the site. There it is connected with the other, non-nuclear parts of the power plant to form a steel tube about 70 feet long with the nuclear core welded into the bottom like the eraser in a pencil. The assembly is then lowered into a concrete housing buried in the ground, making it as immune to attack or theft as a missile in its silo.

The reactor has almost no moving parts except for a magneto-hydro-magnetic pump and doesn't need many operators. The nuclear reaction is controlled by a reflector that slowly slides over the uranium core and keeps it in a critical condition.

Because of its design and small size, the reactor cannot overheat or melt down. The nuclear reaction heats liquid sodium in the upper portion of the reactor assembly. It circulates by convection, eliminating pumps and valves that need maintenance. The water coolant liquid extracts the heat from the primary Na coolant and does not activate. Because the reactor assembly is enclosed in a thick steel tube, it will withstand earthquakes and floods.

Liquid sodium eliminates corrosion, which is a possible cause of light water nuclear power plant accidents. The probability of radioactive material leakage for this system would be low.

TECHNICAL SPECIFICATIONS

The 4S reactor design has been described as a nuclear battery. The plant is a small, sodium cooled fast reactor with a rather technologically advanced, compact steam turbine secondary system. Though it is based on sound engineering design work dating back to 1988, there are some areas where the designers and manufacturers will be pressing the boundaries of the known in terms of chemistry, materials, equipment reliability and fluid flow.

The core heat source for this plant is quite compact; it is only about 0.7 meters in diameter and about 2 meters tall. This section of the plant would be at the bottom of the 30 meter deep excavation inside a sealed cylinder, a location that helps to provide the driving force needed for natural circulation cooling and that provides an impressive level of nuclear material security. The active core material is a metallic alloy of uranium, plutonium and zirconium. The material has been extensively tested but it has not been commercially produced and used as a reactor fuel.

Table 3. Specifications of the 4S reactor design.

Electrical output	10 MWe
Thermal output	30 MWth
Core Lifetime	30 years
Fuel	Metallic U-24Pu-10Zr
Primary electromagnetic pumps	2, serial
Secondary electromagnetic pumps	4, parallel
Intermediate heat exchanger tube length	2.6 m
Steam generator type	Once through, Double wall tube, helical coil
Seismic isolation	Horizontal

The 30 year lifetime for the core is achieved through a variety of mechanisms. The core is a metallic alloy cooled by sodium and the overall reactivity is controlled through the use of a movable reflector instead of neutron absorbing control rods. Because of these features, which differ from those of conventional water cooled reactor technology, more of the neutrons that are released by fission either cause a new fission or are absorbed by fertile materials like U^{238}. When fertile materials absorb neutrons, they become fissile and useful as fuel the next time that they are struck by a neutron. It is unclear from available technical materials whether or not the 4S actually produces more fuel than it uses, that is, whether or not it is a breeder reactor, but it is clear that the efficient use of neutrons for converting non fuel materials into fuel materials helps to increase its projected 30 years lifetime.

A hexagonal core barrel was adopted and the reflectors were arranged at the position near the fuel assembly, as a result, a relative increase in the reflector worth was achieved. Additionally, the required reflector worth was decreased by adopting a fixed absorber.

A loop type cooling system was adopted for the miniaturization of the reactor vessel and the physical superiority reduction of the nuclear reactor system. The cooling system was designed as one loop, and composed of the integrated equipment that included the primary and secondary electromagnetic pumps (EMPs), intermediate heat exchanger (IHX) and steam generator (SG).

SAFETY ASPECTS

The safety of the plant is achieved by maintaining a negative temperature coefficient of reactivity throughout the life of the core, and by providing sufficient natural circulation and heat removal capabilities to prevent overheating the core. A negative temperature coefficient of reactivity means that an increase in core temperature will cause a decrease in core power. If the temperature increases too much, the core will shut itself down.

A shutdown reactor still produces heat from the decay of radioactive materials, so there must be some mechanism provided to remove the generated heat. That is the job of the natural circulation and heat removal characteristics.

The use of sodium cooling contributes to the heat removal ability because it is a liquid over a wide range of temperatures, even if the cooling system is kept at atmospheric pressure. In water cooled reactors, which are often required to maintain pressures of 2000 psi, a loss of pressure can be a problem because the cooling medium will flash from a liquid to a gas, which has a much lower ability to remove heat. Since the major possible cause of a pressure loss is a cooling system leak, the hot high pressure water also implies the need for a very strong and pressure tight secondary containment system. The need to maintain a high pressure drives many of the design features and operating procedures for light water reactors; liquid metal cooling changes the equation and shifts some of the concern away from pressure maintenance.

Higher quality steam than is available in a light water reactor because higher coolant temperatures are readily achievable. The system will produce steam temperatures on the order of 500 degrees C or 932 degrees F, which is considerably higher than the 260 degrees C or 500 degrees F temperatures available in conventional water cooled reactors. Higher temperature steam improves thermodynamic efficiency and allows the production of more power per unit size of machine.

The small fast reactor 4S has been under development in Japan since 1988. The core of the 4S doesn’t receive severe damage under ATWS or Anticipated Transient Without Scram (ATWS) accidents because of its negative reactivity coefficients leading to a passive reactor shutdown under accident conditions. The core can be cooled with the decay heat removal system or DHRS using the natural circulation force under the PLOHS or Protected Loss Of Heat removal System (PLOHS) postulated accident event.

It is thought that this small fast reactor can contribute to a multipurpose utilization of nuclear power as an electrical power supply, heat supply, and desalting of seawater, in remote regions like islands where the power transmission infrastructure cannot be maintained.

HYPERION POWER MODULE

Hyperion Power is a Denver, Colorado based private company formed to commercialize a small modular nuclear reactor designed by Los Alamos National Laboratory, LANL meant for controlling fissile nuclear material in a transportable, yet nonproliferation context.

The Hyperion Power Module was originally designed to provide electricity and steam for the mining and refinement of oil shale and oil sands but they can be utilized for any number of mining and industrial applications. The 25 MW units are contemplated to provide power for subdivisions, mining operations, military bases, hospitals, airports, desalination plants, and even cruise ships.

The battery module would provide significantly less expensive power, at $3-5 per million BTU instead of the current $9-14 per million BTUs. They can reduce the cost of extracting and refining oil shale and tar sands and make these efforts worth the capital investment to jump-start shale operations and improve the cost-efficiency of existing oil sands facilities.

The units can play a "game-changing" role in providing power for permanent bases in the USA and around the globe, especially in remote locations independent of the local, often more fragile and vulnerable, public utility.

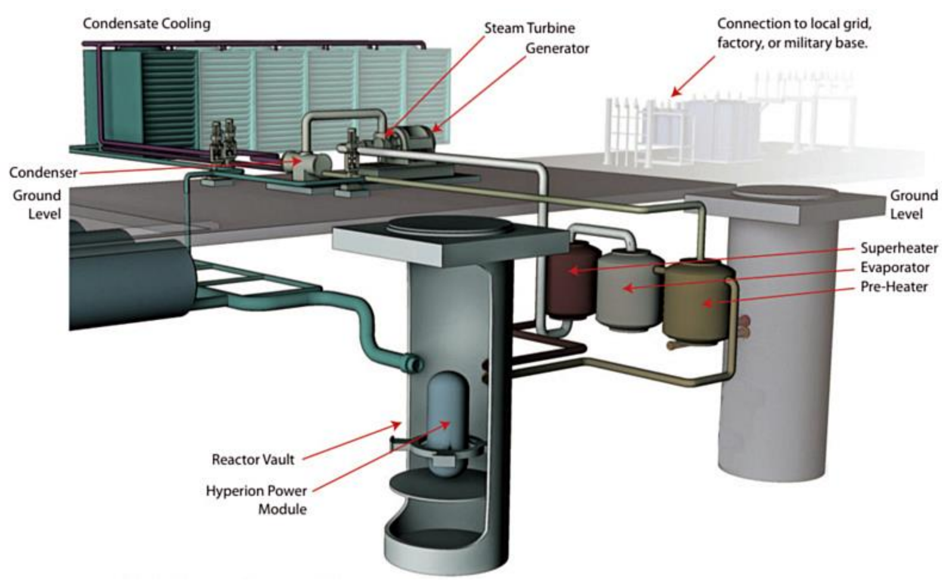

Figure 28. Hyperion Power Module with two 25 MWe units. Source: Hyperion Power.

Table 4. Technical Specifications of the Hyperion Power Modules.

Reactor power	70 MWth
Electrical output	25 MWe
Lifetime	8 –10 years

Size	1.5 m x 2.5 m
Weight	<50 tons
Structural material	Stainless Steel
Coolant	PbBi
Fuel composition	Stainless steel clad, uranium nitride
Fuel enrichment	< 20 percent U^{235}
Refuel on site	No
Sealed core	Yes
Passive shutdown	Yes
Active shutdown	Yes
Transportable	Yes, intact core
Factory fueled	Yes
Safety and Control Elements	Two redundant shutdown systems and reactivity control rods

The Hyperion Power Module has the following characteristics:

1. Transportable: Unit measures about 1.5m wide x 2.5m tall and fits into a standard fuel transport container to be transported by ship, barge, rail, or truck. The modular design allows for easy and safe transport.
2. Sealed Safe and Secure Core: The core would be factory sealed without need for in-field refueling with a closed fuel cycle. The unit is to be returned to the factory for fuel and waste disposition.
3. Safety: The system would prevent accidents through a combination of inherent and engineered features. It possesses an inherent negative feedback that keeps the reactor stable and operating at a constant temperature. The module is sited underground. It is proliferation resistant, never to be opened once installed.
4. Operational Simplicity: Operation is limited to reactivity adjustments to maintain a constant temperature output of 500^{o}C. It is meant to produce power for 8-10 years of operation.
5. Minimal In-Core Mechanical Components: The operational reliability is greatly enhanced by the reduction of multiple moving mechanical parts in the core.
6. Isolated Power Production: The electric generation components requiring maintenance are completely separated from the reactor, allowing existing generation facilities to be easily retrofitted and maintained.

GLOBAL AND USA URANIUM RESOURCES

Depleting hydrocarbon fuel resources and the growing volatility in fossil fuel prices, have led to an expansion in nuclear power production. However, without the adoption of breeding technology, the production of uranium globally is expected to peak in the period 2030-2040, if all the planned plants are built. The current production is 42,000 t/year and the consumption is 67,000 t/year. The mismatch is being met by existing stockpiles including Highly Enriched Uranium, HEU from dismantled aged Russian nuclear devices.

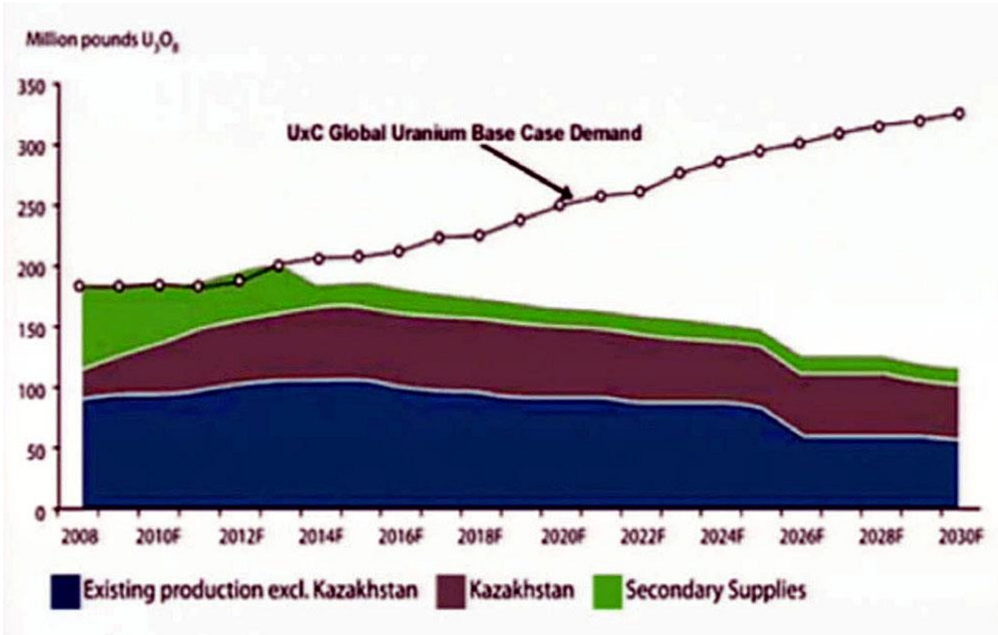

Figure 29. Expected Global demand and shortfall in million lbs of U_3O_8 over the period 2008-2030 from conventional and secondary sources. The shortfall implies the need to supplement uranium resources with the thorium resources. Source: EIA.

As of 2010, there were 56 nuclear power reactors under construction worldwide, of which 21 are in China. Some are replacing older plants that are being decommissioned, and some are adding new installed capacity. The Chinese nuclear power program is probably the most ambitious in history. It aims at 50 new plants by the year 2025 with an additional 100, if not more, completed by the year 2050. Standardized designs, new technology, a disciplined effort to develop human skills and industrial capacities to produce nuclear power plant components all point to a likely decline in plant construction costs in coming years and growing interest in new nuclear projects with ensuing pressure on nuclear fuels.

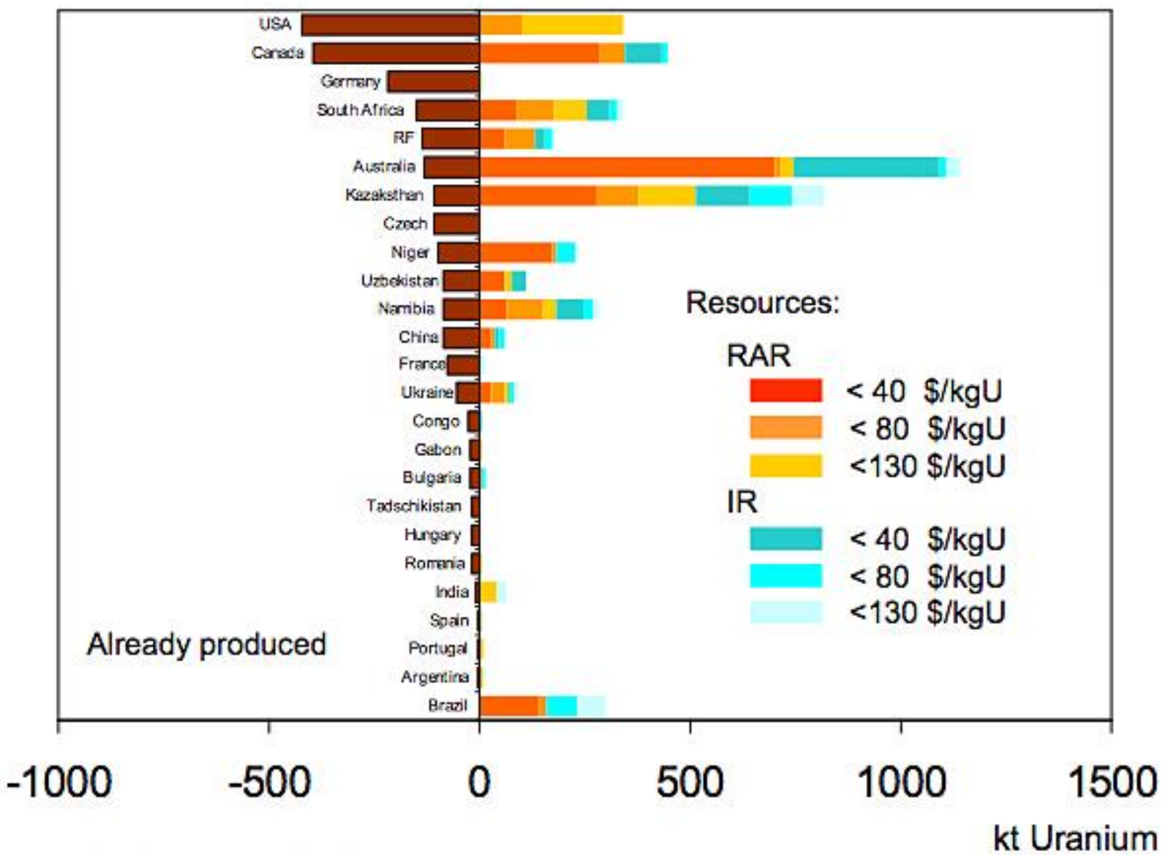

Figure 30. Already produced and reserve uranium supplies as of 2006. Source: NEA

It should be noted that there are currently 150 international reactor projects in some advanced permitting stage. An additional 300 projects are in some early planning stage. Added to a significant fraction of the currently 439 operating power reactors will likely double global nuclear capacity in the coming couple decades (most countries seem willing to try to extend the operating lives of existing reactors through safety-compliant upgrades and retrofits). Building a nuclear power plant practically requires contracting its fuel supply for 40-60 years. When adding all new projects it is reasonable to conclude that fuel requirements could double in the coming couple decades.

About 30 percent of the known recoverable global uranium oxide resources are found in Australia, followed by Kazakhstan (17 percent), Canada (12 percent), South Africa (8 percent), Namibia (6 percent), and Russia, Brazil and the USA, each with about 4 percent of the world production [21].

The uranium resources are classified into “conventional” and “non-conventional” resources. The conventional resources are further categorized into “Reasonably Assured Resources,” RAR and the believed-to-exist “Inferred Resources,” IR.

The RAR and IR categories are further subdivided according to the assumed exploitation cost in USA dollars. These cost categories are given as < 40 $/kg, < 80 $/kg, and < 130 $/kg.

The non-conventional resources are split into “Undiscovered Resources,” UR, further separated into “Undiscovered Prognosticated Resources,” UPR with assumed cost ranges of < 80 $/kg and < 130 $/kg, and “Undiscovered Speculative Resources” USR.

The USR numbers are given for an estimated exploitation cost of < 130 $/kg and also for a category with an unknown cost.

In the twentieth century, the USA was the world leading uranium producer until it was surpassed by Canada and Australia. In 2007, Canada accounted for 23 percent and Australia for 21 percent of global production, with the USA at 4 percent. Africa is becoming a new frontier in uranium production with Namibia 7 percent, Niger 8 percent, and South Africa 1 percent. Exploration and new mine development is ongoing in Botswana, Tanzania. Jordan and Nigeria.

The federal, provincial and local governments in Australia have all unilaterally and forcefully banned the development of any new uranium mines, even though existing mines continue operation. The French company Areva was not successful in receiving approval to build a new uranium mine in Australia. It has mining activities in the Niger Republic and received exploration licenses in other countries such as Jordan.

Canadian producer Cameco rates as the first world producer of uranium oxide, followed by French Areva, and then Energy Resources of Australia (68 percent owned by Rio Tinto), which produces some 6,000 tons per year.

As of 2007, five operating uranium mines existed in the USA, with 3 in Texas, one in Wyoming and one in Northern Nebraska as shown in Table 5. The state of Texas has a positive attitude towards uranium mining, and energy production in general, with an advantageous regulatory framework that streamlines the permit process using in situ leaching of uranium. Texas, being an “Agreement State,” implies that the USA Nuclear Regulatory Commission (NRC) has delegated its authority to the state regulatory agencies such as the Texas Commission on Environmental Quality (TCEQ), and companies deal directly with the state agencies in Texas rather than with the federal government’s NRC. Most of the uranium mining operations in the USA and Kazakhstan use in situ leach methods, also designated as In Situ Recovery (ISR) methods. Conventional methods are used in 62 percent of U mining, with 28 percent as ISR and 9 percent as byproduct extraction.

By 2008, U production in the USA fell 15 percent to 1,780 tonnes U_3O_8. The U production in the USA is currently from one mill at White Mesa, Utah, and from 6 ISR operations. In 2007, four operating mines existed in the Colorado Plateau area: Topaz, Pandora, West Sunday and Sunday-St. Jude. Two old mines reopened in 2008: Rim Canyon and Beaver Shaft and the Van 4 mine came into production in 2009.

As of 2010, Cameco Resources operated two ISL operations: Smith Ranch-Highland Mine in Wyoming and Cross Butte Mine in Nebraska, with reserves of 15,000 tonnes U_3O_8. The Denison Mines Company produced 791,000 tonnes of U_3O_8 in 2008 at its 200 t/day White Mesa mill in Southern Utah from its own and purchased ore, as well as toll milling.

Table 5: World main producing uranium mines, 2008. Source: World Nuclear Association, WNA.

Country	Production [tonnes U]	Share of world production	Main owner	Extraction method	Mine

		[percent]			
Canada	6,383	15	Cameco	Conventi onal	McArthur River
Australia	4,527	10	Rio Tinto	Conventi onal	Ranger
Namibia	3,449	8	Rio Tinto	Conventi onal	Rδssing
Australia	3,344	8	BHP Billiton	Byproduc t	Olympic Dam
Russia	3,050	7	ARMZ	Conventi onal	Priargunsky
Niger	1,743	4	Areva	Conventi onal	Somair
Canada	1,368	3	Cameco	Conventi onal	Rabbit Lake
Niger	1,289	3	Areva	Conventi onal	Cominak
Canada	1,249	3	Areva	Conventi onal	McLean
Kazakhstan	1,034	2	Uranium One	In Situ Retorting, ISR	Akdata
Total	27,436	62			

Uranium in the Colorado Plateau in the USA has an average grade of 0.25 percent or 2,500 ppm uranium in addition to 1.7 percent vanadium within the Uravan Mineral Belt.

Goliad County, Texas has an average grade of 0.076 percent (760 ppm) uranium oxide in sandstone deposits permeated by groundwater suggesting in situ leaching methods where water treated with carbon dioxide is injected into the deposit. The leachate is pumped and passed over ion exchange resins to extract the dissolved uranium.

Table 6. Uranium concentrates production in the USA, 2007.

Mine	**Location**	**Company**	**Production 2005 [10^6 lb U_3O_8]**	**Production 2006 [10^6 lb U_3O_8]**
Smith Ranch/Highland	Wyoming	Cameco (Power resources)	1.3	2.0
Crow Butte	Nebraska	Crow Butte Resources, Cameco	0.8	0.7
Vasquez	South Texas	Uranium Resources	0.3	0.2
Kingsville Dome	South Texas	Uranium Resources	-	0.1
Alta Mesa	South Texas	Alta Mesa	0.3	1.0
Total USA production			2.7	4.0

Figure 31. Thorium dioxide with 1 percent cerium oxide impregnated fabric, Welsbach incandescent gas mantles (left) and ThO_2 flakes (right). Yttrium compounds now substitute for Th in mantles.

Phosphate rocks containing just 120 ppm in U have been used as a source of uranium in the USA. The fertilizer industry produces large quantities of wet process phosphoric acid solution containing 0.1-0.2 gram/liter (g/l) of uranium, which represent a significant potential source of uranium.

THE THORIUM FUEL CYCLE ALTERNATIVE

One of the most negative impediment to nuclear power growth in the USA is that the used nuclear fuel is not being recycled to minimize its volume, isolate its fission products and burn its actinides, producing useful energy in the process. If recycled, the resulting waste would deteriorate to the level of, and then lower than, the radioactive toxicity of the already radioactive uranium ore (from billions of years ago, and for billions of years into the future) from which it was mined in the first place within about 500-600 years.

In the unsustainable once-through fuel cycle that is currently used, the spent fuel still containing usable fissile elements, together with its cladding and spacers materials, has been conveniently stored in large volumes on plant sites for a half-century in used water fuel storage pools or in dry storage consisting of concrete and steel silos built at the plant sites. The USA Nuclear Regulatory Commission has determined that this used fuel can be safely stored on these plant sites for another century, turning them into a distributed instead of a centralized depository.

The clear alternative is to hand down future generations a sustainable technology with its problems solved with present-day knowledge. Regardless, the amount of used fuel produced each year by the average 1,000 MWe USA reactor is small and can fit in the bed of a standard long-bed pickup truck, as compared to burning 4 million tons of coal or 62 billion cubic feet of natural gas to produce the same amount of electricity.

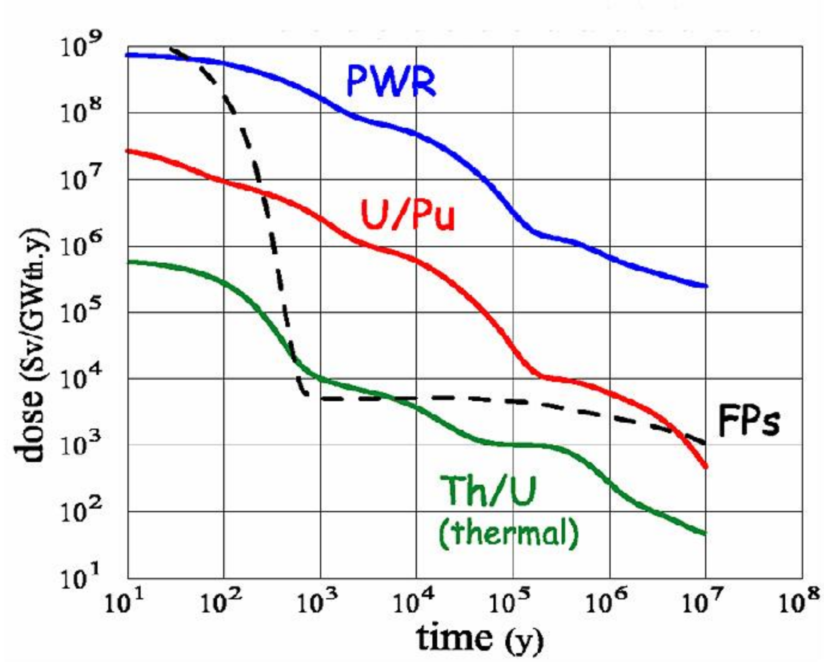

Figure 32. Relative toxicities of the actinides and fission products (FPs) in the different fuel cycles. FPs: Fisssion Products, PWR: Pressurized Water Reactor [2].

In another alternative, the adoption of the Thorium-U^{233} fuel cycle as a complement and eventual replacement of the present Uranium-Pu^{239} fuel cycle would offer a four-times larger resource base (Th^{232} is 4 times more abundant than U in the Earth's crust), lower wastes generation, as well as higher proliferation resistance prospects. What historically favored the U-Pu^{239} fuel cycle to the Th-U^{233} was a need to provide the world weapons stockpiles with Pu^{239}, and the initial unavailability of fissile isotopes to jump-start the thorium fuel cycle. Uranium occurs in nature with the fissile U^{235} isotope allowing the attainment of a critical fissile mass, whereas Th occurs in nature as the single non-fissile isotope Th^{232}.

PROPERTIES OF THORIUM

Thorium (Th) is named after Thor, the Scandinavian god of war. It occurs in nature in the form of a single isotope: Th^{232}. Twelve artificial isotopes are known for Th. It occurs in Thorite, $(Th,U)SiO_4$ and Thorianite (ThO_2 + UO_2). It is four times as abundant as uranium and is as abundant as lead and molybdenum.

Table 7. Relative abundances of some elements in the Earth's crust.

Element	Symbol	Abundance [gms / ton]
Lead	Pb	16
Gallium	Ga	15

Thorium	**Th**	**10**
Samarium	Sm	7
Gadolinium	Gd	6
Praseodymium	Pr	6
Boron	B	3
Bromine	Br	3
Uranium	**U**	**2.5**
Beryllium	Be	2
Tin	Sn	1.5
Tungsten	W	1
Molybdenum	Mo	1
Mercury	Hg	0.2
Silver	Ag	0.1
Uranium^{235}	**U^{235}**	**0.018**
Platinum	Pt	0.005
Gold	Au	0.02

It can be commercially extracted from the Monazite mineral containing 3-22 percent ThO_2 with other rare earth elements or lanthanides. Its large abundance makes it a valuable resource for electrical energy generation with supplies exceeding both coal and uranium combined. This would depend on breeding of the fissile isotope U^{233} from thorium according to the breeding reactions [20]:

$$\begin{aligned}
{}_0n^1 + {}_{90}Th^{232} &\rightarrow {}_{90}Th^{233} + \gamma \\
{}_{90}Th^{233} &\rightarrow {}_{91}Pa^{233} + {}_{-1}e^0 + \nu^* + \gamma \\
{}_{91}Pa^{233} &\rightarrow {}_{92}U^{233} + {}_{-1}e^0 + \nu^* + \gamma \\
\hline
{}_0n^1 + {}_{90}Th^{232} &\rightarrow {}_{92}U^{233} + 2\,{}_{-1}e^0 + 2\nu^* + 3\gamma
\end{aligned} \tag{1}$$

Together with uranium, its radioactive decay chain leads to the stable Pb^{208} lead isotope with a half-life of 1.4 x 10^{10} years for Th^{232}. It contributes to the internal heat generation in the Earth, together with other radioactive elements such as U and K^{40}.

As Th^{232} decays into the stable Pb^{208} isotope, radon^{220} or thoron forms in the chain. Rn^{220} has a low boiling point and exists in gaseous form at room temperature. It poses a radiation hazard through its own daughter nuclei and requires adequate ventilation in underground mining. Radon tests are needed to check for its presence in new homes that are possibly built on rocks like granite or sediments like shale or phosphate rock containing significant amounts of thorium. Adequate ventilation of homes that are over-insulated becomes a design consideration in this case.

Thorium, in the metallic form, can be produced by reduction of ThO_2 using calcium or magnesium. Also by electrolysis of anhydrous thorium chloride in a fused mixture of Na and K chlorides, by calcium reduction of Th tetrachloride mixed with anhydrous zinc chloride, and by reduction with an alkali metal of Th tetrachloride.

Thorium is the second member of the actinides series in the periodic table of the elements. When pure, it is soft and ductile, can be cold-rolled and drawn and it is a silvery white metal retaining its luster in air for several months. If contaminated by the oxide, it tarnishes in air into a gray then black color.

Thorium oxide has the highest melting temperature of all the oxides at 3,300 degrees C. Just a few other elements and compounds have a higher melting point such as tungsten and tantalum carbide. Water attacks it slowly, and acids do not attack it except for hydrochloric acid.

Thorium in the powder form is pyrophyric and can burn in air with a bright white light. In portable gas lights the Welsbach mantle is prepared with ThO_2 with 1 percent cerium oxide and other ingredients.

As an alloying element in magnesium, it gives high strength and creep resistance at high temperatures. Tungsten wire and electrodes used in electrical and electronic equipment such as electron guns in x-ray tubes or video screens are coated with Th due to its low work function and associated high electron emission. Its oxide is used to control the grain size of tungsten used in light bulbs and in high temperature laboratory crucibles.

Glasses for lenses in cameras and scientific instruments are doped with Th to give them a high refractive index and low dispersion of light.

In the petroleum industry, it is used as a catalyst in the conversion of ammonia to nitric acid, in oil cracking, and in the production of sulfuric acid.

ADVANTAGES OF THE THORIUM FUEL CYCLE

The following advantages of the thorium fuel cycle over the U^{235}-Pu^{239} fuel cycle have been suggested [8-14]:

1. Breeding is possible in both the thermal and fast parts of the neutron spectrum with a regeneration factor of $\eta > 2$.

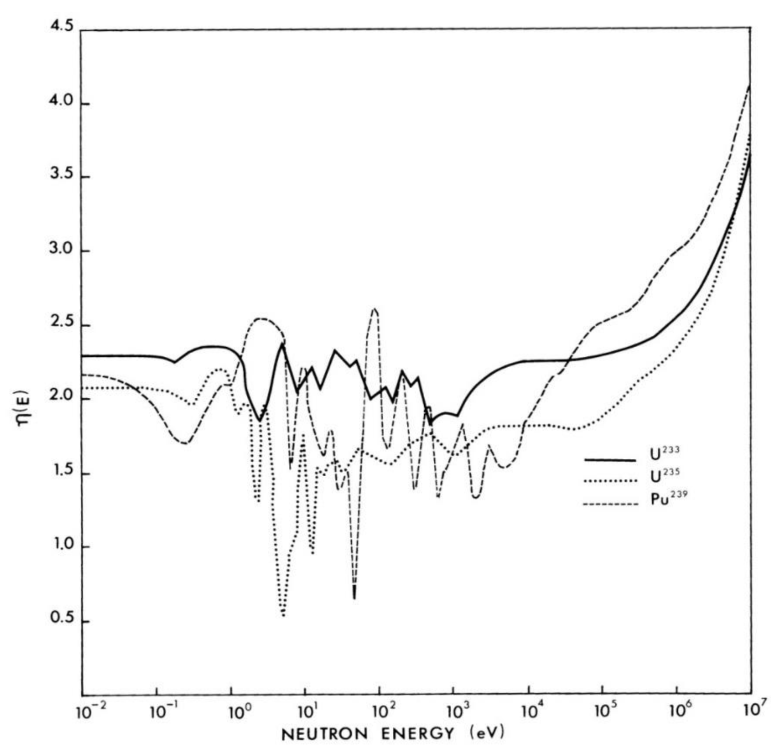

Figure 33. Regeneration factor as a function of neutron energy for the different fissile isotopes.

2. Expanded nuclear fuel resources due to the higher abundance of the fertile Th^{232} than U^{238}. The USA resources in the state of Idaho are estimated to reach 600,000 tons of 30 percent of Th oxides. The probable reserves amount to 1.5 million tons. There exists about 3,000 tons of already milled thorium in a USA strategic stockpile stored in Nevada.
3. Lower nuclear proliferation concerns due to the reduced limited needs for enrichment of the U^{235} isotope that is needed for starting up the fission cycle and can then be later replaced by the bred U^{233}. The fusion fission hybrid totally eliminates that need. An attempted U^{233} weapon test is rumored to have evolved into a fizzle because of the U^{232} contaminant concentration and its daughter products could not be reduced to a practical level.
4. A superior system of handling fission product wastes than other nuclear technologies and a much lower production of the long lived transuranic elements as waste. One ton of natural Th^{232}, not requiring enrichment, is needed to power a 1,000 MWe reactor per year compared with about 33 tons of uranium solid fuel to produce the same amount of power. Thorium is simply purified then converted into a fluoride. The same initial fuel loading of one ton per year is discharged primarily as fission products to be disposed of for the fission thorium cycle.
5. Ease of separation of the lower volume and short lived fission products for eventual disposal.
6. Higher fuel burnup and fuel utilization than the U^{235}-Pu^{239} cycle.
7. Enhanced nuclear safety associated with better temperature and void reactivity coefficients and lower excess reactivity in the core. Upon being drained from its reactor vessel, a thorium molten salt would solidify shutting down the chain reaction,
8. With a tailored breeding ratio of unity, a fission thorium fueled reactor can generate its own fuel, after a small amount of fissile fuel is used as an initial loading.
9. The operation at high temperature implies higher thermal efficiency with a Brayton gas turbine cycle (thermal efficiency around 40-50 percent) instead of a Joule or Rankine steam cycle (thermal efficiency around 33 percent), and lower waste heat that can be used for desalination or space heating. An open air cooled cycle can be contemplated eliminating the need for cooling water and the associated heat exchange equipment in arid areas of the world.

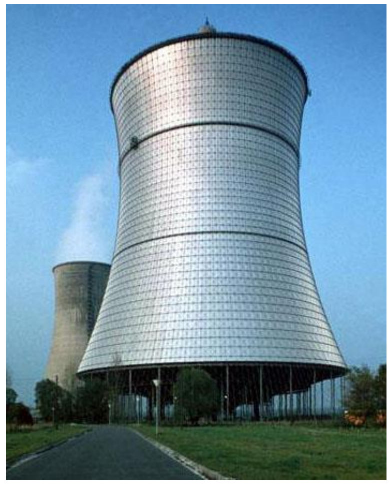

Figure 34. Dry cooling tower in foreground, wet cooling tower in background in the THTR-300 pebble bed Th reactor, Germany.

10. A thorium cycle for base-load electrical operation would provide a perfect match to peak-load cycle wind turbines generation. The produced wind energy can be stored as compressed air which would be used to cool a thorium open cycle reactor, substantially increasing its thermal efficiency, yet not requiring a water supply for cooling.
11. The unit powers are scalable over a wide range for different applications such as process heat or electrical production. Units of 100 MWe capacity can be designed, built and combined for larger power needs.
12. Operation at atmospheric pressure without pressurization implies the use of standard equipment with a lower cost than the equipment operated at a 1,000-2,000 psi high pressure in the LWRs cycle. Depressurization would cause the pressurized water coolant to flash into steam and a loss of coolant.
13. In uranium-fuelled thermal reactors, without breeding, only 0.72 percent or 1/139 of the uranium is burned as U^{235}. If we assume that about 40 percent of the thorium can be converted into U^{233} then fissioned, this would lead to an energy efficiency ratio of 139 x 0.40 = 55.6 or 5,560 percent more efficient use of the available resource compared with U^{235}.
14. Operational experience exists from the Molten Salt reactor experiment (MSRE) at Oak Ridge National Laboratory (ORNL), Tennessee. A thorium fluoride salt was not corrosive to the nickel alloy: Hastelloy-N. Corrosion was caused only from tellurium, a fission product.

Four approaches to a thorium reactor are under consideration:

1. Use of a liquid molten Th fluoride salt,
2. Use of a pebble bed graphite moderated and He gas cooled reactor,
3. The use of a seed and blanket solid fuel with a Light Water Reactor (LWR) cycle,
4. A driven system using fusion or accelerator generated neutrons.

THORIUM ABUNDANCE

Thorium is four times as abundant than uranium in the Earth's crust and provides a fertile isotope for breeding of the fissile uranium isotope U^{233} in a thermal or fast neutron spectrum.

In the Shippingport reactor it was used in the oxide form. In the HTGR it was used in metallic form embedded in graphite. The MSBR used graphite as a moderator and hence was a thermal breeder and a chemically stable fluoride salt, eliminating the need to process or to dispose of fabricated solid fuel elements. The fluid fuel allows the separation of the stable and radioactive fission products for disposal. It also offers the possibility of burning existing actinides elements and does need an enrichment process like the U^{235}-Pu^{239} fuel cycle.

Thorium is abundant in the Earth's crust, estimated at 120 trillion tons. The Monazite black sand deposits are composed of 3-22 percent of thorium. It can be extracted from granite rocks and from phosphate rock deposits, rare earths, tin ores, coal and uranium mines tailings.

It has even been suggested that it can be extracted from the ash of coal power plants. A 1,000 MWe coal power plant generates about 13 tons of thorium per year in its ash. Each ton of thorium can in turn generate 1,000 MWe of power in a well optimized thorium reactor. Thus a coal power plant can conceptually fuel 13 thorium plants of its own power. From a different perspective, 1 pound of Th has the energy equivalent of 5,000 tons of coal. There are 31 pounds of Th in 5,000 tons of coal. If the Th were extracted from the coal, it would thus yield 31 times the energy equivalent of the coal.

The calcium sulfate or phospho-gypsum resulting as a waste from phosphorites or phosphate rocks processing into phosphate fertilizer contains substantial amounts of unextracted thorium and uranium.

Uranium mines with brannerite ores generated millions of tons of surface tailings containing thoria and rare earths.

The United States Geological Survey (USGS), as of 2010, estimated that the USA has reserves of 440,000 tons of thorium ore. A large part is located on properties held by Thorium Energy Inc. at Lemhi Pass in Montana and Idaho. This compares to a previously estimated 160,000 tons for the entire USA.

The next highest global thorium ores estimates are for Australia at 300,000 tons and India with 290,000 tons.

THORIUM PRIMARY MINERALS

Table 8: Major Thorium ores compositions.

Ore	Composition
Thorite	$(Th,U)SiO_4$
Thorianite	$(ThO_2 + UO_2)$
Thorogummite	$Th(SiO4)_{1-x} (OH)_{4x}$
Monazite	$(Ce,La,Y,Th)PO_4$
Brocktite	$(Ca,Th,Ce)(PO_4)H_2O$
Xenotime	$(Y,Th)PO_4$
Euxenite	$(Y,Ca,Ce,U,Th)(Nb,Ta,Ti)_2O_6$
Iron ore	Fe + rare earths + Th apatite

Thorium occurs in several minerals [16, 19]:

1. Monazite, (Ce,La,Y,Th)PO_4, a rare earth-thorium phosphate with 5-5.5 hardness. Its content in Th is 3-22 percent with 14 percent rare earth elements and yttrium. It occurs as a yellowish, reddish-brown to brown, with shades of green, nearly white, yellowish brown and yellow ore. This is the primary source of the world's thorium production. Until World War II, thorium was extracted from Monazite as a primary product for use in products such as camping lamp mantles. After World War II, Monazite has been primarily mined for its rare earth elements content. Thorium was extracted in small amounts and mainly discarded as waste.
2. Thorite, (Th,U)SiO_4 is a thorium-uranium silicate with a 4.5 hardness with yellow, yellow-brown, red-brown, green, and orange to black colors. It shares a 22 percent Th and a 22 percent U content. This ore has been used as a source of uranium, particularly the uranium rich uranothorite, and orangite; an orange colored calcium-rich thorite variety.
3. Brocktite, (Ca,Th,Ce)(PO_4)H_2O.
4. Xenotime, (Y,Th)PO_4.
5. Euxenite, (Y,Ca,Ce,U,Th)(Nb,Ta,Ti)$_2O_6$.
6. Iron ore, (Fe)-rare earth elements-Th-apatite, Freta deposits at Pea Ridge, Missouri, Mineville, New York, and Scrub Oaks, New Jersey.

GLOBAL AND USA THORIUM RESOURCES

Estimates of the available Th resources vary widely. The largest known resources of Th occur in the USA followed in order by Australia, India, Canada, South Africa, Brazil, and Malaysia.

Concentrated deposits occur as vein deposits, and disseminated deposits occur as massive carbonatite stocks, alkaline intrusions, and black sand placer or alluvial stream and beach deposits.

Carbonatites are rare carbonate igneous rocks formed by magmatic or metasomatic processes. Most of these are composed of 50 percent or higher carbonate minerals such as calcite, dolomite and/or ankerite. They occur near alkaline igneous rocks.

Table 9. Estimated Global Thorium Resources [16].

Country	ThO_2 Reserves [metric tonnes] USGS estimate 2010 [16]	ThO_2 Reserves [metric tonnes] NEA estimate [22]***	Mined amounts 2007 [metric tonnes]*
USA	440,000	400,000	-**
Australia	300,000	489,000	-
Turkey		344,000	
India	290,000	319,000	5,000
Venezuela		300,000	
Canada	100,000	44,000	-
South Africa	35,000	18,000	-

Brazil	16,000	302,000	1,173
Norway		132,000	
Egypt		100,000	
Russia		75,000	
Greenland		54,000	
Canada		44,000	
Malaysia	4,500		800
Other countries	90,000	33,000	-
Total	1,300,000	2,610,000	6,970

* Average Th content of 6-8 percent.
** Last mined in 1994.
***Reasonably assured and inferred resources available at up to $80/kg Th

The alkaline igneous rocks, also referred to as alkali rocks, have formed from magmas and fluids so enriched in alkali elements that Na and K bearing minerals form components of the rocks in larger proportion than usual igneous rocks. They are characterized by feldspathoid minerals and/or alkali pyroxenes and amphiboles [19].

Table 10. Locations of USA major ThO_2 proven reserves [19].

Deposit type	Mining District	Location	ThO_2 reserves [metric tonnes]
Vein deposits	Lehmi Pass district	Montana-Idaho	64,000
	Wet Mountain area	Colorado	58,200
	Hall Mountain	Idaho	4,150
	Iron Hill	Colorado	1,700 (thorium veins) 690 (Carbonatite dikes)
	Diamond Creek	Idaho	-
	Bear Lodge Mountains	Wyoming	-
	Monroe Canyon	Utah	-
	Mountain Pass district	California	-
	Quartzite district	Arizona	-

	Cottonwood area	Arizona	-
	Gold Hill district	New Mexico	-
	Capitan Mountain	New Mexico	-
	Laughlin Peak	New Mexico	-
	Wausau, Marathon County	Wisconsin	-
	Bokan Mountain	Alaska	-
Massive Carbonatite stocks	Iron Hill	Colorado	28,200
	Mountain Pass	California	8,850
Black Sand Placer, Alluvial Deposits	Stream deposits	North, South Carolina	4,800
	Stream placers	Idaho	9,130
	Beach placers	Florida-Georgia	14,700
Alkaline Intrusions	Bear Lodge Mountains	Wyoming	-
	Hicks Dome	Illinois	-
Total, USA			194,420

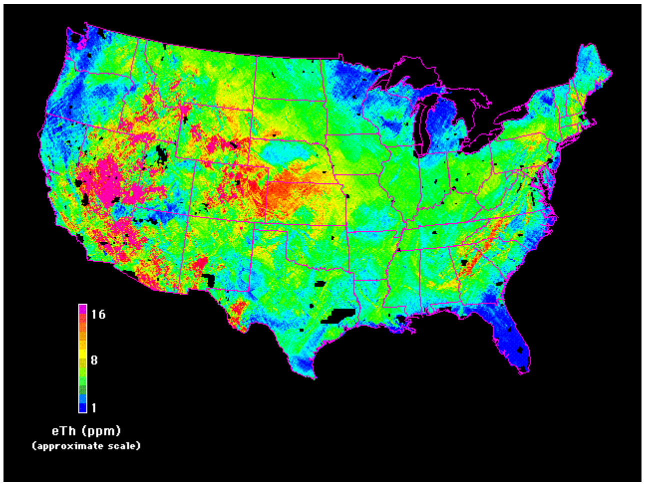

Figure 35. Th concentrations in ppm and occurrences in the USA. Source: USA Geological Survey Digital Data Series DDS-9, 1993.

Figure 36. Lehmi Pass is a part of Beaverhead Mountains along the continental divide on the Montana-Idaho border, USA. Its Th veins contain rare earth elements, particularly Neodymium.

Figure 37. Mountain Pass, California. Source: USGS.

Figure 38. Black sand Monazite layers in beach sand at Chennai, India. Photo: Mark A. Wilson [19].

Figure 39. Thorite (Th, U)SiO4, a thorium-uranium silicate.

NONPROLIFERATION CHARACTERISTICS OF THORIUM CYCLE

In the Th-U^{233} fuel cycle, the hard gamma rays associated with the decay chain of the formed isotope U^{232} with a half life of 72 years and its spontaneous fission makes the U^{233} in the thorium cycle with high fuel burnup a higher radiation hazard from the perspective of proliferation than Pu^{239}.

The U^{232} is formed from the fertile Th^{232} from two paths involving an (n, 2n) reaction, which incidentally makes Th^{232} a good neutron multiplier in a fast neutron spectrum:

$$\begin{aligned}
&{}_0n^1 + {}_{90}Th^{232} \rightarrow 2\,{}_0n^1 + {}_{90}Th^{231} \\
&{}_{90}Th^{231} \xrightarrow{25.52h} {}_{-1}e^0 + {}_{91}Pa^{231} \\
&{}_0n^1 + {}_{91}Pa^{231} \rightarrow \gamma + {}_{91}Pa^{232} \\
&{}_{91}Pa^{232} \xrightarrow{1.31d} {}_{-1}e^0 + {}_{92}U^{232}
\end{aligned} \tag{2}$$

and another involving an (n, γ) radiative capture reaction:

$$\begin{aligned}
&{}_0n^1 + {}_{90}Th^{232} \rightarrow \gamma + {}_{90}Th^{233} \\
&{}_{90}Th^{233} \xrightarrow{22.2m} {}_{-1}e^0 + {}_{91}Pa^{233} \\
&{}_{91}Pa^{233} \xrightarrow{27d} {}_{-1}e^0 + {}_{92}U^{233} \\
&{}_{92}U^{233} + {}_0n^1 \rightarrow 2\,{}_0n^1 + {}_{92}U^{232}
\end{aligned} \tag{3}$$

The isotope U^{232} is also formed from a reversible (n, 2n) and (n, γ) path acting on the bred U^{233}:

$$\begin{aligned}
&{}_0n^1 + {}_{92}U^{233} \rightarrow 2\,{}_0n^1 + {}_{92}U^{232} \\
&{}_0n^1 + {}_{92}U^{232} \rightarrow \gamma + {}_{92}U^{233}
\end{aligned} \qquad (4$$

The isotope Th^{230} occurs in trace quantities in thorium ores that are mixtures of uranium and thorium. U^{234} is a decay product of U^{238} and it decays into Th^{230} that becomes mixed with the naturally abundant Th^{232}. It occurs in secular equilibrium in the decay chain of natural uranium at a concentration of 17 ppm. The isotope U^{232} can thus also be produced from two successive neutron captures in Th^{230}:

$$\begin{aligned}
&{}_0n^1 + {}_{90}Th^{230} \rightarrow \gamma + {}_{90}Th^{231} \\
&{}_{90}Th^{231} \xrightarrow{25.52h} {}_{-1}e^0 + {}_{91}Pa^{231} \\
&{}_0n^1 + {}_{91}Pa^{231} \rightarrow \gamma + {}_{91}Pa^{232} \\
&{}_{91}Pa^{232} \xrightarrow{1.31d} {}_{-1}e^0 + {}_{92}U^{232}
\end{aligned} \tag{5}$$

The hard 2.6 MeV gamma rays originate from Tl^{208} isotope in the decay chain of aged U^{232} which eventually decays into the stable Pb^{208} isotope:

$$\begin{aligned}
&{}_{92}U^{232} \xrightarrow{72a} {}_{90}Th^{228} + {}_2He^4 \\
&{}_{90}Th^{228} \xrightarrow{1.913a} {}_{88}Ra^{224} + {}_2He^4 \\
&{}_{88}Ra^{224} \xrightarrow{3.66d} {}_{86}Rn^{220} + {}_2He^4 \\
&{}_{86}Rn^{220} \xrightarrow{55.6s} {}_{82}Po^{216} + {}_2He^4 \\
&{}_{84}Po^{216} \xrightarrow{0.15s} {}_{82}Pb^{212} + {}_2He^4 \\
&{}_{82}Pb^{212} \xrightarrow{10.64h} {}_{83}Bi^{212} + {}_{-1}e^0 \\
&{}_{83}Bi^{212} \xrightarrow[64\%]{60.6m} {}_{84}Po^{212} + {}_{-1}e^0 \\
&{}_{83}Bi^{212} \xrightarrow[36\%]{60.6m} {}_{81}Tl^{208} + {}_2He^4 \\
&{}_{84}Po^{212} \xrightarrow{0.298\mu s} {}_{82}Pb^{208}(stable) + {}_2He^4 \\
&{}_{81}Tl^{208} \xrightarrow{3.053m} {}_{82}Pb^{208}(stable) + {}_{-1}e^0 + \gamma(2.6146MeV)
\end{aligned} \tag{6}$$

As a comparison, the U^{233} decay chain eventually decays into the stable Bi^{209} isotope:

$$\begin{aligned}
&{}_{92}U^{233} \xrightarrow{1.592x10^5a} {}_{90}Th^{229} + {}_2He^4 \\
&{}_{90}Th^{229} \xrightarrow{7340a} {}_{88}Ra^{225} + {}_2He^4 \\
&{}_{88}Ra^{225} \xrightarrow{14.8d} {}_{89}Ac^{225} + {}_{-1}e^0 \\
&{}_{89}Ac^{225} \xrightarrow{10.0d} {}_{87}Fr^{221} + {}_2He^4 \\
&{}_{87}Fr^{221} \xrightarrow{4.8m} {}_{85}At^{217} + {}_2He^4 \\
&{}_{85}At^{217} \xrightarrow{32.3ms} {}_{83}Bi^{213} + {}_2He^4 \\
&{}_{83}Bi^{213} \xrightarrow{45.6m} {}_{84}Po^{213} + {}_{-1}e^0 \\
&{}_{84}Po^{213} \xrightarrow{4.2\mu s} {}_{82}Pb^{209} + {}_2He^4 \\
&{}_{82}Pb^{209} \xrightarrow{3.28h} {}_{83}Bi^{209}(stable) + {}_{-1}e^0
\end{aligned} \tag{7}$$

A 5-10 proportion of U^{232} in the U^{232}-U^{233} mixture has a radiation equivalent dose rate of about 1,000 cSv (rem)/hr at a 1 meter distance for decades making it a highly proliferation resistant cycle if the Pa^{233} is not separately extracted and allowed to decay into pure U^{233}.

The Pa^{233} cannot be chemically separated from the U^{232} if the design forces the fuel to be exposed to the neutron flux without a separate blanket region, making the design fail-safe with respect to proliferation and if a breeding ratio of unity is incorporated in the design.

Such high radiation exposures would lead to incapacitation within 1-2 hours and death within 1-2 days of any potential proliferators.

The International Atomic Energy Agency (IAEA) criterion for fuel self protection is a lower dose equivalent rate of 100 cSv(rem)/hr at a 1 meter distance. Its denaturing requirement for U^{235} is 20 percent, for U^{233} with U^{238} it is 12 percent, and for U^{233} denaturing with U^{232} it is 1 percent.

The Indian Department of Atomic Energy (DAE) had plans on cleaning U^{233} down to a few ppm of U^{232} using Laser Isotopic Separation (LIS) to reduce the dose to the occupational workers.

The contamination of U^{233} by the U^{232} isotope is mirrored by another introduced problem from the generation of U^{232} in the recycling of Th^{232} due to the presence of the highly radioactive Th^{228} from the decay chain of U^{232}.

DOSIMETRY

The International Atomic Energy Agency (IAEA) criterion for occupational protection is an effective dose of 100 cSv (rem)/hr at a 1 meter distance from the radiation source.

It is the decay product Tl^{208} in the decay chain of U^{232} and not U^{232} itself that generates the hard gamma rays. The Tl^{208} would appear in aged U^{233} over time after separation, emitting a hard 2.6416 MeV gamma ray photon. It accounts for 85 percent of the total effective dose 2 years after separation. This implies that manufacturing of U^{233} should be undertaken in freshly purified U^{233}. Aged U^{233} would require heavy shielding against gamma radiation.

In comparison, in the U-Pu^{239} fuel cycle, Pu^{239} containing Pu^{241} with a half life of 14.4 years, the most important source of gamma ray radiation is from the Am^{241} isotope with a 433 years half life that emits low energy gamma rays of less than 0.1 MeV in energy. For weapons grade Pu^{239} with about 0.36 percent Pu^{241} this does not present a major hazard but the radiological hazard becomes significant for reactor grade Pu^{239} containing about 9-10 percent Pu^{241}.

The generation of Pu^{241} as well as Pu^{240} and Am^{241} from U^{238} follows the following path:

$$
\begin{aligned}
&{}_0n^1 + {}_{92}U^{238} \rightarrow \gamma + {}_{92}U^{239} \\
&{}_{92}U^{239} \xrightarrow{23.5m} {}_{-1}e^0 + {}_{93}Np^{239} \\
&{}_{93}Np^{239} \xrightarrow{2.35d} {}_{-1}e^0 + {}_{94}Pu^{239} \\
&{}_0n^1 + {}_{94}Pu^{239} \rightarrow \gamma + {}_{94}Pu^{240} \\
&{}_0n^1 + {}_{94}Pu^{240} \rightarrow \gamma + {}_{94}Pu^{241} \\
&{}_{94}Pu^{241} \xrightarrow{14.7a} {}_{-1}e^0 + {}_{95}Am^{241}
\end{aligned}
\qquad (8)
$$

Plutonium containing less than 6 percent Pu^{240} is considered as weapons-grade.

The gamma rays from Am^{241} are easily shielded against with Pb shielding. Shielding against the neutrons from the spontaneous fissions in the even numbered Pu^{238} and Pu^{240} isotopes accumulated in reactor grade plutonium requires the additional use of a thick layer of a neutron moderator containing hydrogen such as paraffin or plastic, followed by a layer of neutron absorbing material and then additional shielding against the gamma rays generated from the neutron captures.

The generation of Pu^{238} and Np^{237} by way of (n, 2n) rather than (n, γ) reactions, follows the path:

$$\begin{aligned}
&{}_0n^1 + {}_{92}U^{238} \rightarrow 2\,{}_0n^1 + {}_{92}U^{237} \\
&{}_{92}U^{237} \xrightarrow{6.75d} {}_{-1}e^0 + {}_{93}Np^{237} \\
&{}_0n^1 + {}_{93}Np^{237} \rightarrow \gamma + {}_{93}Np^{238} \\
&{}_{93}Np^{238} \xrightarrow{2.12d} {}_{-1}e^0 + {}_{94}Pu^{238}
\end{aligned} \tag{9}$$

The production of Pu^{238} for radioisotopic heat and electric sources for space applications follows the path of chemically separating Np^{237} from spent LightWater Reactors (LWRs) fuel and then neutron irradiating it to produce Pu^{238}.

Table 11. Typical compositions of fuels in the uranium and thorium fuel cycles.

Isotopic composition [percent]	Pu^{239} weapons grade	Pu^{239} reactors grade	U^{233}	U^{233} + 1 ppm U^{232}
U^{232}			0.0000	0.0001
U^{233}			100.0000	99.9999
Pu^{238}	0.0100	1.3000		
Pu^{239}	93.8000	60.3000		
Pu^{240}	5.8000	24.3000		
Pu^{241}	0.3500	9.1000		
Pu^{242}	0.0200	5.0000		
Density [gm/cm^3]	19.86	19.86	19.05	19.05
Radius [cm]	3.92	3.92	3.96	3.96
Weight [kg]	5	5	5	5

Table 12. Glove box operation dose rate required to accumulate a limiting occupational 5 cSv (rem) dose equivalent from a 5 kg metal sphere, one year after separation at a 1/2 meter distance [2].

Fuel, U^{232}/U^{233}	Time to 5 cSv effective dose [hr]	Effective dose rate cSv/hr
0.01	0.039	127.0000
100 ppm	3.937	1.2700
5 ppm	84.746	0.0590
1 ppm	384.615	0.0130
Reactor grade Pu^{239}	609.756	0.0082
Weapons grade Pu^{239}	3846.154	0.0013

Both reactor-grade plutonium and U^{233} with U^{232} would pose a significant radiation dose equivalent hazard for manufacturing personnel as well as military personnel, which precludes their use in weapons manufacture in favor of enriched U^{235} and weapons-grade Pu^{239}.

Table 13. Dose equivalent rates in cSv (rem)/hr from 5 kg metal spheres at a 1/2 meter distance for different times after separation [2].

Material	Type of radiation	Dose equivalent rate at time after separation [cSv(rem)/hr]				
		0 yr	1 yr	5 yr	10 yr	15 yr
Pure U^{233}	γ total	0.32	0.42	0.84	1.35	1.89
U^{233} +1 ppm U^{232}	γ total	0.32	13.08	35.10	39.57	39.17
	γ from Tl^{208}	0.00	11.12	29.96	33.48	32.64
Pu^{239}, weapons grade	γ	0.49	0.71	1.16	1.57	1.84
	neutrons	0.56	0.56	0.56	0.56	0.56
	γ + neutron	1.05	1.27	1.72	2.13	2.40
Pu^{239}, Reactor grade	γ total	0.49	5.54	16.72	28.64	37.54
	γ from Am^{241}	0.00	3.24	14.60	26.00	34.80
	neutrons	2.66	2.66	2.65	2.64	2.63
	γ + neutrons	3.15	8.20	19.37	31.28	40.17

ACTINIDES PRODUCTION

There has been a new interest in the Th cycle in Europe and the USA since it can be used to increase the achievable fuel burnup in LWRs in a once through fuel cycle while significantly reducing the transuranic elements in the spent fuel. A nonproliferation as well as transuranics waste disposal consideration is that just a single neutron capture reaction in U^{238} is needed to produce Pu^{239} from U^{238}:

$$
\begin{aligned}
&{}_0n^1 + {}_{92}U^{238} \rightarrow {}_{92}U^{239} + \gamma \\
&{}_{92}U^{239} \xrightarrow{23.5m} {}_{93}Np^{239} + {}_{-1}e^0 \\
&{}_{93}Np^{239} \xrightarrow{2.35d} {}_{94}Pu^{239} + {}_{-1}e^0
\end{aligned} \tag{10}
$$

whereas a more difficult process of fully 5 successive neutron captures are needed to produce the transuranic Np^{237} from Th^{232}:

$$
\begin{aligned}
&{}_0n^1 + {}_{90}Th^{232} \rightarrow {}_{90}Th^{233} + \gamma \\
&{}_0n^1 + {}_{90}Th^{233} \rightarrow {}_{90}Th^{234} + \gamma \\
&{}_{90}Th^{234} \xrightarrow{24.1d} {}_{91}Pa^{234} + {}_{-1}e^0 \\
&{}_{91}Pa^{234} \xrightarrow{6.70h} {}_{92}U^{234} + {}_{-1}e^0 \\
&{}_0n^1 + {}_{92}U^{234} \rightarrow {}_{92}U^{235} + \gamma \\
&{}_0n^1 + {}_{92}U^{235} \rightarrow {}_{92}U^{236} + \gamma \\
&{}_0n^1 + {}_{92}U^{236} \rightarrow {}_{92}U^{237} + \gamma \\
&{}_{92}U^{237} \xrightarrow{6.75d} {}_{93}Np^{237} + {}_{-1}e^0
\end{aligned} \tag{11}
$$

This implies a low yield of Np^{237} however, as an odd numbered mass number isotope posing a possible proliferation concern; whatever small quantities of it are produced, provisions must be provided in the design to have it promptly recycled back for burning in the fast neutron spectrum of the fusion part of the hybrid.

In fact, it is more prominently produced in thermal fission light water reactors using the uranium cycle and would be produced; and burned, in fast fission reactors through the (n, 2n) reaction channel with U^{238} according to the much simpler path:

$$
\begin{aligned}
&{}_0n^1 + {}_{92}U^{238} \rightarrow 2\,{}_0n^1 + {}_{92}U^{237} \\
&{}_{92}U^{237} \xrightarrow{6.75d} {}_{93}Np^{237} + {}_{-1}e^0
\end{aligned} \tag{12}
$$

The Np^{237} gets transmuted in the Th^{232} fuel cycle into Pu^{238} with a short half-life of 87.74 years:

$$
\begin{aligned}
&{}_0n^1 + {}_{93}Np^{237} \rightarrow {}_{93}Np^{238} + \gamma \\
&{}_{93}Np^{238} \xrightarrow{2.12d} {}_{94}Pu^{238} + {}_{-1}e^0
\end{aligned} \tag{13}
$$

A typical 1,000 MWe Light Water Reactor (LWR) operating at an 80 percent capacity factor produces about 13 kgs of Np^{237} per year.

This has led to suggested designs where Th^{232} replaces U^{238} in LWRs fuel and accelerator driven fast neutron subcritical reactors that would breed U^{233} from Th^{232}.

Incidentally, whereas the Pu^{238} isotope is produced in the Th fuel cycle, it is the Pu^{240} isotope with a longer 6,537 years half-life, that is produced in the U-Pu fuel cycle:

$$
\begin{aligned}
{}_{0}n^{1} + {}_{92}U^{238} &\rightarrow {}_{92}U^{239} + \gamma \\
{}_{92}U^{239} &\rightarrow {}_{93}Np^{239} + {}_{-1}e^{0} + \nu^{*} + \gamma \\
{}_{93}Np^{239} &\rightarrow {}_{94}Pu^{239} + {}_{-1}e^{0} + \nu^{*} + \gamma \\
{}_{0}n^{1} + {}_{94}Pu^{239} &\rightarrow {}_{94}Pu^{240} + \gamma
\end{aligned}
\tag{14}
$$

LEGISLATIVE INITIATIVES

Interest in Th as a fuel resource, as well as the discontinuation of the Yucca Mountain once-through fuel cycle in the USA, led to an initiative, Senate Bill S.3680, by USA Senators Orrin Hatch (Utah) and Harry Reid (Nevada): The Thorium Energy Independence and Security Act of 2008, which amends the Atomic Energy Act of 1954, would establish offices at the USA Nuclear Regulatory Commission (USNRC) and the Department of Energy (DOE) to regulate domestic thorium nuclear power generation and oversee possible demonstrations of thorium nuclear fuel assemblies. The bill was read twice and referred to the Committee on Energy and Natural Resources, but has not become law.

This was followed by Congressional Bill HR1534 by Congressman Joe Sestak (Pennsylvania): To direct the Secretary of Defense and the Chairman of the Joint Chiefs of Staff to carry out a study on the use of thorium-liquid fueled nuclear reactors for naval power needs and other purposes. This bill has been referred to the Subcommittee on Seapower and Expeditionary Forces. The USA Navy declined the offer and its allocated funds.

Senator Evan Bayh (Indiana) and Representative Mike Coffman (Colorado) included amendments in the Fiscal Year 2010 National Defense Authorization Act requiring a government assessment of the availability of rare earth materials to support industry and the defense market.

Senators Orrin G. Hatch (R-Utah) and Harry Reid (D-Nevada), on March 3rd, 2010, reintroduced earlier legislation: the Thorium Energy Security Act of 2010; to accelerate the use of thorium-based nuclear fuel in existing and future USA reactors. Their legislation establishes a regulatory framework and a development program to facilitate the introduction of thorium-based nuclear fuel in nuclear power plants across the USA.

It must be noted that the majority of bills and resolutions are primarily political gestures and never make it out of committee.

THORIUM AS AN UNUSED RESOURCE

New green developing technologies depend on the availability of the rare earths metals. As petroleum set a record price in 2008, the technology of hybrid cars was widely adopted, achieving a mileage of 48 miles/gallon in city driving. A shortage of such vehicles occurred as a result of a shortage of the rechargeable Ni metal hydride (NiMH) batteries using lanthanum.

Thorium supplies constitute a yet unused energy resource. They occur primarily in the rare earth ore mineral Monazite and the thorium mineral thorite. The size of the global resource is estimated at 1.3×10^6 metric tonnes of ThO_2. The USA and Australia hold the world's largest known reserves with uncertain estimates ranging from $0.19 \times 10^6 - 0.44 \times 10^6$ metric tonnes of ThO_2. Many of the USA reserves sizes are not known, as a result of unavailable data for lack of economical extraction attractiveness without an energy use option for thorium.

The main international rare earths processors presently opt to process only thorium-free feed materials to avoid its radioactive content, even though they still have to cope with the radioactive isotope Ce^{142} which occurs in cerium. Cerium is used in batteries and to cut auto emissions. This has been negative for the low-cost monazite ores and other thorium bearing ores. This could change in the future if thorium is adopted as a byproduct for energy use. Supplies of rare earth elements are globally available in the international trade pipeline from diverse sources without discerned immediate shortages or bottlenecks.

Thorium occurs associated with uranium in some ores such as Thorite $(Th,U)SiO_4$ and, if exploited, would help expand the known U resource base.

Other ores are associated with rare earth elements or lanthanides such as monazite $(Ce, La,Y,Th)PO_4$ which also contain other economically significant metal occurrences such as yttrium. In this case, Th as a fuel resource could be extracted for future energy applications as a byproduct of the other more important rare earth elements extraction process until such time when primary Th ores such as thorite and monazite would be exploited.

DISCUSSION

For utilities, a small reactor has several advantages, starting with cost. Small reactors are expected to cost about \$5,000 per kWe of installed capacity, or about $125 \times 10^3 \times 5{,}000 =$ \$625 million for a single 125 MWe unit.

For a combined 500 MWe, four units installation, the total cost would be 4 x 625 = \$2.5 billion.

Large reactors cost \$5 billion to \$10 billion for reactors that would range from 1,100 to 1,700 MWe of generating capacity.

The first units likely would be built adjacent to existing nuclear plants, many of which were originally permitted to have 2-4 units but usually have only one or two. An example is the Clinton Power Plant in Illinois that operates a single BWR unit with space available next to it for a second unit.

Ageing equipment has to be replaced with new equipment in all fields of engineering to avoid unforeseen serious accidents. New Boeing 767 tankers will replace the aging Boeing KC-135, which first entered service in 1957. Aerial refueling tankers allowed the military to refuel aircraft in mid-flight, greatly extending the range of operation for smaller aircraft, while also providing the capability to carry cargo and airlift personnel. About 100 of the oldest "Stratotanker" models have been grounded since 2006 due to age. Originally needed to keep B-52 nuclear bombers in the air for long periods of time, the Stratotankers quickly found new missions in Vietnam, where it enabled small fighter bombers to strike targets anywhere in the country. It revolutionized the use of air power, and continued to play that role in Iraq and Afghanistan. In much the same manner, the ageing fleet of nuclear reactors have admirably served their purpose and need to be promptly replaced by more modern safer versions.

In the future, the nuclear and fossil fuel generation utilities could replace existing nuclear and coal-fired power plants with compact reactors in order to take advantage of sites already served by transmission lines and, in some cases, needed for grid support. Like any other power plants, these small reactors could be easily hooked up to the power grid.

The most prominent attraction of the prospect is that utilities could start with a few reactors and add more units as needed. By contrast, with large reactor units, utilities have what is called in the industry a "single-shaft risk," where billions of dollars are tied up in a single plant.

Another advantage is that reactors will store all of their waste on each site for the estimated 60-year life of each reactor.

The slow pace of nuclear power development mandates that the next wave of large reactors would not begin coming on line until the 2016 – 2017 period. The first certification request for a small reactor design is expected to be Babcock & Wilcox's request in 2012. The first units could come on line after 2018. However, as some experts believe that if the USA utility industry embraces small reactors, nuclear power in the USA could become pervasive because more utilities would be able to afford them.

Small reactors should be as safe, or safer, than large ones. A reason is that they are simpler in design and operation and have fewer moving parts that can fail. Small reactors produce less decay heat power per unit making it easier to shut them down, should a malfunction occur. With a large reactor, the response to a malfunction tends to be quick, whereas in smaller ones, they respond more slowly which makes them easier to control.

Once on site, each reactor would be housed in a two-story containment structure that would be buried beneath the ground for added security. They would run round the clock, stopping to refuel every five years instead of 18 to 24 months, like existing reactors.

The compact reactors promise fewer jobs than a large plant, which offers 700 - 1,000 permanent jobs. Small plants satisfy the same security and safety standards as large plants but would require a smaller work force because they would run much longer between their refueling and maintenance outages.

When the existing 104 nuclear power plants in the USA were built in 1960-1970 period, the utilities did not have to sell the anticipated power output with power purchase agreements before their plants came into operation since they were supplying their own customers. The customers had no choice of suppliers. In the present era, a restructured electric open bidding system for electricity covers more than half the USA. The projected new units Calvert Cliffs 3 and South Texas 3 and 4 were meant to blaze the trail for the construction of dozens of new units. For this to be realized, capital must be available for their economical viability.

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APPENDIX

Table A1. Short Term Global Energy Resource Base in ZJ (Zetajoules)[1]

Resource	Type	1998 Yearly Consumption [ZJ/yr]	Reserves	Resources	Resource Base[2]	Consumed By end of 1998	Additional Occurrences
Oil	Conventional	0.13	6.00	6.08	12.08	4.85	-

	Unconventional	0.01	5.11	15.24	20.35	0.29	45
	Total Oil	0.14	11.11	21.31	32.42	5.14	45
Natural Gas	Conventional	0.08	5.45	11.11	16.56	2.35	-
	Unconventional	0.00	9.42	23.81	33.23	0.03	930
	Total Gas	0.08	14.87	34.92	49.79	2.38	930
Coal	Total Coal	0.09	20.67	179.00	199.67	5.99	-
Total Fossil		0.31	46.65	235.23	281.88	13.51	975
Uranium	Open Cycle Thermal Reactors[4]	0.04	1.89	3.52	5.41	-	2,000[3]
	Closed Cycle Fast Reactors	negligible	113.00	211.00	324.00	-	120,000
Thorium		6,970[6]	-	-	1,300,000 -2,610,000[6]	-	-

[1] 1 ZJ (ZetaJoule) = 10^3 EJ (ExaJoule) = 10^{21} J (Joule)
[2] Resource Base = Reserves + Resources
[3] Includes uranium from sea water
[4] 1 tonne Uranium = 589 TJ
[5] 1 tonne Uranium = 35,340 TJ, a sixty times increase over the open cycle
[6] metric tonnes, ThO_2