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21st CENTURY ENERGY SUSTAINABILITY -- NUCLEAR'S ROLE*

by

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1. INTRODUCTION

In contemplating nuclear’s role in 21st century energy sustainability, it has been useful to consider energy supply infrastructures as a whole and the historical and projected future technological trends of the infrastructure elements (resource, conversion, and carrier). The intent has been to identify the future energy clients and their special energy product needs in the decades following 2030 so as to tailor the proposed sustainable nuclear energy supply concept to those perceived needs.

While this approach has suggested a long-term nuclear supply configuration and has identified the R&D effort which should be initiated to emplace the technology by 2030,[1] it has been necessary as well to identify a transition strategy which builds on the existing institutional, industrial, and technology base as it exists today and, in an era of deregulated energy industry, to identify potential R&D funding mechanisms for reaching the long-term goal.

Finally, it has been recognized that technology innovations, while necessary are not sufficient; institutional innovations will be necessary as well for the solution proposed here. They are identified and discussed briefly.


2. ENERGY TRENDS

Energy availability and use drives society’s economic development and quality of life. Today energy use per capita is markedly inhomogeneous. The richest 20% of global population use 55% of final energy; the other 80% of global population use 45% of final energy. Global energy demand growth in the 21st century, therefore, will be driven not only by population growth but especially by dramatic increases of energy intensity per capita as the economies and associated living standards rise in developing countries. Capacity additions will be dominated by additions made in developing economies – while at the same time the replacement market in industrialized nations will remain significant in light of the high baseline on which their modest growth is occurring.

21st century energy demand projections released recently[5] by the IIASA/WEC employ several scenarios to attempt to encompass plausible outcomes over the coming decades. Realistic scenario assumptions concerning resource mix are used as well. In any case, it is found to be prudent to base our planning on a need for upwards of 2000 units of 1000 MW_e nuclear plants by the year 2050. The only point of note for the discussion
is that the number of required new plants is very large—large enough to consider a strategy relying on economy of mass production as a viable alternative to the traditional economy of scale strategy for nuclear plants.

The more interesting trends in energy supply are occurring in the converter and carrier components of the infrastructure. Nuclear plants worldwide currently couple to steam turbine energy conversion equipment—which is limited to efficiencies near 35%. As shown in the plot of time evolution of energy conversion efficiency (Fig. 1), it has increased from 1% to 50% in 300 years; it is currently at 50% using gas turbines and it can be anticipated that by 2020, fuel cells can advance this to 70% efficiency. Steam turbine technology at ~35% efficiency and high capital and operating/maintenance manpower cost per unit conversion efficiency, already competes unfavorably with combustion gas turbines; fuel cells of even higher efficiency are under intense development and will be in widespread use by 2030. By then, the era of steam turbines will be long past.

Fuel cells are expected to find their first widespread application in the transportation sector (one-third of primary energy consumption). Anticipating emissions control limits, Daimler/Chrysler, Toyota, Ford, and other major vehicle companies are investing hundreds of millions to billions of dollars to bring fuel cell powered automobiles to market in the early decades of the century. The currently high capital cost (~1,500$/kw) of hydrogen-consuming fuel cells can be expected to be driven downward as a result of future massive production runs in the vehicle industry. But reduced greenhouse gas emission benefits of fuel cell usage will accrue only if the hydrogen fuel to supply them derives from a non-carbonaceous source—such as the cracking of water using nuclear generated electricity and/or heat.

While use of hydrogen to drive fuel cells vehicles is likely to emerge as the first new widespread market for hydrogen (beyond the current ammonia/fertilizer market), Fig. 2 reveals[9] the market inexorably trending over the past century and a half to hydrogen-rich/carbon-poor chemical energy carriers for the entire non-electric two-third segment of the energy market. Based on this trend it is projected[9] that by 2030 methane will join coal and oil in market share decline and that hydrogen can be expected to hold the dominant market share of chemical energy carriers (complimentary with electricity) in subsequent decades.

The market trends discussed above suggest that the nuclear energy supply approach targeted for the mid to late decades of the 21st century should couple to modern energy converters (gas turbines, fuel cells), and energy carriers (electricity and hydrogen) predicted by market trend analysis to be contemporary at that time. Additionally, other analyses[10] suggests that fast spectrum reactors capable of “burning” U^{238} and/or Th^{232} will be required by mid century owing to the (by then) scarcity of fissile U^{235} and of Pu^{239} from past thermal reactor operations.

A hydrogen based global energy supply infrastructure was proposed in the 1970s as the sustainable solution for global growth[2]—long before sustainability reached its current level of governmental attention. This visionary infrastructure relies on solar and nuclear fission for the essentially infinite energy resource, complete fission consumption of the basic actinide resource, and on electricity and hydrogen (generated by cracking water) as complimentary dual energy carriers. Fission products having an ~300 year toxic lifetime
the only waste emerging from the energy supply infrastructure because the hydrogen burning product recycles as water and greenhouse gas emissions are altogether avoided. Since the 1970s, market forces have (or soon will) emplace the requisite energy converters and carriers; specifically, the energy converters in widespread use in the decades ahead will be fuel cells, combustion gas turbines, and electric motors, and a partially developed hydrogen distribution system should be in place imminently to service the transportation sector. Only the sustainable resource segment of the envisioned infrastructure remains to be emplaced; nuclear should position itself to do so.

The hydrogen/electric energy architecture, already presaged thirty years ago, quite obviously favorably addresses the now intensely discussed definition of sustainable development:

Sustainable development defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs.”

It addresses the essential inexhaustibility of the basic energy resource U$^{238}$, Th$^{232}$, and sunlight, and it achieves the near total elimination of greenhouse gas emissions and the responsible minimization of solid radioactive waste mass and the duration of its toxicity. Moreover, this architecture unfetters the nuclear energy resource from its -- up to now -- exclusive applicability to the one-third electricity segment of primary energy need, so as to (via synthetic chemical fuel, hydrogen) apply greenhouse-gas-free fission energy to the much larger (two-thirds of primary energy) segments of societal energy use.

By further expanding the menu of energy-intensive products produced using nuclear process heat, other sustainability needs of society could also be addressed. Of particular note is the impending need by 2030 and beyond for potable water. The World Bank has estimated that a billion people currently have poor access to clean drinking water; and by 2025 that number will more than double. The problem is most intense in large cities, the focus of demographic migrations; where the need to provide and maintain both supply source and delivery infrastructure applies equally in developing and developed economies. Unlike electricity, water, similar to hydrogen, is a storable energy commodity ideally suited for base loading the costly nuclear supply assets and for flexibly diversifying resulting energy-intensive saleable product mix. Additionally, the distribution infrastructures for hydrogen and for water are suited for regional scale, and they similarly rely on networks of pipeline easements. Drinking water supply is currently a $400 billion a year industry[11] and has been predicted to be, for the 21st century what the oil industry was for the 20th. Boiling water is what nuclear currently does well. In future, manufacture of potable water from cheap or free brackish or salt water to provide the feedstock to the water cracking hydrogen production plant as well as for sale as a valuable commodity should become a natural additional contribution from nuclear for meeting society’s sustainability needs.

The trends described above are market driven; they will happen, and although major infrastructural changes such as those described require decades to complete,[12] it is only sensible to take note of these trends in planning the role and configuration for nuclear power in 2030 and the ensuring decades.
3. A PROPOSED APPROACH FOR NUCLEAR’S LONG-TERM ROLE IN 21st CENTURY ENERGY SUSTAINABILITY – AND ITS RATIONALE

On the basis of the trends discussed above, a concept for post 2030 nuclear-based sustainable global energy supply contribution is proposed. It is at a very early stage of consideration at Argonne in association with several domestic and foreign collaborators. The concept incorporates a modular-sized (300 MWth), passively safe, Pb-cooled, fast spectrum reactor driving an integrated process heat cascade comprised of a thermochemical water cracking cycle, optional mid temperature range process heat applications and finally, a low temperature desalinization plant. The Pb coolant outlet temperature is ~900°C and an intermediate helium loop carries the heat to the integrated process heat cascade.

A fast-spectrum, fissile self-sufficient converter reactor using heavy liquid metal coolant is proposed for the nuclear heat source because it enables the fission consumption of virtually all actinide feedstock achieving a high utilization of the multi century nuclear fuel resource base and it minimizes the radioactive waste stream – which will be comprised only of fission products but essentially no actinides.[13] The use of a heavy liquid metal coolant preserves the traditional benefits of liquid metal coolant (fast neutron spectrum, compact, low-pressure heat transport with separate coolant and working fluids). Moreover, its use coupled with a fissile self-sufficient fast spectrum core realistically enables ultra-long core refueling interval (15 years) to achieve ultra high capacity factor and reduced accessibility to fissile material. Lead coolant also facilitates reaching the high temperature (~900°C) required for coupling to a thermochemical hydrogen production process -- and to do so in a sustainable fast spectrum reactor suitable for continuing use after depletion of U^{235} and stored plutonium reserves predicted to occur near mid century.

The nuclear module achieves 15-year refueling interval by derating the power density and by achieving an internal conversion ratio near unity. Fresh cartridge refueling and used cartridge removal is provided as a service to the module owner/operator by a separate fuel owner operating from a regional front and back end service park maintained under international oversight.

Since economic competitiveness is the crucial prerequisite to market penetration, attractiveness to investors requires low capital and operating costs, as well as short construction time. This proposed concept relies on radical simplification, and on standardization, modularization, serial factory fabrication and fast, onsite assembly and startup to achieve favorable capital cost. Radical simplification of the nuclear plant exploits the derating and long refueling interval and the Pb coolant to eliminate primary coolant pumps and the onsite refueling equipment. It relies on serial-factory fabrication of modular-sized plants to lower construction cost and on passive safety to limit all safety-grade equipment and construction and operations practice to the reactor module alone and to avoid it in the balance of plant.[7]

Operating cost reduction is based on ultra high capacity factor due to the long refueling interval with base loading of the plant facilitated via energy storage products (hydrogen and potable water). It achieves maximum fission conversion of the fuel (U^{238}}
or Th\textsuperscript{232}) feedstock. It employs semi-autonomous operation (passive load following) to reduce operating staff levels. It relies on the high-energy conversion factor per unit of cost, which is achievable with modern energy converters.

The 300 MW\textsubscript{th} power rating was chosen not only to facilitate modularization and serial fabrication but also to provide capacity addition increments suitable in those developing economies having an initially spare infrastructure and/or industrial base. For industrialized economies, module batching would be used, if desired, to achieve large increment replacements or additions at no cost penalty because economy of serial fabrication of modules compensates for economy of scale.

The economy of scale facilities (enrichment, fuel fabrication, factory for module construction, recycle facility and waste management facility) are coalesced into large regional service parks operating under international oversight to service multitudes of distributed modular plants sited throughout the region. The facilities in these parks benefit naturally from economy of scale, and such regional centers localize a significant fraction of the fissile management oversight costs, high technology manpower requirements, and nuclear waste management activities into a limited number of parks worldwide --- while hundreds to thousands of energy modules are distributed at client locations supplying energy-intensive products to local regions.

The approach to safety of the nuclear module borrows extensively from the IFR concept\cite{7} and is based on exploiting the ambient pressure and large thermal inertia conditions attainable with liquid metal coolant; extensive reliance on passive safety response; and innate passive load following in response to the heat demand presented from the process heat cascade. Safety benefits derive from the chemical inertness of heavy liquid metal coolant, passive channels for decay heat removal, and the intermediate helium heat transport loop which (except for heat demand) decouples the events in the process heat cascade from the reactor module. The passive safety approach not only enhances safety, it lowers cost by confining safety grade equipment to the module itself -- allowing construction and operations of the process heat plant to employ industrial grade practices.

Proliferation resistance features of the concept are based on the long refueling interval; no onsite fuel handling equipment; and cartridge refueling with used cartridge return to the regional service center -- all of which reduce opportunities for access to fissile material at distributed sites. The front and back end (including waste management) fuel cycle operations which must of necessity be conducted on bulk materials are all performed exclusively at the regional facilities under international oversight. No fissile material is consigned to geologic waste.

A Sulfur-Iodine (S-I) thermochemical water cracking cycle is currently being considered for this concept. It has been a leading contender among the numerous thermochemical water cracking cycles studied for twenty years and is currently under development at ENEA (Italy), JAERI (Japan), and elsewhere.

Desalinization is a key element of the concept. When potable water is scarce, it is appropriate to use waste heat from the energy plant with non-potable ocean or brackish
feedstreams as the means to generate feedstock needed for hydrogen production. Moreover, fresh water, already a premium commodity, increasingly will have a high sales value similar to energy; it will represent a market of significant growth and because of similar pipeline network delivery technology, can be foreseen to co-develop with the hydrogen infrastructure and market.

The S-I process hydrogen production, integrated with electricity and potable water manufacture and tied to a fast neutron spectrum reactor are packaged specifically to achieve long-term sustainability on the basis of both electricity and synthetic chemical (H₂) energy products having no carbon emission at any point in the supply chain and using an essentially inexhaustible energy resource – i.e., only plentiful (U²³⁸ and/or Th²³²) feedstock. It is sized to accommodate a client base in developing countries, which may desire small capacity additions, and it is configured to provide process heat capacity, which can be utilized for adding value to local natural resources in developing economies as a means to grow the indigenous economy. Since reliance on economy of serial factory fabrication and standardization allows for module batching at no cost disadvantage when large capacity increments are desired, the concept is directly applicable as well to large replacement power missions in developed economies and to diversification of product mix there as energy sites evolve into industrial eco parks.

4. R&D CHALLENGES

The plant concept proposed here builds on but markedly extends work already in progress at the proposer’s institutions and elsewhere. The reactor design is an extension to lead coolant and to higher outlet temperature of a modular, lead-bismuth cooled reactor design currently being researched at Argonne National Laboratory. The design approach draws heavily on the demonstrated passive safety approaches used for the Integral Fast Reactor and on the heavy liquid metal coolant technology recently declassified from the Russian nuclear submarine experience base. The factory fabrication/modular construction approach rests on the General Electric technology for their S-PRISM Advanced Liquid Metal Reactor offering.

Many significant technical challenges remain to be solved. The S-I process or any alternative requires substantial R&D to move it from bench scale to an industrially deployable state. An extensive program of R&D will be required to establish a licensing data base for coolant/structure compatibility at the 900°C temperature range. (But, since that situation exists for any heavy liquid metal cooled innovative reactor, no matter what temperature is chosen, we have elected to use very high boiling point lead and to set our goal to achieve a step change in the future role for nuclear power by initiating development of a sustainable nuclear-driven hydrogen economy – (which would seem to be achievable only with higher coolant temperatures such as currently are attainable only in gas cooled thermal reactors operating on U²³⁵ or plutonium – which are of significant but not sustainable longevity.) Currently nitride and carbide based fuels are considered; either choice will necessitate a significant fabrication, recycle, and irradiation testing program.

The most crucial feasibility issue concerns economic competitiveness. For this concept, it is proposed to trade traditional economy of scale for radical simplification and
economy of serial factory fabrication. As discussed earlier, a market potential of thousands of units is projected — indeed providing an opportunity for economy of serial fabrication. Economy of scale is retained for front and back end fuel cycle service centers where it is undoubtedly advantageous. Several of the radical design simplifications (e.g., elimination of pumps, elimination of onsite refueling equipment) were attained only by derating the operating power density, which, however, offsets the capital cost gains of simplification. The high temperature suggests the need for expensive refractory alloy structural materials unless a way to exploit modern ceramic composites can be found. It will take several years of design and evaluation to ascertain the sign and value of the net cost impact of these many tradeoffs.

5. INSTITUTIONAL CHALLENGES

Institutional innovations will also be necessary to establish the international consensus and norms which are prerequisite to the deployment of proposed regional front and back end service centers providing the nuclear fuel fabrication, 15-year refueling services, and back end recycle and waste management activities — all conducted under international oversight. These services would be provided only to those clients who agree to abide by the portfolio of safety, safeguards, liability, radiation safety, emissions, and etc. norms and who perhaps share in ownership and operation of the regional centers. That such international norms can be achieved is evident by past successes in the areas of safeguards regimes, safety norms, indemnification norms, radiation exposure standards, and etc. Building international consensus none-the-less takes substantial resolve and many years of effort and should be initiated coincident with the technology R&D.

6. NEAR- TO MID-TERM TRANSITION STRATEGIES

The trends toward decarbonization of chemical fuels, transportation sector reliance on hydrogen burning fuel cells, potable water as a valuable commodity and a duel energy carrier infrastructure based on grid delivery of electricity and hydrogen — and perhaps with distributed final energy conversion based on microturbines and fuel cells decentralized to a neighborhood level of granularity — these will occur under the influence of market forces over the coming decades. A strategy for ensuring that nuclear energy can contribute to global energy sustainability rests on anticipating the outcome of these trends and initiating the R&D required to position the sustainable nuclear energy resource so that it can in the future couple to these emerging developments in client base and energy conversion and carrier infrastructure elements.

In the near- to mid-term, as discussed in other papers at this conference, the technologies are already in place and should be exploited to apply nuclear energy to the development of the hydrogen economy based on thermal spectrum reactors. Electrolysis during periods of off peak electricity load[17] and near- to mid-term use of high temperature gas reactors for process heat and water cracking[18] are two examples. Eventually, however, fast spectrum reactors consuming \( \text{U}^{238} \) and/or \( \text{Th}^{232} \) will be necessary for achieving sustainability.

The transition period of 20 to 40 years during which the new infrastructure establishes itself should be ample to accomplish the required technical and institutional innovations to
add the sustainable fast reactor element to the mix. While ample, a sense of urgency in starting the innovation efforts is warranted. Trending projections forecast that the current glut of fissile inventory will be consumed by the mid century. Therefore, by that time it is essential that a substantial number of the fast spectrum modules should already be in place such that their reload cartridge cores can be reconfigured from fissile self sufficient to breeding configurations so as to manufacture fissile to supply the working inventories of new installations in the growing economy. In the event that fissile shortfalls were to occur, dedicated fissile manufacturing systems located at the regional service centers could be emplaced. The applicability of fast spectrum subcritical source-driven systems – having a remarkable excess neutron balance – to manufacture fuel for thermal reactors of low fissile working inventory might find a role should the fissile price escalate sufficiently due to shortages.

The R&D to emplace a long-term concept such as the one proposed here is at a very early stage of development. Its design goals will take several decades to achieve -- and yet this long-term development effort must find funding sources in a deregulated energy market where planning horizons are rather short. Even so, in a deregulated market numerous opportunities should exist for the fossil and nuclear sectors to find mutually supportive (symbiotic) arrangements, which can help both sectors to achieve the transition to energy sustainability. For one example, as multinational oil and gas conglomerates transition to become energy conglomerates, the nuclear R&D community should give consideration to schemes for nuclear heat assisted reforming or pyrolysis of fossil fuel as a means to increase hydrogen yield per unit of CO₂ release from the fossil resource. For another, as energy parks transition to become multi industry eco parks, with diverse industries mutually exchanging mass and energy flows, opportunities may emerge for applications of greenhouse-gas-free nuclear heat delivered over the full range of temperature from ambient to the highest temperature reachable by the technology of that decade.[18] In short, by integrating itself into the larger energy supply sector and adding value to competitors for market share, mutual benefits should make self evident the efficacy of further nuclear R&D; wider support for public and/or private funding could be the result.

7. ACKNOWLEDGMENTS

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The notions presented here represent the author’s viewpoint and do not constitute an official Argonne position.
REFERENCES


FIG. 1. Improvement in the efficiency of motors and lamps analyzed as a sigmoid (logistic) growth process. NOTE: Shown in a linear transform that normalizes the ceiling of each process to 100%. MAIN DATA SOURCES: for lamps, Encyclopedia Britannica (1964); for motors, Thirring (1958). Copyright 1997 by the National Academy of Sciences.