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ENHS: THE ENCAPSULATED NUCLEAR HEAT SOURCE – A NUCLEAR ENERGY CONCEPT FOR EMERGING WORLDWIDE ENERGY MARKETS

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ABSTRACT

A market analysis is presented which delineates client needs and potential market size for small turnkey nuclear power plants with full fuel cycle services. The features of the Encapsulated Nuclear Heat Source (ENHS) which is targeted for this market are listed, and the status of evaluation of technological viability is summarized.

INTRODUCTION

Global Energy demand growth during the 21st century has been projected by numerous organizations – often in connection with the study of sustainable development or of global climate change. Starting with projections of population growth and economic development (GDP) by region, these energy demand projections incorporate historical trends of energy use per capita vs GDP and energy intensity vs GDP to produce regional energy demand projections for a range of conceivable futures, and aggregate these to produce a range of global energy demand projections. Market shares of various energy resources (fossil, renewables, nuclear) are also projected under various assumptions concerning technological and institutional futures [1].

Common to all projections is a forecast of massive growth in global demand for energy services over the next century. For example the Case B "just muddling thru" scenario from reference 1 shows that even for cases where fossil continues to dominate the market, there is potential of 2000 GWe nuclear by 2050 and nearly 6000 GWe by 2100. The spread of projected nuclear futures from alternate studies range from 1200 GWe to as high as 6000 GWe in 2050. Also common to all projections is a forecast that the dominant growth will be occurring in the currently developing economies due to two factors; greater population growth there than in developed (OECD) countries and higher growth rate of energy use per capita and concomitant GDP per capita there than in developed countries. Historically it is found that once the developed countries reached an energy use per capita in the range of 6-9 toe/capita, energy use tended to saturate, and

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further growth depends mostly on population increases. However population growth rates also tend to saturate with increasing GDP/capita, and in many developed countries the birth rate has reduced to a self sustaining level only.

The projected massive increases in worldwide energy demand will create markets for all segments of the energy supply chain including nuclear production – which currently provides 17% of the world's electricity (6% of the world's primary energy). But the fact that much of the growth will be in developing nations means that market conditions for nuclear deployment will be different in the first half of the 21st century from those historical conditions of the past 50 years during which nuclear energy deployment occurred primarily in industrialized countries.

One of the challenges for the DOE's Gen-4 initiative is to tailor a portfolio of nuclear energy concepts for applicability in the global market conditions of the coming decades. The purpose of this paper is to attempt to delineate market needs likely to prevail especially in the developing country segment of the market and to describe the design rationale being taken for the Encapsulated Nuclear Heat Source (ENHS), a concept which is directed to small reactors for that market. [2]

Projected Market Conditions and Client Needs

Sufficient energy is an essential driver of economic growth. Diffuse energy density supplies such as available from renewables, while suited for low population density agrarian economies, are at a disadvantage when population density and economic intensity are high. Demographic projections forecast that by 2050, 80% of the world's population will reside and work in urban areas. Here, high energy density resources such as nuclear have an increasing role to play. The US-DOE's Generation-4 initiative is directed to develop nuclear energy systems to support world energy supply in the 21st century and beyond. The features of the nuclear offerings will have to be tailored for the needs of the future clients, which in some cases will be quite different from the regulated utility market conditions which prevailed in OECD countries during the 1960's to 1990's. What will future clients want?

Safety

Given siting requirements for nuclear plants to support the needs of urban societies and given that their deployment could dramatically increase into the range of thousands of plants worldwide, unprecedented levels of safety will be appropriate. The design trend in recent years has been to make increasing use of a passive safety strategy wherein safe response of the power plant to initiators exploits natural laws of physics such as thermal expansion to terminate the chain reaction, and natural circulation to remove decay heat. This trend, which decreases plant complexity and which reduces vulnerabilities to equipment malfunctions and/or maintenance errors, should receive increasing application for future plants.

Security of Supply

Energy supply security is essential to a nation's welfare. Indigenous resources or diversity of external supply sources have been the historical strategies taken in the era of fossil fuel. During the 1970's France and Japan, lacking indigenous fossil resources, made major structural changes in their energy supply infrastructure – taking advantage of the million-fold higher energy density of uranium fission as compared to fossil combustion – to compensate their lack of indigenous fossil resources. (Even at only 1% use of the ore as in the LWR-UOX once thru cycle, whereas 10 tonnes of oil would meet the annual needs of one person, 10 tonnes of uranium would meet the annual needs of ten thousand.) This change in the structure of energy supply required not only the deployment of nuclear power plants themselves, but deployment of indigenous front and back end fuel cycle services also.

However, in the future, it is not clear that all nations will wish to undertake the cost of deploying an entire indigenous fuel cycle if there is an alternative for assuring energy security. One such alternative, discussed and evaluated already in the late 1970's as part of the International Nuclear Fuel Cycle Evaluation (INFCE) activity [3], is the use of regional fuel cycle service centers for providing front and back end fuel cycle services to regional clients. If such regional fuel cycle service centers were to be chartered as consortia under the control of the member regional client nations, and were operated under international nonproliferation oversight, the institutional arrangement could be foreseen to meet needs both of client energy security *and* of worldwide nonproliferation goals. If in addition, national membership on the board of directors of the consortia and receipt of services by the nation's client utilities were to be granted contingent on a national commitment to operate and regulate their nuclear plants according to international norms on safety, safeguards, early notification, third party liability, etc., then a uniform worldwide set of nuclear operational standards could be brought into existence in parallel to those already existing for other international commerce such as airlines, shipping, etc.

Development of institutional arrangements, treaties, and norms regarding civilian nuclear energy has been ongoing since the 1950's and many of the required institutional arrangements are already in place [4] through the auspices of the IAEA and the OECD among others. There is reason to be hopeful that continuation of this evolution can lead to a regime of regional fuel cycle centers which localize into a finite number of worldwide sites the activities for handling of front and back end fuel cycle services – taking advantage of economy of scale for bulk fissile handling and waste management and of institutional oversight. Trending in this direction is evident already with the large facilities at LaHague and Sellefield servicing international markets for recycle and refabrication and the imminent entry of Russia into the international arena of spent fuel storage and reprocessing – using facilities at Krasnoyarsk.

Public Acceptance

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A finite number of such regional fuel cycle centers handling the majority of bulk fissile material processing has obvious attractive features for the worldwide nonproliferation regime. [5] The costs of international safeguards can be capped by avoiding fuel cycle facility deployments in each nation wishing to benefit from a civilian nuclear energy supply component in their energy mix.

And the aggregation into a small number of radioactive waste management sites worldwide can also be foreseen to make nuclear more attractive to countries which will initially have only a few reactors and will therefore not favor placing themselves into a position of owning a waste management mortgage.

Affordability

Consistent with the notion of regional fuel cycle service centers to facilitate a client's "outsourcing" fuel cycle support, the notion of purchasing "turnkey" power plants of small power rating could potentially be attractive for a significant segment of future clients in search of safe, assured energy supply. For clients in countries which are in the early stages of development, competition for capital financing of economic development projects is fierce; therefore incremental additions to infrastructure and rapid achievement of revenue better suits such financial conditions than do "economy of scale" deployments requiring large up-front investment loans and long payback intervals. Economic growth can be assisted using a "bootstrap" approach wherein initial incremental investments in energy supply foster incremental business investments which create wealth which can be partially plowed back for further energy supply infrastructure expansion – in an accelerating pattern.

"Merchant plant" clients in developed countries having deregulated power markets also face financial conditions of high expected rate of return on investment and short payback interval. And, in deregulated power markets, such clients are free to offer alternative energy services such as water desalinization, process heat, etc; they are not confined to the historical electricity supply mission for nuclear.

From the client's point of view in both developing and developed countries, small turnkey power plants with full fuel cycle services will, in the future, become an attractive product offering.

Summary of the Potential Market Conditions and Incentives for Suppliers

To summarize, owing to energy supply demand growth in the urban centers of the developing world, and of energy market deregulation, one can foresee a market segment for:

- Turnkey plants of small power rating and high degree of passive safety.
- Supported by regional fuel cycle service centers operating under international oversight which are potentially owned and operated by consortia comprised of the regional client nations and/or companies.

Offerings of this type could be foreseen to meet the client's needs for:

- energy security
- low initial buy-in cost, and reduced back end waste management mortgages
- high levels of safety, and
- a nonproliferation regime which meets international requirements

But --- will suppliers be drawn to this market?

Clearly this is only one of several future market segments for nuclear energy. It favors situations where availability of capital is dear and/or where financing costs are high and payback periods must be short. And it rests on a client acceptance of outsourcing both the power plant fabrication/installation and the fuel cycle services – rather than developing an indigenous front-to-back industry. That it is only a segment market is evident by the fact that China and South Korea have already chosen the historical path of indigenous development and economy of scale infrastructure. But it is also evident that markets with these attributes are already widespread in other industries of large capitalization – for example in the airplane, automobile, construction equipment, military equipment, chemical plant, combustion gas turbine power plant and many other industries. In fact in *most* industries the client desires the *immediate benefit* from deploying a *commodity product* and receiving support services and – in order to avoid development costs and delays – is prepared to pay incrementally for what others have developed and proffered for sale at a profit.

Proffering products to this market will require the nuclear plant supplier to assume a much greater fraction of monetary risk vis-à-vis the client than has been the historical norm in the nuclear business. A supplier would have to foresee a large enough market to invest in the factories required for multiple production runs of such turnkey plants. The client, on the other hand would simply buy a standardized energy supply devise which is delivered ready to go and which starts generating revenues quickly. This business model is widely used as enumerated above, -- where the market is foreseen to be large enough and stable enough to reduce the supplier's investment risk. Consider the range of projections cited previously – from 1200 GWe to 6000 GWe of nuclear capacity deployed worldwide by 2050 – up from ~350 GWe today. Suppose that only half of these additions were in the small modular plant size range. Then the market size for 50 MWe plants starting in 2010 lies in the range of 200 to 1400 new plants delivered each year over the next 40 years. This potential market size could justify supplier interest. A similar business model has already been adopted by ESCOM and is being executed [6] for their 100 MWe Pebble Bed Modular Gas Reactor, (PBMR) offering.

Others have also foreseen this potential market and have initiated development of small power rating thermal reactor concepts cooled by water and gas. The Argentinean CAREM

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integral PWR, the Korean SMART desalinization reactor and the US/Italian/British IRIS PWR are only a few of the many small, modular concepts under current development. The IAEA has for a number of years convened international meetings to stimulate interactions between potential clients and potential suppliers in this future market [7], and has published proceedings from these meetings.

Applications of Fast Reactors – The ENHS Concept

Fast reactors cooled by liquid metal hold several unique advantages for service in this market. First, they can quite easily achieve long refueling interval with minimal reactivity loss because of low sensitivity to fission product poisoning and by employing internal breeding gain. High discharge burnup fuel forms (~150,000 MWd/tonne) are already qualified for use. Long refueling interval has both energy security benefits and capacity factor benefits. Second, the internal breeding can provide for self regenerating fissile fuel supply and waste minimization when combined with recycle at the regional fuel cycle center – again benefiting energy security. Finally, the ambient system pressure of liquid metal cooled systems eliminates the dominant loss of coolant safety vulnerability of other coolant types (water, gas) and (combined with minimal burnup reactivity loss) can lead to remarkable levels of passive safety performance. [8]

Use of fast reactor technology for this potential market was initiated in the early '90's by Toshinsky [9] using Pb-Bi cooling and separately by Hattori [10] using Na cooling. Later, in 1998, Brown [11] at the Lawrence Livermore National Laboratory stimulated the adaptation of Toshinsky's and Hattori's ideas to a set of fast neutron spectrum Secure Transportable Autonomous Reactor (STAR) power plant concepts for proposal submittal to DOE's NERI grant competition. (Among these proposed concepts was ENHS [12], STAR-LM [13] and later STAR-H2 [14].) The ENHS was funded as a NERI-00 grant.

The development targets for the ENHS were to provide a small rating, turnkey power plant which like a "nuclear battery" could be delivered already-fueled to the client's site, would provide energy for 15 to 20 years without refueling, and then would be changed out for a replacement "battery" ENHS module and returned to a regional center for backend fuel cycle services. The ENHS module would be inserted into a permanently sited secondary heat transport circuit driving a Rankine steam cycle at the client's site and would operate in a semi-autonomous, load-following mode – relying on passive reactivity feedbacks to match reactor power to Rankine cycle demand. Natural circulation of Pb-Bi primary and secondary coolant at full power and lift pump assisted circulation options have each been considered and shown to be feasible. The ENHS would remain essentially sealed[1] at the client's site; heat transfer to the secondary coolant tank would be across high surface area IHX walls embedded in the ENHS vessel. Module handling equipment would be brought to the site with the replacement module and would be returned to the regional center with the used module. Fresh and spent module shipping would be conducted with the fuel embedded in solidified and passively cooled Pb-Bi coolant filling the module to an elevation above the core. Filling and remelting of reload modules and partial draining and solidification of spent modules would be performed with the module emplaced in the secondary coolant tank at the client's site. All fissile material handling would be conducted at the regional fuel cycle center using modern recycle/refab technologies which maintain a commixed transuranic product composition. Therefore, fresh, reload, and spent modules would all be comprised of fuel meeting a spent fuel standard of safeguards self protection.

The features targeted for the ENHS, if they prove to be technically feasible, could meet the requirements of the market segment described earlier. Given that technical feasibility were established, then economic viability would remain to be established.

Status of ENHS Concept Development

A DOE goal for NERI projects to stimulate University, Laboratory and Commercial Vendor teaming and innovation and to facilitate international collaboration on advanced nuclear power has been a major success of the ENHS project; numerous innovations have emerged from the joint efforts of U of Cal. (Berkeley) Argonne National Laboratory, Lawrence Livermore National Laboratory, Westinghouse as well as the Korean organizations KAERI, KAIST and U of Seoul. Exchange of information with Japanese organizations, CRIEPI and TOSHIBA also contributed to the success of the ENHS project. Multiple options have been carried in parallel through the design development.

At the end of two year of development by the ENHS team most items of technical feasibility have been established. These are only summarized here, whereas the technology is described in numerous papers including Reference 2, 12, 15-19 and references thereof. Figures 1 through 3 show the plant layout for a 125 MW_{th}/50 MWe ENHS and Table 1 lists the salient plant characteristics. [15] The ENHS vessel is ~3 meters in diameter and ~20 meters high for the 100% natural circulation option or ~10 meters high for the lift pump assisted option. The shipping weights with Pb-Bi coolant filled to the top of the core are 360 and 300 tonnes respectively.

The IHX heat exchanger is comprised of either 40 x 2.5 cm rectangular tubes or of ~40cm diameter multi concentric tube nested channels. [16] In either case these are arrayed around the perimeter of the reactor vessel with top and bottom headers and are sized to transfer 125 MW_{th} of heat with no greater than 50ºC temperature drop across tube walls .

Neutronics feasibility of 15 year refueling interval has been established using U/Pu/Zr metal alloy fuel in a ferritic martensitic cladding, and a derated power density. Natural

[1] Cover gas volume control and coolant chemistry control would utilize small diameter piping through the vessel cover.

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circulation cooling at 100% power has been established via full circuit modeling analyses. [17]

Extensive plant dynamics analyses of operational and upset transients have established a passive safety regime and has partly established an innate passive load following regime. [18]

A heatup/melting approach for fresh modules has been developed. [19]

Several technical feasibility issues are still under investigation. Passive load following over an extended power schedule including startup has yet to be fully worked out. The means, time durations and logistics for partially draining and refreezing a spent module preparatory for return to the fuel cycle center have not been worked out for the case of *short* cooling times. Fuel pin thermo/structural/dynamic design analyses are in progress but not yet complete. While fuel cycle options are presumed to rely on dry process/remote fabrication technologies under development by others, the specific technology has not been decided. There is also the issue of factory fabrication strategies developed to the level of completeness targeted. It will require design details beyond those developed to date to work out the fabrication details and the factory design required to produce many tens to hundreds of reactors per year.

Given that these remaining technical issues will be resolved for ENHS, it will fill the client needs described above. In the end, economic viability vis-à-vis alternative will be the determinant of market penetration in its targeted market segment.

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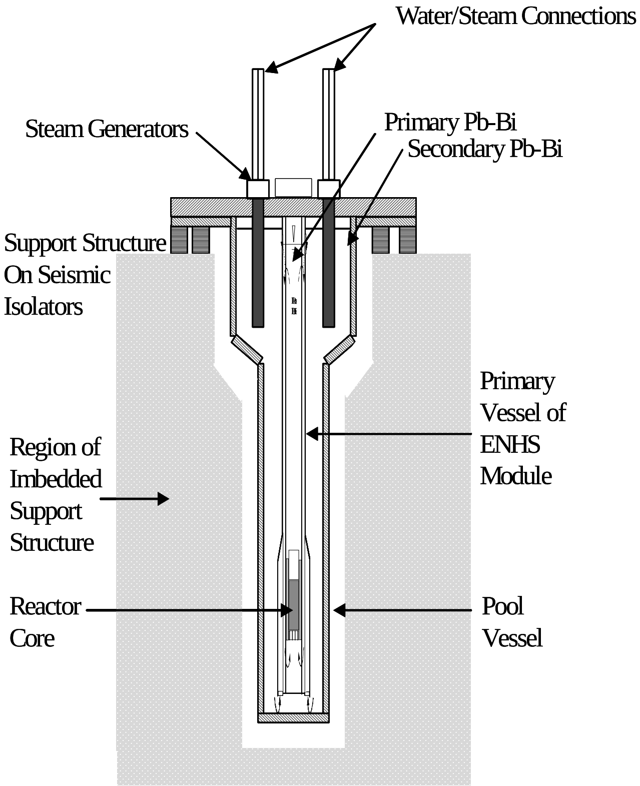

Figure 1. Economic Growth and Energy Consumption (1990)

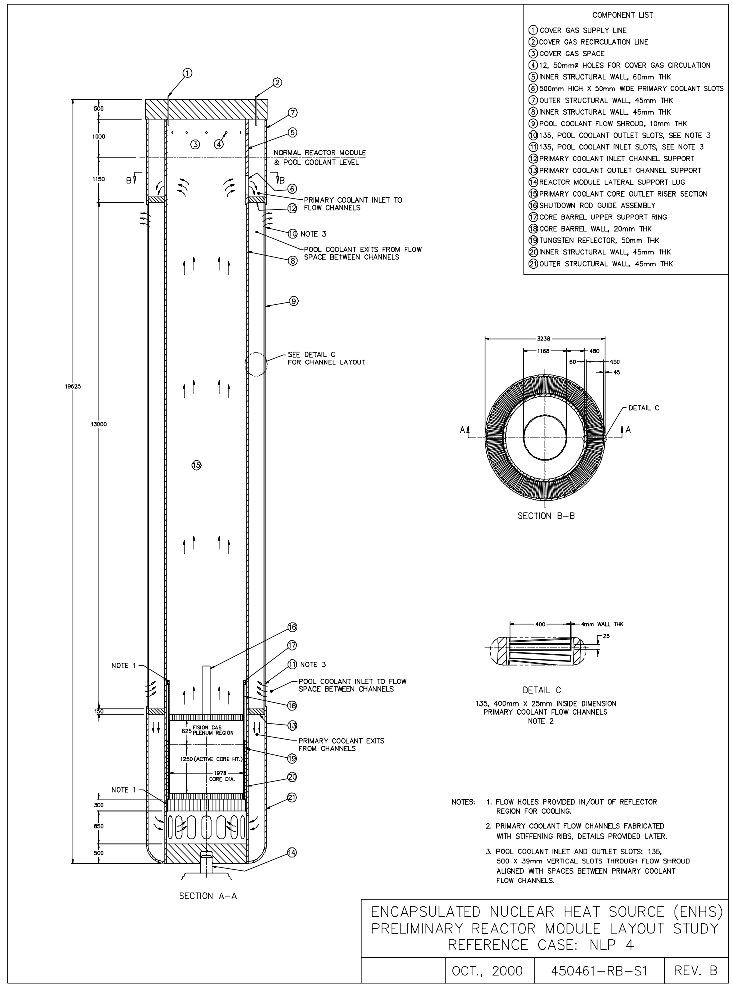

Figure 2. Illustration of ENHS Primary Coolant and Heat Exchanger Regions for LP7 Heat Design Variant. (referred to as ENHS2)

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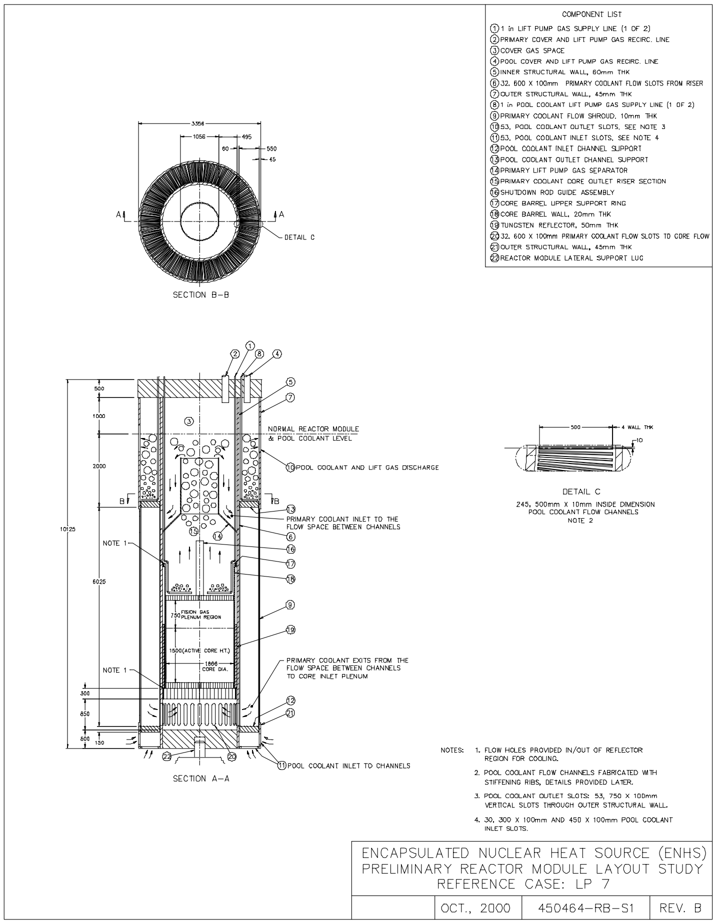

Figure 3. Illustration of ENHS Primary Coolant and Heat Exchanger Regions for LP7 Design Variant.
(referred to as ENHS2)

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Table 1. Selected Design and Performance Characteristics of ENHS Reference Designs

Design Parameter	ENHS1	ENHS2
Primary Pb coolant circulation	100% natural	With lift-pump
Average linear heat-rate (W/cm)	60	60
Average discharge BU* (MWd/tHM)	52,000	52,000
Core life* (effective full power years)	20	20
BU reactivity swing	<1$	<1$
Maximum excess reactivity	<1$	<1$
Core height (m)	1.25	1.50
Core diameter (m)	1.98	1.87
Fuel rod diameter (cm)	1.0	1.0
Clad thickness (cm)	0.1	0.1
Lattice (hexagonal) pitch (cm)	1.45	1.50
Overall module height (m)	19.6	10.1
Outer module diameter (m)	3.24	3.35
Number of rectangular channels in IHX	135	245
Inner dimensions of channel (cm x cm)	40 x 2.5	50 x 1.0
IHX channel length (m)	13	6
Weight of fueled module for shipment (t)	360	300
Primary coolant inlet/outlet temperature (^{o}C)	400/545	400/560
Secondary coolant inlet/outlet temperature (^{o}C)	358/497	390/519
Number of steam generators per ENHS	8	8
Steam generator module diameter (m)	0.78	0.78
Active length of SG tubes (m)	4.6	4.6

* Limited by radiation damage to clad @ $4x10^{23}$ n/cm^2 >0.1 MeV

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