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Nuclear Energy – The Path Forward

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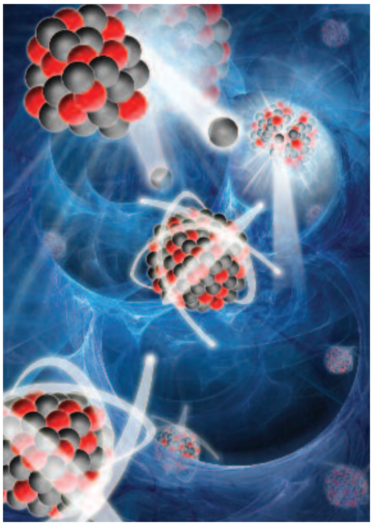


ABSTRACT

Petroleum has been the driving force for building and sustaining societies for more than 100 years. The world now must establish a new primary energy source to relieve the burden on an increasingly scarce and costly petroleum supply. The precise timing is unknown but it is reasonable to assume that, by 2100, a large portion of the world's energy needs must be provided by resources other than petroleum. Uranium is known to be plentiful and, using today's technology, can answer all of humanity's energy needs for at least the next ten thousand years – and likely much longer.

Canada is blessed with several important energy sources and does not suffer from an energy shortage. An indigenous fission energy system named CANDU is fully established, and the required resources of fuel and other materials are available within Canada's borders. Safety, security, and sustainability are demonstrated. It has been shown statistically that uranium energy is cleaner and safer than oil or coal – and best of all, it is available. Canada's uranium resources, both onshore and in adjacent oceans, are truly inexhaustible.

This chapter proposes the concept of large nuclear generating sites producing both bulk electricity and process steam, for use by adjacent industrial parks comprising many high-affinity, energy-intensive industries. A key feature of this concept is that of the "energy cascade" where the inputs and outputs of different industrial activities are both complementary and mutually supportive. Ontario's Bruce Energy Centre is presented as an "example case" of the implementation of a number of these ideas.

Introduction

Commercial nuclear energy systems, now more than 50 years old, utilize a mature technology. These systems are ready to be used more widely in the provision of energy for the benefit of mankind. At the same time, these systems have been applied mostly to one aspect of the needs of society; that is, the production of electricity. A significant opportunity exists to meet many future needs by broadening the market base of nuclear energy to other industrial activities. Scaling up this new primary energy supply is an engineering task of the highest magnitude. It is no longer a subject for scientific research except at the margins; the relevant scientific facts are already well known.

This chapter outlines the major opportunities for diversifying the market for nuclear energy over the next half-century and beyond. The associated challenges form an integrated set ranging from the purely technical to abstract questions of sociology and philosophy, as expected when a major innovative change is introduced to any society. They also touch on broad matters of public policy as well as on future development of the world economy.

Today's challenges to the nuclear industry arise from the world's well-known energy-related challenge; that is, to address climate change by establishing a clean and sustainable alternative to fossil fuels. There may only be two greater challenges: that of managing world over-population, and that of providing sustenance to the billion or more people who still survive with only the most limited access to essential resources. According to the author of the book "The Bottom Billion" (Collier, 2007), these people may be best served in the near term through at least two development phases. In the first phase, restraint in fossil fuel use by the richest societies would result in greater fuel availability for the poorest. If the richest were to fully embrace nuclear energy, the price of fossil fuels would fall, thereby making fossil fuels more affordable to the poorest who then would have a better opportunity to improve themselves. In the second phase, once the basics were established, they could choose their own path. Motivation for the richest to make a change will come from the lower cost and increased cleanliness of nuclear energy when compared with fossil fuels.

Some people believe that petroleum is not, and never will be, in short supply. Better-qualified and more convincing persons and organizations point out the error of this thinking. The world now uses about 1000 barrels of oil in each second of every year (Tertzakian, 2007). This cannot last. As stated by the Chief Economist of the International Energy Agency (Birol, 2006), "We have to leave oil before it leaves us." The world must soon switch to an available, boundless, alternative fuel – uranium (Lightfoot et al, 2006).

Assuming a plant capacity availability factor of 90 percent, the heating value of oil being consumed in the world today is equivalent to the total fission heat produced by at least 7000 nuclear units, each with an equivalent electrical production capacity of one billion watts. This is no doubt a large job, but it is feasible. There is little time to meet this challenge; using the most optimistic assumptions, the job should be completed before the year 2200. This massive change will require the goodwill and the efforts of many thousands of people, backed by both their governments and by the population at large.

Canada's challenges are simpler than are those in the wider world. As one of the great democracies of the world, Canada has a single social system, and the necessary resources, tools, and skilled manpower. Canada already owns a fully developed nuclear energy technology in the CANDU (CANada Deuterium Uranium) system. With strong will and leadership, Canada can install new nuclear plants as a clean, sustainable alternative to fossil fuels and also provide guidance to other countries that share this similar goal.

The Starting Point: Aiming for the Long Term

At the 2013 winter meeting of the American Nuclear Society, Jim Rogers of Duke Energy spoke of the need for "Cathedral Thinking" in planning the world energy supply system. Rogers identified the concept some years ago (Zakaria, 2007). Energy system development is a long, slow, and difficult process similar to that employed in the building of a large cathedral. It requires careful thought, coupled with a large measure of hope, a willingness to take risks, and above all a vision of a better future. Leaders in Canada must begin to practice "Cathedral Thinking." The likely alternative is chaos and starvation.

Humanity is fast approaching a major shift in its environmental and physical health due to a seemingly accelerating and possibly disastrous change in climatic conditions. It is widely accepted that this trend is driven by the accumulation of greenhouse gases in the atmosphere due primarily to the widespread use of fossil fuels. These same fuels are, today, vitally important to human prosperity. Furthermore, the coming environmental crisis may be exacerbated by a shortage of affordable petroleum — the most valuable of available fossil fuels.

These impending difficulties have prompted a number of people to search for means of alleviating the problems on both the demand and the supply side of energy use. These studies rapidly concentrate on the demand side because of the steadily increasing world population and the near-universal aspiration for a better quality of life. Many of these studies, as evidenced in Cohen, 1983 Till 2005; Lightfoot et al, 2006, focus on the positive features of energy from uranium fission because of the vast scale of this resource, its proven feasibility, and economic attractiveness.

What We Have Been Given

The fact that Canada has many cool lakes suggests that ample heat sinks are available for the generation of electricity using conventional Rankine cycle heat engines. Many of Canada's lakes are conveniently located in remote regions, far from population centres, but well within the reach of high voltage transmission lines.

Uranium and thorium are in abundant supply in Canada and the world. Canada has also developed a mature and economical method of producing electricity from uranium, and probably also from thorium. The CANDU reactor is economically competitive with other modern uranium-fuelled plants, and has at least as good a record of safe operation as held by other first-rank reactor designs. Canadians today operate nineteen of these superb machines.

A view of the Bruce Nuclear Generating Station (BNGS) as it appears today is shown in Figure 1. Units 5 to 8 are visible in the foreground while units 1 to 4 are seen in the far background. The small white dome in the left foreground contained a prototype reactor known as Douglas Point that now has been decommissioned. The eight operating Bruce units normally produce some 6300 megawatts of electricity for Ontarians, about 30 percent of the total provincial demand.

Canada has many manufacturing industries that can utilize electricity and hydrogen. These are the best available energy currencies to produce the wide range of finished products useful to modern society around the world (Scott, 2008). Canada also has access to markets through which these products can be sold.

Figure 1
The Bruce Nuclear Power Development Site on Lake Huron

The Next Big Project

It is well established that fission chain reactors can be built to provide reliable electricity. What is now proposed is to broaden the product diversity of future reactors to include other commodities needed by a prosperous society. An excellent beginning in this direction was made more than twenty years ago with the development of the Bruce Energy Centre (BEC) on Lake Huron (Gurbin & Talbot, 1994). Figure 2 provides a broad outline of the concept, consisting of an energy cascade powered by uranium energy. To drive this cascade, in addition to producing electricity, the first four units of BNGS were fitted with steam transformer units. Excess steam to electricity generation needs was sent through the transformers to produce lower-pressure steam in their secondary circuits. This steam was directed to the site-wide bulk steam system, including the BEC steam line.

Delegates to the Engineering Institute of Canada's third climate change conference (Engineering Institute of Canada, 2013) recognized that energy, water, and food form the nexus of human material needs – those which engineers are fully equipped to provide. Energy lies at the very centre of these basic needs; without plentiful energy, it is not possible to "engineer" any of the other solutions.

Canada, and indeed the whole world, needs to look beyond those energy-rich resources that are already in service and toward every plentiful and economical new resource that is available for use in the future. As is true in most parts of the world, uranium is plentiful, if only at low concentrations. Even tiny concentrations of uranium, however, can become important reserves if Fast Neutron Reactor (FNR) technology is introduced. This is due to the fact that each gram of uranium yields a very large amount of energy if irradiated by high-velocity neutrons in this special type of fission reactor. Of course, this fact also means that uranium can be imported or exported without any concern about disturbing the balance of trade, because so little uranium is required to support a large fleet of fast reactors – only two tons per year for each one thousand megawatt electric power plant.

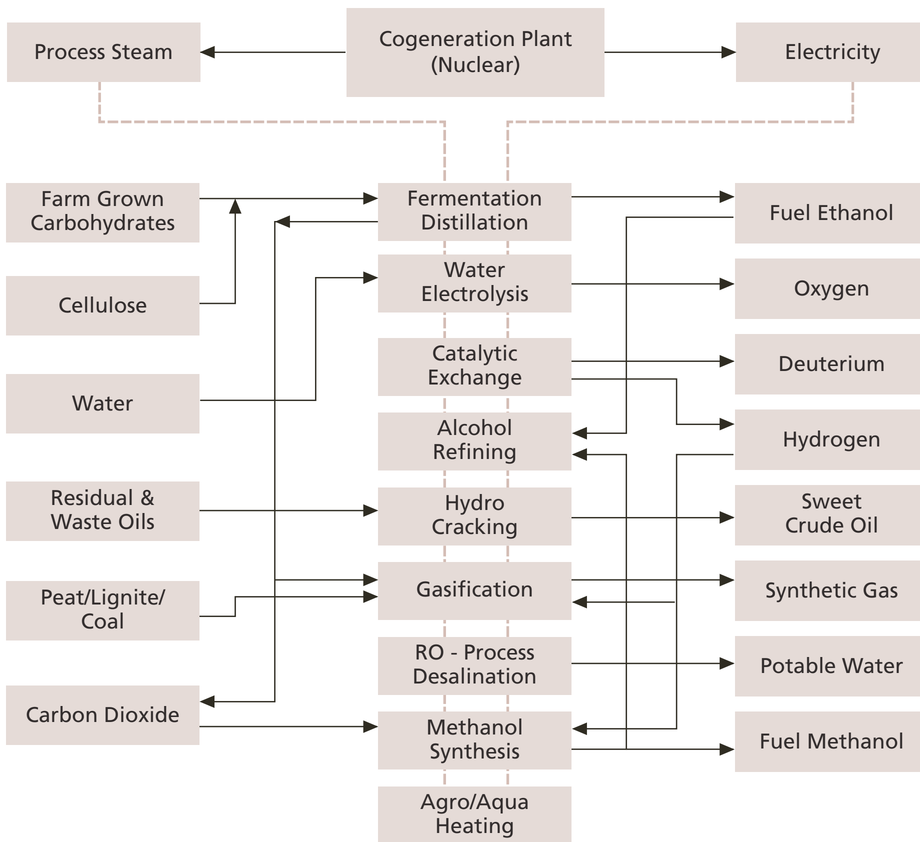
Canadians are familiar with the CANDU reactor that has operated successfully around the world for more than 50 years. CANDU is a thermal reactor, in which most fission is initiated by so-called "slow" – also referred to as "thermal" – neutrons (these "slow" neutrons actually move quite fast – about 8,000 km/hr.). It is recommended by many technical experts that Canada should embark on a venture toward adding the fast neutron reactor (FNR) that offers excellent support advantages for a reactor fleet containing CANDU power plants. FNR reactors have been operated for several decades in a few countries; Russia, China, and India are building this reactor type today. All fission takes place at high neutron velocities in this reactor. At high neutron velocity, the physics of the process is even more advantageous than in the low-velocity CANDU reactor (Till & Chang, 2011). By leveraging their complementary strengths, these two reactor types together offer significant advantages compared to either of them working as independent, stand-alone units.

Drawing on the analogy of the oil fields in the Middle East, Canada - using technologies available today - can establish a local energy supply larger than that offered by all of the Middle East petroleum producing countries taken together. Furthermore, this "Saudi in Canada" concept can be cheaper, cleaner, and more sustainable than those Middle East oil and gas fields. A recent paper (Meneley, 2010) outlines some of the characteristics of a typical industrial complex centered on nuclear power plants, using the Bruce site on Lake Huron as an example.

A Beginning – The Bruce Energy Centre

This bold idea (Gurbin & Talbot, 1994) was founded on the recognition that the Bruce nuclear plant could supply steam in excess of the capacity of its four turbine-generators. A 24-inch steam main and a 10-inch water return line were built to supply steam generated in steam transformers. The steam, along with electricity as required, was to be delivered to a large tract adjacent to the BNGS site, and was to service an energy cascade similar to that shown in Figure 2.

Figure 2
Example of an Energy Cascade Powered by Nuclear Electricity and Steam



Steam from Bruce nuclear plant could be diverted to the BNGS bulk steam supply system to provide energy for the production of heavy water, to heat buildings within the development, and to provide energy for industries at the Bruce Energy Centre at the boundary of the site. One of the largest bulk steam systems in the world, this system was capable of producing 5,350 MW of medium-pressure process steam from the reactors' high-pressure process steam (CNWC, 2014).

Views of the existing Bruce Energy Centre (BEC) are shown in Figure 3. The original concept relied on a supply of low-cost steam from the Bruce reactors. That supply was terminated when Bruce units 1 to 4 were shut down following decisions made by Ontario Hydro senior management in 1997. While the Bruce units 1 to 4 have since been refurbished and are now fully operational, the steam transformer system has not been reactivated.

Figure 3
Views of the Bruce Steam Line and the Bruce Energy Centre

In 1996, a new oil-fired steam plant was constructed to replace the then-inoperable units of Bruce 1 to 4. This plant can deliver up to 250,000 pounds per hour of steam at a pressure of 300 pounds per square inch. This temporary arrangement is unsuitable for the longer term.

Bruce Energy Centre was a great beginning. It is an outstanding example of what can be done with goodwill and determination to expand the future prospects for Canadians through the utilization of home-grown technology – technology that can make many other things grow to the benefit of all Canadians.

Potential Energy Centre Systems

Adjacent to a large nuclear generating site such as Bruce, one might establish a large industrial park similar to the Bruce Energy Centre. As mentioned previously, such a site would benefit from the proximity of bulk electricity and steam, and be home to a number of enterprises, each benefiting from their unique location.

Basic Processes

The left-hand column of Figure 2 shows the raw materials that could conceivably be input to the Bruce Energy Centre. The original concept was that these materials would be transformed through the judicious application of nuclear process steam and electricity into useful products as shown in the right-hand column. The production processes were aligned as a cascade in which the steam enthalpy requirement for the next step of the cascade matched the discharge enthalpy of the previous step to take advantage of the steadily decreasing enthalpy of the process steam. The promise of the Bruce Energy Centre, however, was crippled by events beyond control of its founders. The temporary closing of the Bruce units 1 to 4 in 1997 drastically raised the price of process steam. Future economic viability of energy centers such as this will depend on the availability of cheap process steam from nuclear units.

The mixture of intermediate and final products shown on the right-hand side of Figure 2 is by no means exhaustive, and virtually any process that requires a unique input material and that needs some combination of electricity and steam could benefit from association with the Bruce Energy Centre.

High temperature process steam produced by electrical heating of high-pressure water is an additional input that can be added to the list in Figure 2 and can be supplied by CANDU reactors. While the economics of this supply of high-temperature process fluid are unknown at this time, there is no question that such operation is technically feasible. The process steam temperature associated with a fast neutron reactor system will be about 550 Celsius, which is high enough to support the Copper-Chloride process of water splitting (Naterer et al., 2013).

A number of industrial processes, such as steel-making, depend on the availability of high-temperature process gas which, in turn, appears to work against the CANDU reactor because of its relatively low operating temperature. These reactors, however, are fuelled with cheap natural uranium and have very economical fuel manufacturing processes. One convenient source of high temperature process gas is the plasma torch (Plasma Torch, 2012) that requires direct-current electricity, normally provided by a DC converter connected to a conventional AC power supply. In principle, an electrical plasma torch could be used to raise the temperature of the process fluid to the level required by the Copper-Chloride water splitting process mentioned above.

Synthetic Petroleum Production

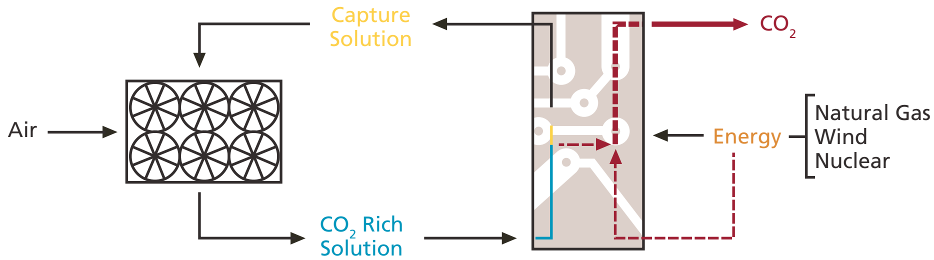
As detailed by David Sanborn Scott (Scott, 2008), hydrogen and electricity together can provide the essential energy currencies on which to base a strong industrial society. Electricity can be produced with relative ease from uranium (or thorium) in fission chain reactors. The reverse process, that is converting energy to mass (stored energy) in the form of hydrogen or hydrocarbons, is more difficult. The most promising method for hydrogen production is a combined chemical-electrical process now under development (Naterer et al., 2013). This process splits water into hydrogen and oxygen; hydrogen then can be combined with carbon to produce synthetic petroleum or natural gas. Some of the valuable mass is lost (and converted back into energy) in this chemical reaction, but the resultant hydrocarbon molecules are much easier to manage than hydrogen. The massive infrastructure currently used to store and transport natural petroleum products can be utilized directly for this purpose.

To provide an idea of the scale of electrical systems required, the direct energy equivalent of 300,000 barrels of gasoline, an amount comparable to that consumed in Ontario each day, equals the total electrical energy output of eighteen large (1.0 GWe) nuclear units. In other words, Ontario's daily gasoline demand corresponds to the total electrical output of about twenty nuclear units. Manufacturing synthetic gasoline is an energy-intensive industry due to the process of converting energy to mass, according to Einstein's famous equation ($E=mc^2$). Aside from inevitable efficiency losses inherent in this conversion process, energy - after being converted to mass - remains stored in the gasoline product to be released later on as needed.

But where does one find carbon to combine with the nuclear-produced hydrogen? Commercially, the correct answer is "from the cheapest source." One's first thought might be that any artificial petroleum process proposed here must add to the atmospheric carbon inventory. Research by Carbon Engineering in Calgary (Holmes et al., 2013), however, is aimed at extraction of carbon directly from ambient air. If successful, this would mean that the same amount of carbon dioxide could be continuously cycled from the liquid hydrocarbon phase to the atmospheric phase, and then back to hydrocarbon.

Figure 4 illustrates the direct capture process in a simple form. Energy is required for circulation of the capture fluid, for operation of the air-flow fans, and for extraction of carbon dioxide from solution.

Figure 4
Carbon Engineering Direct Air Capture Process



Capturing CO_2 directly from the air allows emissions originating from any source to be managed with standardized, scalable industrial facilities. Carbon Engineering's full-scale design, for example, could absorb the emissions created by 300,000 typical cars.

In research conducted at the University of Calgary, David Keith and a team of researchers showed it is possible to reduce carbon dioxide (CO_2) – the main greenhouse gas that contributes to global warming – using a relatively simple machine that can capture the trace amount of CO_2 present in the air at any place on the planet (Keith, 2008). Figure 5 shows the Carbon Engineering prototype system (Holmes et al., 2013).

"At first thought, capturing CO_2 from the air where it's at a concentration of 0.04 per cent seems absurd, when we are just starting to do cost-effective capture at power plants where CO_2 produced is at a concentration of more than 10 per cent," says Keith), "but the

Figure 5
Carbon Engineering Outdoor Air Capture Prototype

(Holmes et al., 2013)

Carbon Engineering's air capture prototype uses an oxy-fuel natural gas kiln to drive the CO_2 out of the solid calcite.

thermodynamics suggest that air capture might only be a bit harder than capturing CO_2 from power plants. We are trying to turn that theory into engineering reality."

This research is significant because air capture technology is the only way to capture CO_2 emissions from transportation sources such as vehicles and airplanes. These so-called diffuse sources represent more than half of the greenhouse gases emitted on Earth.

"The climate problem is too big to solve easily with the tools we have," notes Keith. "While it's important to get started doing things we know how to do, like wind power, nuclear power and 'regular' carbon capture and storage, it's also vital to start thinking about radical new ideas and approaches to solving this problem."

Short and Medium Term Electricity Storage

Many people think that large nuclear power plants cannot be operated to adjust to short-term electricity demand fluctuations. In fact, existing CANDU units, and many others (World Nuclear Association & EDF, 2010), are designed to maneuver daily. CANDU units can do so down to about 60% of full power and return. Smaller power reductions are, of course, easier to accommodate. It is true, however, that power maneuvering is an expensive procedure for a large generator with relatively high specific capital cost and low fuel cost. Experience has shown that frequent reactor power changes may cause increased failure rates of plant components. Subsequent aging of units, resulting in the tightening of operating limits, makes daily maneuvering even more difficult.

Alternatively, it is possible to divert excess generating power to secondary generators (Forsberg, 2011). Night-time storage of hydrogen and oxygen, followed by daytime burning of these gases in specialized gas turbines, provides an efficient electrical system with peaking capacity. Modern electronic DC conversion technology could instantaneously divert electric power to hydrogen electrolysis loads, thereby maintaining fission energy production at maximum levels while producing a second, valuable energy currency. This capability would be most practical for CANDU reactors because of the low cost of natural uranium fuel.

Storage of electricity involves the same basic processes as the production of synthetic petroleum. Energy is used to produce mass, which can then be stored.

Hydrogen production provides the opportunity for extraction of two other valuable products. The first is oxygen and the second is deuterium. Deuterium is a rare isotope, present in natural hydrogen, in concentrations of approximately 1 in 7000 molecules. It is a vital component in the CANDU reactor. Deuterium can be extracted from hydrogen gas using the combined electrolysis catalytic exchange process developed by AECL some years ago (Hammerli et al., 1978).

Industrial Steam Supply

The Bruce Energy Centre (BEC) utilized medium-pressure steam produced on the secondary side of steam transformers. The maximum energy delivery was approximately 300 megawatts thermal. This steam was used by a variety of facilities on the BEC site.

Other Suitable Energy Centre Industrial Processes

As illustrated in Figure 2, many other processes could benefit from the ready availability of economical heat and electricity, not to mention processes based on a variety of agricultural or biomass feedstocks. These include fermentation, distillation, ethanol and methanol production, and purification of water via reverse osmosis. It may also be worth examining the feasibility of connecting a DC generator to the main AC generator shaft, so that bulk DC power would be available on-site (Scott, 2009) or, alternatively, the addition of electronic converters to provide bulk DC power supply to the site.

Collaborative Operation of CANDU and Fast Neutron Reactors

A fleet of CANDU power plants can benefit from the exchange of nuclear fuel components within fast neutron reactors (Meneley, 2010). The fast neutron reactor (FNR) creates an excess of fissile isotopes, while a normal CANDU plant is always a little bit short of those same isotopes. At the same time, used fuel discharged from CANDU reactors contains exactly the mixture of heavy elements (actinides) that are necessary for the first fuel charge of any fast reactor. There is significant merit in considering fuel cycles integrated between these two nuclear reactor types within the same industrial park.

Fuel Production, Reprocessing, and Waste Management

These separate support functions could be established either at the energy park or might be separated by some distance, depending on site and other conditions. Fuel production for the reactors located at the main site, or even fuels for use as export commodities, might be associated with the energy park to some degree.

A large energy park might include the capability of supporting much smaller remotely located power reactor facilities such as the Secure Transportable Autonomous Reactor (STAR) concept (Wade, 2010). The idea is to deliver a "package" system to a remote site, in a style similar to a conventional battery. This nuclear battery would, however, be capable of delivering megawatt-scale energy supply for several years, after which the "package" would be returned to the energy park for reprocessing. A fresh "package" would be shipped to the remote site. A simple system might consist of a large nuclear plant, local electrical grid, and boilers positioned at or near each major wellhead. Cheap nuclear fuel could make such a network feasible.

Establishment of Functionally Separate Energy Centres

A large nuclear energy park might be developed as separate components; that is, large-scale electricity generation might separate naturally from the growing industrial facilities. The main reason for such separation is the special security and radiation protection requirements at a so-called "nuclear" site. Other industries also may have unique hazard characteristics that might best be isolated from nuclear site safety and security requirements – such as deuterium production using hydrogen fluoride gas. It might also prove advantageous to separate the facilities supported by fast neutron reactors – which, as pointed out in the next section, will likely NOT be primarily bulk electricity producers– from the purely electrical utility functions. Once again, security and unique hazards may be sufficient cause for separation of the various industrial components.

Challenges

The Nuclear Fission Enterprise

Transition from a successful stand-alone thermal reactor fleet to a combined thermal and fast reactor fleet will be difficult for several reasons. The first, and perhaps most difficult task, will be to convince operating organizations of the need for change. They have been operating Generation II or III reactors for decades and the price of fuel has always been a small fraction of the total operating cost. The price of fuel will rise in the future, however, and (perhaps the most convincing reason) the volume of stored used fuel on the site will someday reach difficult proportions.

The above suggests the establishment of a purpose-built fast neutron reactor (FNR) site that serves three primary functions. The first is for processing used thermal reactor fuel into minor actinides, fission products, and Uranium 238. The second is for producing energy (both electrical and thermal) from recovered minor actinides plus a small part of the U238 recovered in the separation process. The third is for storing excess recovered U238 in an adjacent underground storage facility that is sufficient also to retain fast reactor waste products (fission products), and to separate useful fission products from true waste. The U238 would be utilized as needed to sustain long-term FNR operations. Given the expected quantities of actinides and uranium on the site, the fast reactors will never need an off-site source of fuel, after their first startup.

The FNR is, by its nature, a potential net producer of fissionable material. This material could be fabricated into new fuel assemblies to be used either to fuel new fast neutron reactors or to provide thorium fuel containing fissile topping for thorium-fuelled CANDU reactors.

The primary purpose of this distinct type of nuclear site may be to produce products other than electricity. It will not likely be owned solely by a single entity, but rather by a consortium led by a provincial or national government, with the operation of particular industries "farmed out" to specialist organizations. In short, it is an industrial complex whose goal is development of energy-related enterprises for the benefit of the whole nation, and possibly of the wider world.

Synthetic Oil Production

The primary technical challenge in this case is to determine whether or not it is feasible to produce sufficient synthetic petroleum economically to replace all or at least a significant part of our natural petroleum supply.

The best known case of such production was in South Africa some years ago, when the petroleum embargo forced the company known as SASOL (Sasol, 2014) to produce oil from coal by means of an improved version of the Fischer-Tropsch (National Energy Technology Lab, 2014) process developed in Germany before World War II.

Recently, a number of large oil companies have investigated oil and gas production options utilizing coal, oil, and other basic hydrocarbon sources. None of these, however, have looked at the possibility of using cheap uranium as the basic energy source for synthetic fuel production. The most advanced analysis of this type was published in the MIT white paper by Bersak & Kadak, 2007. The specific application was for extraction and upgrading of product from Alberta's oil sands. As such, this application is not "portable." At the same time, the essential added ingredient, once hydrogen has been produced, is a cheap source of carbon. Hydrocarbon is, after all, the energy storage medium "chosen" by nature and one from which humanity has derived great benefit.

Strong support for the feasibility of synthetic oil production can be found in a recent US Navy report (Williams et al, 2010). The authors propose using shipboard nuclear power to produce hydrogen, along with carbon dioxide extracted from seawater, to produce jet fuel. Cost analysis of this system is shown to be highly favorable. The present context using commercial-scale nuclear plants and air-derived carbon dioxide (Keith, 2008) should be even more feasible. Obviously, work must be done before such a system could enter commercial service – and proving out a land-based system will take time. But, the system looks promising for the longer term.

Nuclear Waste Management

While this issue is not a major technical concern within the technical community, it has become a "signature" issue among those dedicated to the opposition of the use of nuclear energy. It is important to address this issue in some depth.

The materials we now identify as nuclear waste have been present in our environment since the earth was born. Ionizing radiation strikes our bodies every second of every day. We have evolved into our human form in the presence of ionizing radiation. We inhale radioactive materials, we eat them, and we carry them in our bodies from birth to death. Because ionizing radiation is so pervasive, our bodies have adapted to constant irradiation. It is true that irradiation causes damage to our cells. It is also true that there are many other damage mechanisms, some much more damaging than radiation. Fortunately, powerful defenses exist. Our cells have adapted by producing the means for repairing damage and rejecting badly damaged cells, so that we live normal lives, unaware of all those events going on inside each of us.

When the centre of an atom changes by releasing a particle, energy is released. The fact that energy is stored inside atoms makes them interesting. Heat is released from the breaking up of atoms, in exactly the same way as happens during the burning of fossil fuels, except for a unique advantage granted by the virtually limitless supply of energy available from fission of uranium or atoms. We know that the supply of electricity from uranium can continue for at least as long as humanity exists on this planet. The broken fragments of atoms have done their work. Energy has been released and used to make electricity. Some of these fragments or "fission products" emit intense ionizing radiation, most intensely in the first seconds after fission. The intensity of this radiation decreases steadily but continues at a low level for many years. Used fuel material eventually will become almost identical to the uranium ore first taken out of the ground.

Used CANDU fuel is not waste. It still contains more than 99 percent of the potential energy of the original uranium. Only a very small portion, less than 1 percent of the mass, is strongly radioactive in the short term after being in the reactor. Used fuel bundles are handled, at first, by computer-operated machines that take them out of the reactor for wet storage and place them in racks in deep water-filled pools at each power station. At this point in time they are dangerous, giving off both heat and intense ionizing radiation.

After a few years, both the radiation and heat production levels are sufficiently low that the bundles can be moved for dry storage in concrete and metal-lined canisters; the small amount of heat still being produced by the used fuel bundles is taken away by conduction and air convection. The canisters usually are stacked in a regular array on the reactor site or at a central storage location. Fuel could, in principle, remain safely stored in these canisters as long as the concrete and steel last – at least several hundred years.

Used fuel three hundred years old (or even much younger) could be processed very easily and safely should our descendants want to recover the remaining 99 percent of the potential energy still resident inside the old used fuel (this is good fuel for fast reactors). Alternatively, the canisters could be moved to an underground repository or new canisters could be built, the fuel could be moved to them, and the cycle repeated. It would be truly presumptuous of us to try to foretell what these people will do with the fuel – each of the above three options can be chosen with a very high assurance of safety.

Assuming that our descendants choose to simply place the used fuel bundles underground, it will be feasible for them to copy, or to improve upon, the characteristics of geological formations that exist today – and will exist then, three hundred years from now. Such formations are known to have trapped massive quantities of uranium and other radioactive materials for billions of years.

Canadian plans for long-term waste management of used nuclear fuel are in good hands. The Nuclear Fuel Waste Management Organization (NWMO) was mandated to do the job by the Canadian Federal Government (Government of Canada, 2002); they are now considering options to select one informed and willing community to host this important facility. Their work is funded by nuclear plant operating organizations. There is plenty of time – used CANDU fuel is and will continue to be safely managed – NWMO expects that selection of a location may require several years of work.

Nuclear waste management entails no significant danger either for today's generation or for future generations of society. The small volume and simple containment of these materials entails no significant risk to the human environment.

The Issue of Economics

While nuclear generating stations are expensive, they are in the same class as expressways, hydroelectric works, production oilfields, standing armies, and other elements of national infrastructure. These enterprises all share the characteristic that they are national enterprises intended to serve the community as a whole. Large portions of these systems might be built by private enterprise but, in the end, their natural owner is the provincial or national government. "Ownership" might be expressed in a number of different ways, such as direct management, indirect regulatory control, "permitting" of business activities, collection of royalties, or via taxation. The common factor is that the enterprise cannot and does not proceed without government permission of some sort.

Given the fact of government control of the nuclear energy enterprise, it follows that this activity must be deemed of value to the nation before the enterprise actually begins. Given the fact that the enterprise is intended to benefit the whole community, it follows that both expenditure and revenue should be shared with that community.

Ontario has a strong industrial base, as is evidenced by the knowledge that more than nine-tenths of the total cost of the Darlington Generating Station was expended in Canada, with the majority of the cost incurred in Ontario. It is fair to say then, that the main expenditure was represented by the energies of the people who designed, manufactured, and constructed the plant along with those who now operate it. It can be expected that future nuclear capacity expansion will have a similar ownership distribution, and will bring strong benefits to Canada's economy.

Public Acceptance

The most powerful factor that delays utilization of uranium and thorium to produce plentiful energy is the fear of ionizing radiation – a primordial fear that need not have a basis in reality. Spencer Weart presents a careful analysis of this phenomenon (Weart, 2007). Many people fear ionizing radiation without understanding that it is actually a very weak carcinogen – in other words, this fear is based, wrongly, on fear of cancer (Cuttler, 2013). This climate of dread has been stimulated and sustained by a variety of opponents set against the utilization of nuclear energy. The underlying motives of these opponents range from sincere dislike of everything nuclear to obvious self-interest, mostly driven by the possibility of losing market share. Political opposition tends to support uninformed public opinion and is likely driven by an overwhelming desire for re-election.

A large amount of scientific research has been conducted to elucidate the effects of ionizing radiation on live cells and their reproduction. The findings are complex but nonetheless strongly support the case that the earlier assumption that damage is proportional to dose, all the way down to zero, is incorrect. In fact, low doses of radiation may be beneficial to health; at least, there is no net negative effect. Recognition of this established fact by the public and by health regulatory agencies would lead to a profound improvement in the public perception of the whole nuclear enterprise. Wade Allison (Allison, 2013) has given simple and useful advice in consideration of this issue:

"There are 3.5 things to be said in a public forum:

1. Radiation is almost harmless (Fukushima, Chernobyl, Goiania, etc.)
2. Fear of low doses of radiation is very dangerous and has killed many and caused great economic damage, in Japan and around the world for no benefit. This fear, perpetuated by ALARA, was inspired by WWII and the Cold War (but not linked to UV in sunshine).
3. Medium and high doses of radiation as used in medical scans and radiotherapy are highly beneficial and widely appreciated

3.5. Finally, radiobiologists have shown that low chronic exposure to radiation actually reduces cancer risks (which is not surprising if you think about it)."

The essence of Dr. Allison's argument is that fear of radiation is a problem of leadership. The lack of leadership is shown in both government and professional organizations. One suspects that the governmental problem arises from the fact that much "scientific" opinion falls within the jurisdiction of government-controlled bureaucratic organizations that confuse policy imperatives with the very real need for truth about ionizing radiation.

A closely-related and greatly exaggerated fear is of "radioactive waste," or more precisely that of used reactor fuel, that must be isolated and stored for a long time. Ted Rockwell (Rossin, 2013), a pioneer of radiation study and effects, maintained that there is no problem with used fuel as long as it is treated with reasonable care and attention – as we must also treat many other articles we use in our ordinary lives. Rockwell's statement succinctly captures the essence of a complex issue. As evidenced above, effective nuclear waste management strikes a balance between seizing the vast opportunities for additional energy in used reactor fuel, and storing it safely in the meantime. Further, safe storage of used thermal reactor fuel is not expected to be difficult over the next few hundred years. In the very long term, the advent of FNR reactors promises a definitive solution to the waste disposal question.

In recent years, a number of environmentalists have come to the realization that nuclear energy, though it must be treated with care and due caution, is the best hope for sustaining our energy supply and thereby our social stability (Stone, 2013).

The broader world outside the so-called developed economies has already made the decision to install large capacity nuclear generating stations. It is to be expected that the demonstrated success of these foreign ventures, combined with steadily increasing costs and prices associated with fossil fuels at home, will finally result in a change of opinion in Europe and North America, so that a sustained "nuclear renaissance" can arise.

It is well established that acceptance of major activities such as this one are founded on trust. In Canada, public acceptance is a rare and precious commodity, difficult to earn and easy to spend. The good news is that public trust is increasing, especially in the domain of nuclear power plant operations. This aspect of acceptance will become more and more important as the number of successful operating stations increases. In contrast, research and development directed toward new plant concepts will gradually become less important as the industry reaches full maturity. Few energy studies recognize this reality but concentrate instead on government, research, export issues and similar subjects (Public Policy Forum, 2014). Meanwhile, the utilities operating nuclear plants work steadily to build their reputation for economy, reliability, and safety.

Public acceptance and trust grows from clear evidence of good performance over a long period of time. The operating organizations are therefore the logical base from which to expand public acceptance. In Canada, it can be seen that government backing and support normally follows public acceptance rather than leading it. The message, then, is to work from the utility operating history toward the goal of general public support for the nuclear enterprise. Development of designs and basic research should now follow what the market (i.e. the utility group) requires. Generally, this leads in the direction of evolutionary rather than revolutionary changes in design, construction, and operation.

The Long-Term Prospect

The central idea suggested in this chapter is that uranium energy can and should be applied much more broadly in society rather than only to the production of electricity, as it is today. Broadening of the market for nuclear energy to the full range of energy-intensive industries can significantly impact Canada's ability to add value to a variety of products while reducing the carbon footprint of energy production and use.

Any energy and industrial facility such as the one proposed here exists to serve the community, and will undoubtedly evolve with the needs and economics of the world. One thing can be assured, however. Given a similar nuclear energy infrastructure, as long as humanity exists there will be a plentiful and reliable energy supply under control of the citizenry.

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Biography

Dr. Daniel A. Meneley is Adjunct Professor, University of Ontario Institute of Technology. Dr. Meneley served as AECL Chief Engineer for 9 years including postings in Korea and China. He established AECL's Shanghai office and lectured extensively on CANDU. During an earlier seven-year Professorship at UNB, he served on the first IAEA-INSAG safety advisory committee. He was employed by Ontario Hydro from 1972 to 1984; first as supervising design engineer, then Manager of Safety Design and Reactor Licensing, and finally as Manager of the 350-person Nuclear Group responsible for design, safety, licensing, and waste management during the building of twelve CANDU stations comprising Pickering B, Bruce B, and Darlington. Before that time he supervised fast reactor physics research, development and design at Argonne National Laboratory. Dr. Meneley graduated from the University of Saskatchewan (1958) with Great Distinction in Civil Engineering. He earned a Doctorate from the Imperial College of the University of London in 1963. He is Fellow of the Canadian Academy of Engineering, Fellow of the Canadian and American Nuclear Societies and Member of the Canadian Society of Senior Engineers. He has published in nineteen refereed journals, more than fifty refereed conference proceedings and has supervised twelve post-graduate theses.