TRANSITION TO LARGE SCALE NUCLEAR ENERGY SUPPLY

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Abstract

We can expect to see the peak of world oil production very soon. Some say that we can see that peak now in our rear-view mirrors as we drive into an oil-poor future. Natural gas already is in short supply in North America. Nuclear energy must make up the lion's share of the world's energy deficit.

This paper examines, in very general terms, the implications of today's shifting prospects for nuclear energy, as it exists today, and how those prospects might develop in the future. The time span under consideration is the remainder of the 21st century.

Introduction

During the working lives of many professionals active today, the nuclear power industry has hovered on the brink of extinction. Will people accept the technology? Who will buy the next plant, and if they buy, at what price? Will the competition get the job? Will government support pre-commercial product development? We all have asked these questions. Now, the questions are changing.

Oil supply analysts[1] agree that world oil production must decline at some time during the 21st century. Huge imports of natural gas to North America will be needed in the near future. Which projection is correct? Will new discoveries solve the problem? Will demand moderate as prices increase? Where can we find alternative energy sources on a massive scale?

Obviously, when looking at a 100-year time frame it makes no sense to propose the solution to energy supply questions. Rather than make such an attempt, the author has chosen to follow published projections as far as they go and then to make reasonable guesses at a series of development steps that can be taken to reach a defined goal at the end of this century. To some extent this process is based on a recent IAEA symposium[2] with the declared goal of looking at the future of the world nuclear industry.

History

Uranium was recognized as a vast potential source of energy from the first days after the discovery of nuclear fission[3]. Leo Szilard[4] quickly recognized its potential for both good and bad purposes.

When R&D for the nuclear-electric industry began in the 1940's and 50's one of the main concerns was the potential shortage of uranium fuel. At the time, exploration for uranium was limited and only low ore concentrations had been found. This apparent resource shortage led to intensive work on fast-spectrum reactors; indeed, the first-ever electricity production from uranium was from a fast reactor-- the Experimental Breeder Reactor (EBR1) in Idaho. During my own time of research at Argonne National Laboratory, a great deal of work centered around calculation of the breeding ratio – a figure indicative of the amount of fresh fissile material that can be produced by a fast reactor power plant.

Dr. W.B. Lewis[5] was deeply involved with the uranium supply question, both nationally and internationally. Both uranium and thorium fuel cycles were studied in detail. The latter element, of course, suffers from a lack of any naturally occurring fissile isotope so that uranium must provide the initial fuel supply. Atomic Energy of Canada (AECL) under Lewis' direction studied several other means of producing fissile isotopes, notably by accelerator-driven spallation reactions capable of producing large numbers of neutrons for subsequent capture in the abundant fertile isotopes Thorium-232 and Uranium-238.

Successful uranium exploration in the 1960's and 70's greatly increased known uranium reserves. Large ore deposits were found in Canada, the Soviet Union and Australia, along with important quantities in several other countries. The total amount of uranium in the earth's crust is immense – and yet we do not know how much recoverable ore might be found in the future. At the present time the supply-demand pendulum appears to be swinging back toward higher prices, as the demand for fresh nuclear fuel increases.

This paper is not a "hard-and-fast" plan for the future. Further, it makes no pretence toward arguing that this future conceptual plan is the only one possible, or even that it may be the preferred plan. The objective of this paper is to illustrate some of the opportunities along with a few of the hurdles that must be passed along the way, in order to realize the vision of a secure and sustainable energy supply in the future world.

The Need for Nuclear Energy

Today's world depends heavily on petroleum, both oil and natural gas. It is still an open question as to what energy source or sources can and will take over the burden once this resource is depleted. Many options are available that can contribute to the solution, but it appears that nuclear energy must be a major contributor[6].

There has been much talk in recent years about the "Hubbert's Peak"[7] of world oil production. According to that model, once the peak has been reached one should expect that only one half of the total resource remains to be found. Now that prices have been high and rising for 5-10 years and yet production has been decreasing over the same period, we can safely conclude that we have passed the peak of world production.

Conservation, along with a number of alternate energy supply options, has been studied for a number of years with limited success. It has slowly become obvious that nuclear energy is the only resource available today that could take over a large fraction of the world demand for oil and gas, and yet remain neither capacity nor resource limited – that is, to be "inexhaustible" or "renewable". There is enough accessible uranium to supply the total present-day demands of humanity for at least several thousand years[8].

The question "How much energy does the world need?" is the most important and most difficult question of all, and well beyond this author's capability to estimate. As a scale comparison, the total world energy demand of the World Energy Council (WEC) 'middle course' scenario in 2050 is given as about 400 million barrels per day of oil equivalent[9]. The WEC scenarios show a slowly decreasing role for coal, a large role for natural gas, and a steadily increasing contribution from solar and biomass at that time. As noted briefly in this paper there is a real possibility for using coal or biomass to manufacture synthetic transportation fuels by adding hydrogen. Nuclear energy can be used in this way to produce fuels that are fully compatible with today's transportation, heating, and other industrial systems.

Since coal and natural gas do not seem to be scarce in a worldwide context, this work concentrates on substitution of nuclear energy for oil – a commodity that is rapidly becoming scarce.

General Industrial Plan[10, 11]

Presumed world oil demand in this study is shown in Figure 1. Up to 2030, the estimate is taken from the 2005 International Energy Agency (IEA) projection[12]. Beyond that time demand is assumed, arbitrarily, to flatten out at 140 million barrels per day.

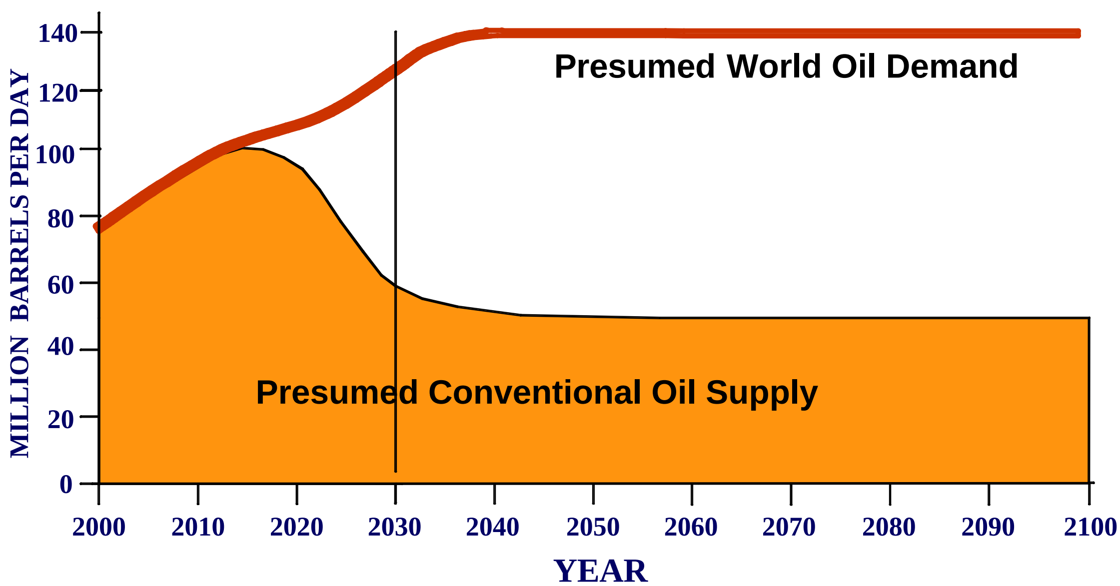

Figure 1: Presumed oil supply and demand vs. time

The supply curve for conventional oil also is taken from IEA figures up to 2030, without non-conventional supply and new discoveries. After that time supply is assumed to flatten out at 50 million barrels per day, or about half of the peak production in 2005. (Note:

There is no presumption that the long-term "Supply" curve in Figure 1 is a prediction of what will happen. The essence of the question is the timing of the expected supply deficit and the fact that it will continue indefinitely into the future.) Some fraction of the deficit between conventional supply and total supply will be filled from other sources such as conservation, introduction of hybrid vehicles, new oil discoveries, wind, solar, and so on. It is important to note that the particular timing of peak world oil production is quite unimportant. It is necessary only to agree that there will be a peak of production, at some future time. In other words it is necessary only to accept the fact that recoverable oil is a finite commodity on earth.

So, what should we do about it? There have been many studies conducted, and many proposals put forward. The present-day situation has recently been summarized[6, 8]. These modern assessments differ little from that described in the International Institute for Applied Systems Analysis (IIASA) study carried out more than 20 years earlier[13]. The main change since the IIASA study is that the needed replacement for fossil fuels is now urgent. Nuclear energy using uranium offers the only practical answer for filling in a major part of the gap between supply and demand shown in Figure 1. Even then, the enormous scale of the replacement task cannot be over-emphasized. This is not to belittle contributions of other renewable resources and conservation. The statement is meant only to emphasize the central role of nuclear energy in any sound plan, regardless of what other partial solutions are adopted.

Substitution of nuclear fuels for fossil fuels in the supply of primary energy is not a simple task. For instance, transportation requires a portable fuel of high energy density and low weight – that is, if we choose to mimic today's pattern of transportation. The refining and distribution of fossil fuels now embodies a massive infrastructure that pervades nearly every corner of North American society. A similar complex infrastructure is seen in the electricity distribution system – it is difficult to scan the horizon in any industrial nation today without seeing some evidence of this second system. Could they/should they be combined in some way? This might increase efficiency, but might at the same time increase the system's vulnerability.

Substitution of nuclear for fossil supply can be approached in different ways. It is possible to expand the electrical distribution system and then to provide local service either for battery-powered vehicles or for some form of hybrid. The next question is whether or not batteries can be developed that can match the excellent characteristics of gasoline- and diesel-powered systems. Today's answer seems to be "not yet" though there is hope that this will be possible soon[14].

A second method of substitution is to produce an intermediate energy carrier[15] such as hydrogen that can be utilized in different ways such as local night-to-day storage for peak leveling, in fuel cells, or as feedstock for manufacture of hydrocarbons. Hydrocarbon production is practiced today in South Africa[16], using an improved process relative to the basic method developed in Germany in the 1920's[17]. Production of hydrogen can be done either by direct electrolysis or by a number of alternate chemical processes. Hydrogen is particularly difficult to store and transport; local generation of hydrogen from electricity is being considered as an alternative to central generation and pipeline distribution. No single method has yet emerged as being superior to others.

Strategies for Installation of Large-Scale Nuclear Supplies

Even though there is strong evidence that the long-term nuclear future must be based on fast reactor technology, almost all nuclear plants operating in the world today are powered by thermal reactors. As a result we must consider the necessary steps in a transition from today's technologies to those appropriate for the long-term future in which the predominant source of primary energy is nuclear fission.

Figure 2 is adapted from an earlier paper[18]. It is a concept sketch of an "energy park", as several authors have discussed over the past decades. This version of the energy park concept includes all components essential to production, from fuel input to waste disposal. These components may of course, be either dispersed or concentrated. It is useful to think of them as being co-located on an "energy island", either figurative or literal. An actual island might be preferred if security and safeguards are assumed to be dominant factors in this postulated future scenario.

Figure 2 can be considered as a "target scenario"; that is, a future energy system toward which we could now aim, while recognizing that its actuality will be achieved only after several steps and stages collectively requiring several decades for implementation. The system includes fuel recycle facilities such as electrochemical reprocessing[19] or direct use of PWR fuel in CANDU (DUPIC)[21].

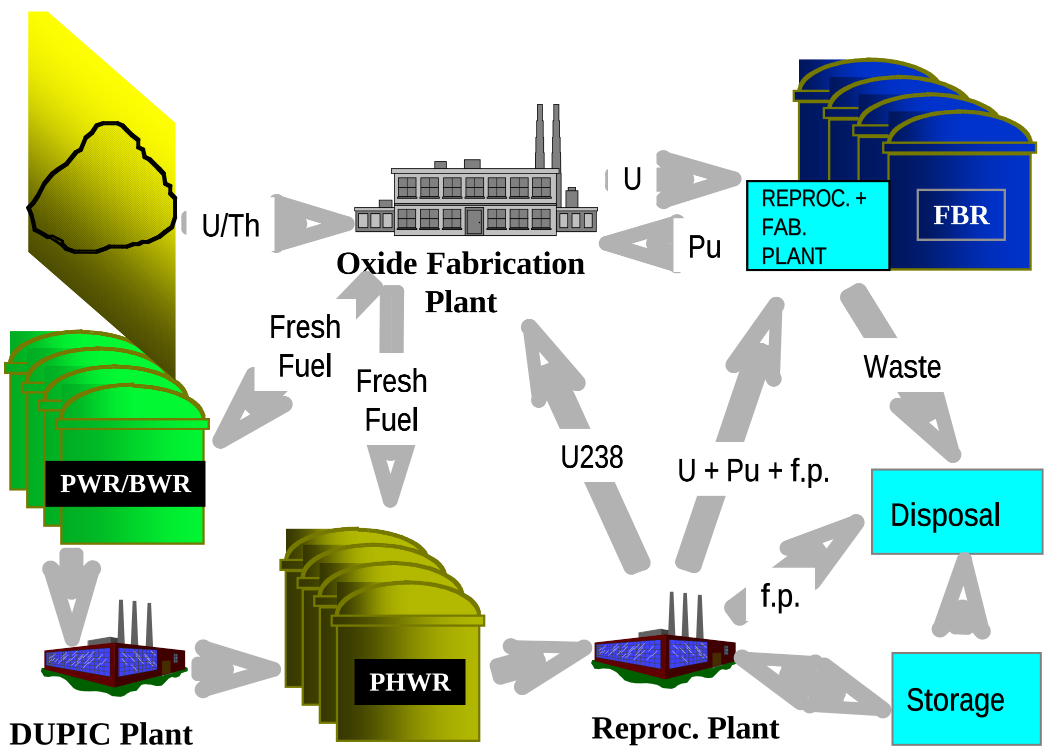

Figure 2 – Conceptual Arrangement of a Nuclear Energy Park

An energy park such as this brings with it several advantages. First it is large, so that costs of perimeter security are distributed over a number of profit centers. In addition, this large scale permits the establishment of a large staff with diverse technical skills, and a revenue base capable of supporting effective waste management systems such as zeolite trapping of radioactive noble gases. Energy from such a facility may be distributed by electrical Plant commitment strategies power lines, via tankers in the case of synthetic fuel production, or in the form of solid products such as industrial chemicals or fertilizer.

Given the high probability of ongoing supply crises in world oil and gas supply during the next couple of decades it is obvious that the only nuclear technologies ready for immediate deployment in large numbers are the pressurized water reactor (PWR), the boiling water reactor (BWR), and the pressurized heavy water reactor (PHWR). All of these reactor types produce electricity at mutually competitive prices. Further, if the authorities that must buy these power plants are conservative in their choice of appropriate technology, these plants are likely to be the same or very similar to plants operating today. As decades pass, new improved designs based on similar technologies will be chosen more frequently as their advantages come to be more strongly assured.

Recognizing that hundreds of thermal reactor plants will be operating before a significant shift toward fast-reactor powered plants comes onto the market, it may be possible to choose some variant of thermal reactor that would make the later transition easier. From the point of view of fuel cycle sustainability, the most important thermal-reactor characteristic is the amount of electricity that can be produced per unit of natural uranium required to supply fuel to the plant. By this measure, the PHWR is clearly superior. Table I shows the energy produced per Megagram of mined uranium[18]. It shows that a fleet of PHWR reactors can produce 30-60% more electricity than can the same number of PWRs, from a given amount of mined uranium. Fuel discharged from a once-through cycle in a PHWR can be sent to a reprocessing plant to extract uranium 238 as well as some high-absorption fission products and produce fresh, recycled fuel.

Table I – Energy Output per Megagram of Uranium Mined

	MWy(e)/Mg
Enriched U in PWR, BWR	4.61
Pu Recycle in PWR, BWR	5.41
DUPIC (PWR-CANDU)	6.37
Natural U in CANDU	6.37
1.2% Enriched U in CANDU	8.77

Another advantage of the PHWR is illustrated by considering a simple equilibrium steady-state ratio of thermal reactors to fast reactors in a combined system where fast reactors provide fissile isotopes to thermal reactors. Wade[10] shows that this ratio is given by the equation

$$\text{Number of thermal units/Number of fast units} \approx (BR-1)/(1-CR)$$

The approximate values of conversion ratio (CR) and breeding ratio (BR) are: FBR=1.4, PWR, BWR=0.6, PHWR=0.8, PHWR(Th)=0.95. Table II lists the consequent ratio of thermal to fast reactor plants for each thermal reactor system.

Table II – Equilibrium Ratio of Thermal to Fast Reactors – Equal Energy Output	
Reactor Type	Thermal/Fast Ratio
PWR, BWR	1.0
PHWR	2.0
PHWR (Th)*	5.0
* Seed-blanket fuelling with Pu-U driver fuel and Thoria blanket fuel.	

When the first fast reactor begins operation the actual ratio will be much larger than this equilibrium value. As more fast reactors are started up the actual ratio will decrease with time, toward this equilibrium. New fast reactors will be fuelled from processed PWR, BWR and PHWR materials along with excess plutonium recovered from operating metal-fuelled fast reactors via electrochemical (pyrometallurgical) processing[19].

Success of the PHWR (Th) system depends entirely on the presumed capability for reprocessing discharged Th-U233 fuel and utilizing the bred uranium-233 in fast reactors. It must be recognized, however, that the achievable maximum breeding ratio with Th-U fuel in a fast reactor is somewhat lower than is achievable in a uranium-plutonium cycle. For simplicity, for this discussion we can lump uranium and thorium together as fuels, because in our integrated system all isotopes of the thorium and uranium series will be totally consumed at some step in the cycle.

A serious restriction on the growth rate of the integrated nuclear generating system arises from the shortest-achievable value of compound doubling time of FBR reactors – which is about ten years. This figure sets an upper limit (about 5 percent per year) on the rate of increase of fast-reactor-powered nuclear stations, even if all the fuel produced is recycled into new units. Of course, if other recycled fuel is available from thermal reactors, this rate can be increased so long as such recycled materials are available. Y.I. Chang[11] gives an excellent summary of these fuel-supply limitations. Clearly, the high cost of fuel would soon limit any system using only thermal reactors because they can utilize only about one percent of the potential energy in mined uranium.

Technologies – What more is needed?

The predominant area of need for new industrial capacity relates to fuel recycle. The technology of the Integral Fast Reactor (IFR) is well established[19], and a viable commercial plant design is in hand[20]. Pyroprocessing is known to work at the bench scale but still must be demonstrated on a larger scale before qualifying fully as a commercial process.

Recycling of used fuel from thermal reactors first requires extraction of uranium 238; separation of some neutron-absorbing rare earth elements via an oxidation-reduction process known as OREOX[21] could be used to improve the recycled product. The product then consists of transuranic elements and some fission products. This mixture is excellent as a fuel for fast reactors.

In a combined fuel cycle system such as this, the last step of the cycle will be located in metal-fuelled fast reactors with integral reprocessing facilities. During this final step (which will include a few recycles within each plant's reprocessing facility), essentially 100% of the transuranic elements will undergo fission. The processing facility output will, as a result, consist almost totally of fission products – an important feature of this fuel cycle, because it reduces the necessary time of waste isolation to five hundred years or less. This eliminates the need for a special long-term waste repository – final waste disposal probably can be located directly under the energy park, in a deep borehole.

Within a static or slowly growing fleet of power plants, provided that more fast reactor units are operating than the equilibrium number indicated above, the configuration of some reactors can be adjusted to reduce the amount of plutonium produced. However, in a growing fleet with fewer than the equilibrium number of fast reactors operating, the total inventory of fissile material will decrease steadily unless more is added from an external source such as reprocessed LWR fuel or newly mined uranium. The total quantity of the first is known, and limited. The quantity of uranium available is flexible and depends on the price that buyers are willing to pay. This 'demand price' can be extremely high in an equilibrium system of thermal and fast reactors because of the enormous amount of energy that can be extracted from each unit of uranium[8].

Clearly, in a system including a supra-equilibrium number of fast reactors every fissile atom has a high value because it represents an opening toward extraction of 100% of the potential energy in mined uranium. Mining, even in very low-grade deposits, still benefits from a strong economic incentive. Uranium enrichment may be required in times of rapid energy demand growth; even in that situation uranium tails may still have positive economic value because of their eventual application as blanket materials in fast reactors.

In summary, the major new components yet to be established are:

- A large and growing fleet of fast-reactor-powered nuclear plants
- An integral pyroprocessing/fabrication plant for metallic fuel at each unit
- Reprocessing plants for recycling LWR and HWR fuels
- Fabrication plants for fuel recycled from LWR and HWR units

Means other than isotopic separation may be feasible for sustaining the fissile isotope inventory in times of rapid electricity demand growth. Accelerator-driven spallation is one such possibility[5]; a fusion-fission hybrid concept also has been proposed[22].

<u>Power Plant Sites and Characteristics</u>

The large scale of nuclear production facilities that may be required might influence our consideration of options. To get an impression of the scale involved, the total output of about 630 one-gigawatt-electric (GWe) nuclear units would be required to replace the daily average energy released by burning gasoline in North America today.

Today's worldwide fleet of nuclear plants comprises about 430 units that in total generate less than 400 Gwe. These plants are accommodated on more or less conventional sites.

However, if plants with a projected total capacity of 5,000-10,000 Gwe are to be installed over the next decades the choice of plant sites will become a substantial problem. Very large sites (up to ~50 Gwe each) will be preferred. These sites would be large enough to sustain a broad array of technical expertise as well as fuel cycle support and security facilities. Comprehensive security systems would be a necessary and affordable feature. Recycling, waste management and disposal systems would be included. Secondary industries such as hydrogen production and synthesis of liquid transportation fuels could be established on the same site. Distribution of energy from such sites will require a large infrastructure – not unlike that surrounding large oil and gas production centers such as those in the Persian Gulf. Manufacture of satellite power systems[10,10a] also may be undertaken. These satellite systems can be considered as a further means of distributing potential nuclear energy from these large central sites.

Site Facilities

An energy center should be built step by step, according to a broad but adaptable overall plan. The Bruce site on Lake Huron provides a good example of how such a complex might begin[23]. The site now includes about 7 Gwe of generation plus a number of support facilities. Some years ago, a conceptual plan[24] was put forward for a multi-stage energy cascade system adjacent to the site. On-site used fuel storage facilities are already in place. Heavy water production plants that were a feature of the site in earlier days are shut down.

The next step of site development could be addition of more generation capacity; if this step is taken in the near future a good choice will be CANDU reactor units, either of the type now operating or the new ACR type. Later on, integral fast reactors might be added as a first move toward a system with a closed fuel cycle. These reactors could utilize the used CANDU fuel now stored on site, given the addition of a processing plant. (There is already sufficient used fuel on site to power an integrated generation complex of ~15 Gwe for several hundred years.) A U238 extraction plant could upgrade this fuel and supply the first charge to each fast reactor as well as recycling mixed-oxide fuel to onsite CANDU units. Depending on the rate of capacity buildup it may be necessary to supply a limited amount of enriched uranium or separated plutonium to the site from external sources.

Depending on circumstances in the external market, management of a mature site such as this might choose to install a number of fast reactors above its equilibrium level, and sell plutonium-bearing fuel to other similar sites still under development under strict international control. The core and radial blanket configuration of each fast reactor can be adjusted to regulate amount of excess plutonium produced on the site.

Fuel Supplies

Fuel requirements are very small at an integrated fast-thermal reactor site. Basically, the amount of fresh uranium needed to sustain a metal-fuelled fast reactor using integral pyroprocessing, located on an ocean site, will be less than the amount of uranium dissolved in the seawater required to cool its turbine condenser (seawater has a dissolved uranium concentration of 3 parts per billion.) In other words, only about 1/100th of the amount of fresh uranium now required per operating megawatt of capacity will be sufficient to sustain generation. The Bruce Energy Centre is a fresh water site; this illustration simply indicates the very small quantity of uranium needed to sustain such an integrated system.

World Nuclear System by 2100

It is possible to imagine a world energy supply system operating in about 100 years. That system could consist of 10,000 Gwe of generation and associated peripheral systems, located on 100-200 sites worldwide. Some of these sites might be dedicated to production of synthetic petroleum liquid and gas as well as a wide range of other industrial processes. At the low-temperature end of production cascades one might find food-related installations such as fertilizer production and fish farming. This network of large energy parks might be interspersed with smaller, independent installations using sealed "nuclear battery" power systems[10]. Reference 10a outlines an extension of this concept.

There is enough uranium available for human use so that this large-scale world energy supply can be sustained for at least several thousand years[8].

Conclusions

This "Blue Sky' concept paper shows that a sustainable nuclear system can be built up, step by step, from components and systems already proven and available today, and augmented by simple extensions of proven concepts – all well within the realm of known technology. Further work is required to guide the selection of reactor types and fuel cycle facilities during development of energy parks. Several prototype facilities must be established before commercial viability can be proven.

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