Nuclear Energy Challenges in this Century
17th Pacific Basin Nuclear Conference
Cancun 2010

Daniel A. Meneley
University of Ontario Institute of Technology
2000 Simcoe St. N., Oshawa, Ontario, Canada, L1H 7K4

Abstract

The past fifty years have witnessed the advent of a new energy source and the beginning of yet another in the series of energy-use transitions that have marked our history since the start of our technological development. Each of these transitions has been accompanied by adaptive challenges. Each unique set of challenges has been met. Today the world faces the need for another transition. This paper outlines some of the associated challenges that lie ahead of us all, as we adapt to this new and exciting environment. The first step in defining the challenges ahead is to make some form of prediction of the future energy supply and demand during the period. Herein, the future up to 2010 is presumed to include two major events -- first, a decline in the availability and a rise in price of petroleum, and second a need to reduce greenhouse gases in our atmosphere. Both of these events are taken to be imminent. Added to these expected events is the assumption that the total of wind, solar, and other such energy sources will be able to contribute, but only in a relatively small way, to the provision of needed energy to our ever-expanding human population.

1. INTRODUCTION

Nuclear energy systems, now more than 50 years old, use a mature technology. They are ready to take on larger and larger roles in the provision of energy for the benefit of mankind. Utilization of this new primary energy source is an engineering task of first magnitude, and is no longer a leading subject of scientific research, except at the margins.

This paper outlines the major tasks remaining for nuclear energy professionals over the next half-century and more. These challenges form an integrated set ranging from the purely technical to abstract questions of sociology and philosophy. They touch on broad matters of public policy as well as on the future development of the world economy.

Today's challenges to the nuclear industry all arise from the known great energy-related challenge to the world; that is, to find a clean and sustainable source of energy to replace petroleum. The only greater related challenge of our day is to find a solution to the problem of world over-population. Without a sufficient energy supply there can be little hope for successfully managing this underlying issue.

Some people say that petroleum is not, and never will become, a commodity in short supply. Better-qualified and convincing persons and organizations point out the error of this thinking. The world now uses approximately 1000 barrels of oil in each second of each year.

The latest annual report of the OECD's International Energy Agency states simply "we must leave oil before it leaves us".

This technical challenge to the nuclear industry is indeed very large. Assuming a plant capacity factor of 90 percent, the higher heating value of oil being consumed in the world today is equivalent to the total fission heat produced by about 7000 nuclear units, each with an equivalent electrical capacity of 1 Gigawatt.

At the same time there are other, perhaps greater challenges facing us. Among them is the matter of urgency. We have very little time to meet the main challenge. Using the most optimistic assumptions, the job should be complete before the year 2200. This massive change will require the good will and the effort of many thousands of people, backed by their governments and the population at large.

The following headings address the main challenges ahead of the world nuclear energy enterprise. The opinions addressed herein are completely my own, and make no pretense of being complete. These opinions are drawn, primarily, from Canadian experience but include some broader aspects of the task ahead. Not all of these challenges are important to any single nation; indeed some have already met some of these challenges to some degree.

2. BACKGROUND

Formulating a list of "challenges" requires, of course, some sort of prediction of the future. This is a notoriously difficult process, and in many circumstances is impossible [1].

In their 2008 report entitled "International Status and Prospects of Nuclear Power" [2] as updated in 2010 [3], the IAEA lists nine key issues and trends, shown in Table I, that constitute challenges for near term development of the nuclear industry. This author prefers to call the first item in Table I a "pre-condition" rather than an issue. Unless the operators of nuclear plants are prepared to operate these plants reliably and safely, they would be wise not to operate them at all, and to find another line of work that is less exacting. Similarly, economic competitiveness is considered a pre-

Table I. IAEA Listing of Issues and Trends

SHORT TERM
Safety and Reliability
*Economic Competitiveness and Financing
*Public Perception
Human Resources
*Spent Fuel and Waste Management and Disposal
Transport
Proliferation Risks and Nuclear Security
Infrastructure Building in New Nuclear Countries
*Relationship Between Electricity Grids and Reactor Technology
LONG TERM
*Effective Use of Available Resources
Reactor Design Innovation
Fuel Cycle Innovation
* Updated, 2010

condition, because unless it exists, nuclear energy will not go forward at all.

A more limited prediction was made by the Massachusetts Institute of Technology, as reported in their document "The Future of the Nuclear Fuel Cycle" [4]. The MIT study is focused primarily on the US scene. This report is formulated in terms of findings and recommendations. The main points of the Executive Summary have been recast in terms of challenges, in Table II. Several entries are equivalent to those in the IAEA report. The MIT challenge to deploy nuclear capacity at the terawatt scale by mid-century is related to climate change risk in that report. Missing from both of these lists is explicit reference to the impending crisis in world petroleum supply.

Table II. Challenges Identified in MIT Study

<u>SHORT TERM (ZERO to 40 YEARS)</u>
Mitigation of climate change risk
Global Deployment at Terawatt Scale -- LWR Only
+Economic Competitiveness and Financing
+Spent Fuel and Waste Management and Disposal
+Proliferation Risks and Nuclear Security
+Safety and Reliability
Research on Choice of Fuel, Reactor Type, and Fuel Cycle
Preserve Options
<u>LONG TERM (40 to 90 YEARS)</u>
+Reactor Design Innovation
+Fuel Cycle Innovations
+ Same as IAEA list

Table III – Expected Challenges Facing Nuclear Industry

<u>SHORT TERM (ZERO to 50 YEARS)</u>
Gain Public Acceptance
Restore Realism to Assessment of Radiation Risk
Complete the Technical Task – Replace Petroleum
Establish the Means for Financing Nuclear Energy Projects
Answer Power Plant Site, Security, Energy Transport Questions
Eliminate Nuclear Weapons Proliferation
<u>LONG TERM (50 to 100 YEARS)</u>
Ensure Commodity Supply and Infrastructure Strength
Grow Nuclear Capacity to More Than Ten Terawatts
Integrate Industrial Systems – Develop "Hydricity" System

Given the extremely optimistic assumption that world petroleum demand based on current projections can be satisfied over the next 90 years [5], the predicted growth of nuclear energy capacity (4 percent per year in the "high" scenario) would seem reasonable. However, if a more realistic assumption of oil production had been used then the Terawatt scale of capacity in the world by mid-century would perhaps best apply to the US alone; the world requirement would be about five times larger. This single change in one fundamental *a priori* assumption would drastically change the list of challenges to be faced in the short term.

Prognostications differ. Various experiences and individual assumptions can lead to widely different future scenarios. Without by any means exhausting the possibilities, this paper presents one more set of challenges, underlain by a somewhat different idea of how the future should unfold. Table III, representing this author's predictions, shows a list similar to those of the IAEA and the MIT studies, but with differences. The item first listed in Table III shows what is, in this author's opinion, the most difficult challenge of all.

3. GAIN PUBLIC ACCEPTANCE

Though political systems and practices vary greatly from one nation to another, it is generally true that unless a substantial majority of the population agrees with a major undertaking such as nuclear energy, it will be very difficult to sustain the undertaking over a long period of time. In many countries a vocal minority opposition to nuclear energy has dogged the industry for many years. As the advantages of this energy system become more apparent, this opposition seems now to be decreasing, but this trend could easily reverse if and when a major problem arises in the industry.

In one sense this opposition is useful – it keeps us on our toes. At the same time this active opposition requires a large amount of effort to repeatedly refute the spurious claims of those who are dedicated – some very deeply dedicated – to opposing any activity associated with the adjective "nuclear". The distribution of these zealots is wide. Some can be found entrenched in government bureaucracies and other respected institutions, at times very near to the top levels.

Do we have any "respected institutions" remaining in our society? Hugh Heclo [6], in his book "On Thinking Institutionally" asks us to re-examine our opinions of those institutions on which we rely so heavily, and yet for which we show very little respect. At times, of course, institutions go off the rails and no longer deserve respect – Heclo addresses this phenomenon as well. He illustrates the situation with many examples, and points out that the systematic denigration of our basic institutions has been building up over the past century, to the point that it is now hardly appropriate to support many of them when speaking in polite company.

It must be obvious that our society cannot function without a large number of institutionalized organizations and processes. It is equally obvious that these institutions must earn and hold the respect to the general population. In the case of an operating nuclear utility, this generates a powerful need to <u>deserve</u> the trust of the people from day to day. The same applies to all aspects of our industry, and more so because the integrity of this institution is always under challenge.

"Deserving of trust" is, of course, in the eye of the beholder. Today's political climate of challenge to all institutional authority, coupled with our new instant and worldwide communications pathways, makes it very easy to generate dissent on virtually any topic. The apparent virtues of "truth telling", and the normal penalties for violating that norm, have decreased in recent years. Herein the root cause of our public relations trouble. Perfectly rational people who have a deep understanding of the nuclear industry criticize the industry for not "standing up" to the onslaught, and presenting the true story. A splendid example of such critical remarks can be found at Ted Rockwell's blogsite, [7]. Many of the truths of our industry are defended therein. Others would do well to follow Rockwell's lead. We must do whatever we can to eliminate the falsehoods, the distortions, and the extreme assumptions from our technical discussions.

Over the years of verbal conflict between scientists and engineers versus their opponents, the "defensive ramparts of truth" have become bent and battered to some degree. This is especially so in the area of nuclear regulation, where the technical arguments of the proponents meet the political reality of the day. The regulator must defend each decision to allow a project to proceed with a very high degree of assurance. That institution also is challenged every day, the same as are all the rest of the several institutions involved with nuclear energy. In order to continue this great enterprise of providing the world with plentiful energy, we must remember always to defend the "ramparts of truth" and to rebuild them as and when necessary.

This author considers that the task of providing the necessary human resources to the industry can be included as an integral part of gaining public acceptance of our enterprise. If the people accept the need for nuclear energy, young people will rise to meet that need with enthusiasm and in great numbers. At the same time, if the majority of young people see the wisdom of the choice, the future of nuclear energy will be assured. The only remaining job will be to provide suitable means for their education and training.

The human resourcing task is by no means trivial, since it involves continued re-staffing and training of at least three generations of operating crews for each power plant over its lifetime. The task falls on the operating utility to sustain detailed information about the plant as its configuration changes over decades of operation. This problem is significant in many plants in operation today. Fortunately, modern CADDS systems and training courses used in the original construction phase, modified as the plant configuration slowly changes, will in the future enable the utility to maintain not only the plant, but a detailed model of the plant at any given time [8].

4. RESTORE REALISM TO ASSESSMENT OF RADIATION RISK

This challenge is related to the public acceptance challenge, and could greatly assist in reaching that goal. During the original development of nuclear fission reactor technology, a number of very conservative assumptions were made; especially with regard to the health consequences of low radiation doses to people, and also with regard to the potential consequences of reactor accidents. Two major factors have changed. First, the effects of small doses of ionizing radiation are found to be much less than expected, e.g. [9]. Second, more careful analyses based on recent experiments show that the consequence of the "bugbear" accident of pressurized reactors – the large loss of coolant event – has been grossly overestimated in many cases. [10]. Extremely conservative analyses have resulted from years of stringent regulatory review and steadily more demanding criteria of proof.

A direct challenge for the technical community is to eliminate, wherever possible, gross conservatism in safety analysis wherever possible. Though this may turn into a long and painful struggle with regulatory bureaucracy, it may be the best way to regain public confidence, in the end. Perhaps the most important example of unjustified extreme conservatism is the almost universal application of the now discredited linear, non-threshold hypothesis for estimating the consequence of low radiation doses to large populations. A growing array of facts drawn from past experience [7] suggests that re-evaluation is required of many of our present-day licensing analyses in the light of improved engineering knowledge and operating experience.

5. COMPLETE THE TECHNICAL TASK – REPLACE PETROLEUM

Electricity supply is only one of the tasks that soon will be required of nuclear generation systems. Petroleum, one of the world's major enabling resources will almost surely rise dramatically in price within this century, but may even become a scarce resource, at least in some parts of the world.

5.1. The Need

There is still some debate regarding the timing, and even the existence, of the "peak oil" phenomenon, the postulate that we are at or near the maximum production rate of petroleum. Recent price fluctuations support this postulate – fluctuating price is seen in many cases when a commodity in demand approaches its maximum production rate. Exploration plays are now rare outside areas controlled by national oil companies, and tend toward deep offshore ventures that are very expensive. Unconventional reserves such as oil sands bring with them high development and production costs that demand higher product prices.

In their latest annual report, the International Energy Agency of the OECD [5] strongly reminds its member nations:

> "One day we will run out of oil, it is not today or tomorrow, but one day we will run out of oil and <u>we have to leave oil before oil leaves us</u>, and we have to prepare ourselves for that day. The earlier we start, the better, because all of our economic and social system is based on oil, so to change from that will take a lot of time and a lot of money and we should take this issue very seriously".

At the same time the world can take comfort in the fact that there is enough nuclear fuel available to supply us with energy for thousands of years. Once again we are fortunate to have "A bird in the hand" in the form of today's mature nuclear technology. Our descendants may well invent a better way to meet this need – but just in case they do not, we know that nuclear fission energy can do the job. Even though a diverse suite of alternative sources likely will persist over time in niche markets, nuclear energy must provide the bulk of the world's supply for a very long time. We must do the heavy lifting!

The latest issue of the IEA report presents a sobering picture in their reference scenario, which follows the expected trajectory of world energy development over the next 20 years, assuming that world governments make no changes to their existing policies and measures for energy supply. This scenario is dominated by large increases in demand for fossil fuels, extensive exploration, and consequent large capital requirements. The expected total investment requirement is 26 <u>trillion</u> US dollars up to 2030. The power sector requires 53% of this total. The IEA report [5] concludes that:

> **"Continuing on today's energy path, without any change in government policy, would mean rapidly increasing dependence on fossil fuels, with alarming consequences for climate change and energy security."**

For the past several years the IEA has urged OECD governments to increase their commitment to nuclear energy. Most countries of the world show signs of taking up this challenge, with the surprising exception of the OECD countries themselves. In both Europe and North America the response is half-hearted at best, up to now. The IEA report notes the following:

> "The main driver of demand for coal and gas is the inexorable growth in energy needs for power generation. World electricity demand is projected to grow at an annual rate of 2.5% to 2030. Over 80% of the growth takes place in non-OECD countries. Globally, additions to power-generation capacity total 4,800 gigawatts by 2030 – almost five times the existing capacity of the United States. The largest additions (around 28% of the total) occur in China. Coal remains the backbone fuel of the power sector, its share of the global generation mix rising by three percentage points to 44% in 2030. Nuclear power grows in all major regions ***bar Europe***, but its share in total generation falls."

The underlying driver of this demand growth usually is, of course, the rise in world population – energy demand growth is a consequence of this seemingly uncontrollable factor. At the present time, however, it seems that much growth arises from the need (or at least the desire) of underdeveloped countries to increase their standard of living. Any energy policy must be coupled with stabilization of the world population along with rising living standards. A sustainable level of energy supply is a necessary prerequisite if we are to provide a respectable living standard for all people.

5.2 Meeting the need

In its 2009-2030 alternative (preferred) scenario, called the "450 Scenario", so named to indicate a target of 450 parts per million concentration of carbon dioxide in the atmosphere, the IEA Executive Summary for 2009 points out:

> "Power generation accounts for more than two-thirds of the savings (of which 40% results from lower electricity demand). There is a big shift in the mix of fuels and technologies: coal-based generation is reduced by half, compared with the Reference Scenario in 2030, while nuclear power and [*other*] renewable energy sources make much bigger contributions."

Three points are notable in this statement. First, I have inserted the word "other" in square brackets to emphasize the now-recognized fact that nuclear fuels are sustainable for many thousands of years [11], so this energy source should be included in the "renewable" category. Second, the hoped-for amount of demand reduction due to conservation in the electricity sector is very large – a most optimistic projection, given past experience. The third item of note is the urgency of action to reduce our reliance on petroleum. There is very little time left for our world to adapt to the coming collapse of the present-day environment in which petroleum is relatively plentiful and cheap. It is quite apparent that someone will repay the tens of trillions of dollars that must be invested in oil supply development to ensure supply of oil up to 2030. It also leaves a big question as to what we might expect to happen during the following quarter-century. For a rather gloomy guesstimate of the upcoming situation, see the apocalyptic prediction in the book "The Long Emergency" [12].

Accepting the IEA estimate of "new build" generation capacity requirements up to 2030, and then assuming that all of these new plants will be powered by uranium, we **would** need to build 240 nuclear units each of capacity 1 gigawatt every year between now and 2030. This ideal situation will not be realized, of course, but the number certainly provides a "stretch" target for new nuclear plant construction. Once again, with reference to the IEA alternative scenario, there is another challenge implied -- the provision of transportation fuels. This most important topic is outlined in subsection 5.3.

Where else could we get this massive energy supply? Dr. Charles Till, retired Associate Director of Argonne National Laboratory [13] reaches the following conclusion:

> "To sum up, the alternatives to fossil fuels are very, very few that could promise the magnitude of energy required to meet our nation's need. It is not as though plentiful alternatives exist, and one can be weighed against another … "
>
> "The blunt fact is that there are the fossil fuels and there is nuclear."
>
> "Failure to recognize this, while focusing on options that do not and cannot have the magnitudes [of supply] required, will inevitably lead to increasingly dangerous energy shortages. Who then will answer? Will [it be] the environmental activist, who blocks real options, and then puts forth options that cannot meet the need?"

Who else indeed? Will it be the politician who is ready to subsidize unsustainable short-term solutions and who forever plans for his re-election, carefully deferring difficult decisions until after that happy day? Not likely.

My expectation is that the engineer will answer, based on past history. More generally, it is the organization that people really expect to deliver the goods – usually the electrical utility or other operating organization. Because of the long time taken for the results of these decisions and their consequent good or bad impact on society to be revealed, politicians usually get away with no need to answer to anyone.

From the point of view of a large-scale enterprise, the uranium industry exhibits characteristics similar to both the oil industry and coal industry. The time scales involved in exploration, development and market delivery times are all very much longer than political cycles. They all require enlightened and consistent public policy over a period of decades to enable them to become effective. Only real statesmen can and do listen to recommendations whose consequences lie further in the future than the next round of the electoral cycle.

To answer the need for sustainable large-scale energy supply, the first step is to examine the available options. Among the options that are concentrated and thereby easily collected, by far the largest energy potential is from coal or uranium [14] Figure 1, pg. 6. Figure 2 in the same document compares nuclear and coal. Wind is included in the Figure only to show the best of the diffuse options – and the most popular today. Its primary disadvantage is its highly variable nature, which must be backed up by either backup sources or by major energy storage facilities.

Coal suffers from an extraction rate limit and an uneven distribution of deposits, thereby causing transportation difficulty in many nations. Nuclear fission energy is the clear choice. It is highly concentrated and so has only minor transportation problems for either fresh fuel or for used fuel. In addition, this fuel is inexhaustible [11].

The very large quantities of fuel available from uranium and thorium are well known [14] Figure 3, page 7. Using today's technology (thermal reactors) along with the 2005 total world energy usage, we see that at least 40 years of fuel supply are assured. Assuming a reasonable rate of exploration and tolerable increases in fuel price, at least 300 years of fuel supply can be assured from uranium resources alone. Accounting for thorium fuel supply would probably double the amount shown in this Figure.

Fast reactors apparently are necessary to extend nuclear fuel availability in time, to well beyond the horizon of human existence. It is not practical to mine uranium from seawater to fuel thermal reactors, because of the very large required extraction rate. Fast reactors do not suffer from this drawback, however, because a one-gigawatt electric unit requires only 2 tons of makeup uranium per year. This makeup fuel also can be obtained from dilute ore deposits, from the ocean, or from depleted uranium from enrichment plants. This huge diversity of fuel sources arises because of the very large amount of potential energy in each unit of natural uranium or thorium,

5.3 Alternative strategies

The world is, at the present time, blessed with a sound cadre of successful nuclear plant designs. Based on direct experience, these designs are seen to be economical, safe and reliable when properly managed and regulated.

The basic choice, then is whether to build a large fleet of existing plant designs (subject, of course, to the slow evolution in detail that always follows from experience) or to re-examine all of the alternatives previously studied, so as to find one or more optimum designs for the future. Based on this author's understanding of the great urgency of building to replace petroleum as its supply declines and its price rises, it is recommended that the correct path can be found closer to the first option than the second. This is mainly due to the urgency of our situation – it is imperative to begin building a large number of power plants <u>now</u>. We have no time to waste. We have no time for long, drawn-out research programs. In this case, in a very real sense "the perfect is the enemy of the good".

Edward Kee, Vice President, NERA Economic Consultants, said in a recent interview [15] that, from the point of view of both vendor and buyer,

> "The most important issue for reactor designs is to get a lot of units built and in operation as fast as possible. This gets the design down the learning curve to lower costs and shorter schedules, but also stimulates additional sales from buyers who look for low risk and demonstrated success. While design features are important, market success is much more important."

This market reality strongly discourages introduction of revolutionary design concepts, especially if private industry is expected to shoulder the majority of project risk. Of course there is no reason that the development of improved or new designs cannot continue in parallel. It must only be assured that any development effort does not interfere with the ongoing production plant capacity buildup.

Existing plant designs can be operated with adequate safety, if they employ conscientious crews led by knowledgeable and "mindful" management [16]. Meeting the need for energy immediately creates the challenge of supplying trained manpower to build and operate the plants. Fortunately, this need is fully recognized within the industry.

Given the fact that thermal reactors must be built in large numbers as soon as possible, the question arises as to which characteristics of these units will ease the transition to new designs when they are available? It is obvious that the transition will begin only when the price of uranium rises; it is also obvious that any new reactor type must have improved characteristics for uranium utilization; preferably, these reactors should produce more fissile material than they consume. Their excess fissile material then could be blended with recycled materials to refuel thermal reactors without using any new uranium. The effect of this strategy will be to control the rising price of natural uranium. The best available system for this purpose is the fast reactor design known as the Integral Fast Reactor, or IFR [17].

Clearly, during the transition between thermal and fast reactor fleets, the less excess fissile material required for refueling of existing thermal reactors, the greater the flexibility for growing the numbers of fast reactors. This indicates that the best strategy to prepare for this transition is a thermal reactor fleet with a high ratio of fissile material produced per unit of fissile material consumed – usually called the "conversion ratio". Commitment of "High-C" thermal reactors such as the PHWR today would considerably ease the future transition toward a mixed fleet of thermal and fast reactors [18].

Nuclear energy also can be used to reduce petroleum use for transportation fuels. For example, the following conclusion is quoted from a recent paper [19]. These concepts are explored further in a later work [20].

> "Liquid fuel demands for transport could be reduced in half by combinations of several options such as diesel engines and plug-in hybrids. Independently, the biomass liquid fuel options could meet existing liquid fuel demands without reductions in oil demand. Rapid technological changes are occurring with the development of biological plants for fuel production, methods to process biomass, and plug-in hybrid vehicles, as well as in other areas. Consequently, the specific combination of biomass, nuclear energy, and liquid fuels for transportation will be determined by the results of this development work."

A great deal of work is now being done in this field. There is a high expectation of success. As a direct result, requirements for additional nuclear capacity might well arise over the next few decades. Nuclear capacity planners should consider this possibility very seriously.

6. Establish means of financing large-scale nuclear energy

Financing is difficult for large projects such as nuclear plants. Two good comparisons are seen in development of a new oil field and the construction of a continental highway network. In the first case large capital resources must be committed many years before any return can be expected. In the second case, people expect that taxpayers will fund major highway construction.

Bill Gates [21] puts forward a precise and simple explanation of the problems of nuclear plant finance. He argues that the private sector will remain unable to finance this new build program, but that governments can help a great deal. The US government has, in fact, begun this process by offering loan guarantees. A similar system was utilized to finance construction of the Qinshan-3 project in China; nations associated with several major systems and components used export development loans of various kinds. This operation was very successful, and the loans are now being paid back expeditiously.

Government loan guarantees could be established in support of the project. Loans would be repaid over time during plant operation. Financing also would be greatly eased if some of the capital expenditures incurred during plant construction could be charged into the rate base, recognizing that plant benefits will eventually accrue largely to those same ratepayers. Both of these alternatives depend completely on the support of the community where the plant is located, thus underlying the paramount importance of their trust that the plant being constructed is truly in their interest. Of course, this is a political and sociological question.

The complexity and uniqueness of project arrangements for building a large plant defeat any attempt to generalize the process. There is no doubt that it is one of the crucial steps toward success. Expert management combined with careful project planning, clear definition of roles and goals, along with comprehensive design and scheduling of each step of the project can lead to timely and economical project completion [8}.

Financing of large projects can benefit from better predictability; this can be achieved through standardizing all or even part of any plant design. Partial standardization implies modularity, and is the preferred alternative recognizing the large span of time involved between projects that might be built on one site as well as the wide diversity of site conditions, in other cases. In most situations it is be wise to restrict evolutionary design changes to infrequent, incremental steps.

All of these arguments support standardized design for new plants and militate against radical changes, even though such changes might be advantageous in theory. In general, such developments must take place outside normal commercial venues. New reactor types must be thoroughly tested and demonstrated before being considered seriously as production options.

7. Answer power plant site, security, and energy transport questions

Assuming the greatly increased scale of this industry, choice of sites for new power plants will become a serious issue in the future. As the application of nuclear energy broadens from electricity production into a wide range of industries [22] it may be necessary to update traditional thinking about these locations. In any case, the area requirements for the plants themselves will not be large; the majority of space will be required to accommodate the "industrial parks" that will surround these plants.

The need for security is another factor in the choice of site. Together, these two factors suggest the establishment of energy parks on which many nuclear units (at least, those of a scale envisaged today) will be co-located along with fuel recycling and possibly long-term fuel storage facilities. Recycling "on site" may well be preferred to drastically reduce the need for shipping of used fuel and other radioactive materials back and forth to the power plants. High security for all nuclear materials is, of course, easier to establish on a large site than it is on a number of small, isolated sites.

Yet another advantage of energy parks is that they can service smaller sites without the need or the capability to grow very large [23]. The so-called "hub and spoke" arrangement is very likely to be chosen in most cases. The idea is that small or medium capacity (SMR) units would receive their fuel from an energy park, and return their used fuel to the energy park for recycling. Several of these satellite units serviced by a single large central site.

Presuming that a few large-scale sites are established raises the question regarding the proper scale of nuclear units to be installed there [24] Those studies indicated that very large (5,000 to 10,000 MWe equivalent) units could be optimal. Industrial application also likely will lead to some of the units being dedicated to supply process heat; these may or may not include electrical generation capability.

When established these energy parks would be similar to large oilfields in production capacity. Their main energy currencies [25] would be electricity and hydrogen; this system could be identified by the newly coined word "hydricity". Transportation fuels may be an important product, carried from the site to consumers via conventional pipelines or supertankers. Location of energy parks on large waterways, ocean shorelines or islands would greatly facilitate transport of products from these sites.

8. Eliminate nuclear weapons proliferation

This issue is really one that must be solved through international diplomacy; technical methods can assist in reaching the goal of eliminating both national and sub-national weapons production; however, in the end it is a matter that must be settled through international agreements. As noted in the book "The Bottom Billion" [26], behavior of individuals and nations is more effectively sustained through social "norms" rather than laws or coercion. Agreements between governments establish these norms of behavior. The nuclear non-proliferation regime constitutes the sum of these agreements. Up to the present day, this network of agreements has been sufficient to avoid any use of these weapons. As technology advances and behavioral norms are even better established, it is reasonable to hope that the use of all weapons of mass destruction, including this one, will be eliminated.

9. Ensure commodity supply and infrastructure strength

By this time (about 50 or so years into the future) one possible issue will be the supply of the necessary materials and equipment to serve an ever-growing population. The underlying issue is, of course, the sustainable limit of human population. Otherwise, just how many people constitute a "full house" on this earth?

Note that two of the IAEA issues do not appear in the present list: reactor design and fuel cycle innovation. This author assumes that these aspects of nuclear energy development will occur more or less automatically as the promised capacity of the system increases. I assume that they will be driven by a combination of human need and commercial enterprise. This is not to say that they are unimportant, but only to recognize that the form and style of these developments will be a matter of trial, error, and discovery.

Fuel supply is one aspect of long-term development that is already established. Several publications e.g. [11], [27], confirm this, provided only that systems capable of transforming almost all of the fertile material into fissile fuel are installed. The Integral Fast Reactor [17] has already demonstrated this basic capability.

10. Grow nuclear capacity to more than ten terawatts (equivalent)

This figure for ultimate nuclear capacity can only be a wild guess. It is intended to indicate a large number, and one that could include not only electricity generation but also a broad array of industrial processes [14]. Ten thousand one-gigawatt units (electricity equivalent) seems to be a large number, but the actual unit capacity will likely be considerably larger by this time.

When the world's nuclear energy system has grown to approximately this scale, it will be capable of supplying all of the energy needs of humanity for thousands of years. Of course, a better way of supplying large amounts of safe and reliable energy may be invented before this time, even though none is apparent on the horizon at this time.

11. Conclusion

The era of cheap and abundant petroleum and natural gas is drawing to a close. Many alternative replacements are proposed. The only clear alternative today is nuclear energy extracted from uranium and thorium. During the past seventy years, this new energy source has been fully developed and installed as a second-rank contributor to the world's energy supply. During the next 50 to 100 years it can and will grow to become a predominant force in sustaining the health and well being of all humanity. If necessary, fission energy can continue this role for many millennia.

No prediction of the future can be reliable, and this prediction is no exception to the rule. By studying our energy supply options we can only hope to improve our understanding of the present, and thereby might improve our descendants' chances of survival in the future.

12. References

1. Orrell, D 2007 *The Science of Prediction and the Future of Everything,* Harper Collins Toronto, Canada
2. International Atomic Energy Agency 2008, *International Status and Prospects of Nuclear Power*, Vienna, Austria
3. International Atomic Energy Agency 1010, *International Status and Prospects of Nuclear Power Report by the Director General GOV/INF/2010/12-GC (54)/INF/5,* Vienna, Austria
4. Massachusetts Institute of Technology 2010 *The Future of the Nuclear Fuel Cycle, An Interdisciplinary MIT Study, Summary Report,* MIT Press, Cambridge, USA
5. International Energy Agency 2009 *World Energy Outlook, Executive Summary,* International Energy Agency, Paris, France
6. Heclo, H 2008 *On Thinking Institutionally*, Paradigm Publishers, Boulder, United States of America
7. Rockwell, T 2010 *Learning About Energy,* http://www.learningaboutenergy.com/, [Accessed 24 Sep, 2010]
8. Petrunik, K; Rixin, K 2003 Qinshan CANDU Project, 2003 Construction Experience and Lessons Learned to Reduce Capital Costs and Schedule Based on CANDU Project in China, *Proceedings of the 24th CNS Annual Conference,* Toronto, Canada
9. Cuttler, JM and Pollycove, M 2009 Nuclear Energy and Health: And the Benefits of Low-Dose Radiation Hormesis, *Dose-Response*, **7**, p. 52-89. Available at: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2664640/ [Accessed 29 Sep, 2010]
10. Muzumdar, AP; Meneley, DA 2010 *Large LOCA Margins & Void Reactivity in CANDU Reactors, Report COG-07-0912,* CANDU Owners Group, Toronto, Canada
11. Lightfoot, HD; Mannheimer, W; Meneley, DA; Pendergast, D; Stanford, GS 92006), Nuclear Fission Energy is Inexhaustible, *Climate Change Technology Conference, Engineering Institute of Canada,* Ottawa, Canada
12. Kunstler, JH (2006), *The Long Emergency: Surviving the End of Oil, Climate Change, and Other Converging Catastrophes of the Twenty-First Century,* Grove/Atlantic, New York, USA
13. Till, CE (2005), Plentiful Energy, The IFR Story, and Related Matters*, The Republic News and Issues Magazine*, Jun-Sep 2005
14. Meneley, DA 92010), Nuclear Energy in this Century – A Bird in the Hand, *Proceedings of the 31st Canadian Nuclear Society Annual Conference,* Montreal, Canada
15. Kee, E (2010), *Asia to Lead the Shift to Nuclear Power*, *NERA Economic Consultants,* http://www.nera.com/67_6964.htm. [Accessed 29 Sep 2010]
16. Weick, KE; Sutcliffe, KM 2007 *Managing the Unexpected – Resilient Performance in an Age of Uncertainty, Second Edition,* San Francisco, USA
17. Beynon, TD; Dudziak, DJ (Ed); Hannum WH (Guest Ed); 1997, The Technology of the Integral Fast Reactor and Its Associated Fuel Cycle, *Progress in Nuclear Energy,* **31**, Number 1&2, Amsterdam, Holland, Elsevier
18. Meneley, DA 2006 Transition to Large Scale Energy Supply, *Proceedings of the 27th Canadian Nuclear Society Annual Conference,* Toronto, Canada
19. Forsberg, CW 2007 Meeting U.S. Liquid Transport with a Nuclear Hydrogen Biomass System, *Proceedings of the American Institute for Chemical Engineers Annual Meeting,* Salt Lake City, USA

20. Forsberg CW, 2009 Sustainability by combining nuclear, fossil, and renewable energy sources, *Progress in Nuclear Energy*, **V. 51:1**, p. 192-200
21. Gates, W; Holliday, C 2010 Energy Sector Poised for Innovation -- with the Right Spark, *Washington Post*, *April 23*, A19
22. Gurbin, G; Talbot, K 1994, Nuclear Hydrogen – Cogeneration and the Transitional Pathway to Sustainable Development, *Proceedings of the 9th Pacific Basin Nuclear Conference,* Sydney, Australia
23. Wade, DC; *STAR H2: The Secure Transportable Autonomous Reactor for Hydrogen Electricity and Potable Water, NERI Project No. 20-00-0060,* Argonne, USA.
24. Hub, KA; Charak, I; Lutz, DE; Thompson, DH; Gast, PF; Meneley, DA 1966, *Feasibility Study of Nuclear Steam Supply System Using 10,000 MW Sodium-Cooled Breeder Reactor, ANL-7183,* Argonne, USA
25. Scott, DS 2007, *Smelling Land – The Hydrogen Defense Against Climate Catastrophe,* The Canadian Hydrogen and Fuel Cells Association, Vancouver, Canada
26. Collier, P 2007, p139 *The Bottom Billion, Why the Poorest Countries are Failing and What Can be Done About It,* Oxford, United Kingdom
27. Cohen, BL 1983 *Breeder Reactors: A Renewable Energy Source*, Am. J. Phys. **51(1),** American Association of University Teachers