STAR-H2: A LONG-REFUELING INTERVAL BATTERY[1] REACTOR FOR HYDROGEN AND WATER SUPPLY TO CITIES OF DEVELOPING COUNTRIES

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ABSTRACT

The STAR-H2 reactor and fuel cycle concept is devised to attain Gen-IV goals by responding to foreseen mid century needs and market conditions. It is targeted to fill all primary energy and potable water needs for urban centers in developing countries and is designed to fit within a hierarchical hub-spoke energy architecture based on regional fuel cycle centers, using nuclear fuel and hydrogen as the long distance energy carriers – with distributed electricity generation as the local carrier to mesh with existing urban energy distribution infrastructures using grid delivery of electricity, hydrogen, potable water, and communications (and sewage return) through a common grid of easements. STAR-H2 is also intended for Independent Power Producers in industrialized countries seeking to service emerging markets for hydrogen and water production.

1 BACKGROUND & GOALS

In his prescient plenary speech "On The Nature of Nuclear Power and Its Future" [1] at the Global 93 conference, Wolf Häfele compared the technical, institutional, and social opportunities for a second wave of nuclear deployments to those which brought about the Industrial Revolution. He argued that the first wave of nuclear deployments – for electricity production and with an open fuel cycle – was *destined* to saturate at under 400 GWe global deployment because:

> "Nuclear power was put into an existing technical and institutional infrastructure without much changing this infrastructure – still characterized by the use of oil in particular but also of coal and gas" [i.e., nuclear was deployed in an energy supply architecture optimized for fossil].

But to paraphrase his view of the analogy:

> The Industrial Revolution exploited the factor of a million between ~1 μ ev due to mass flow (of falling water) and ~1ev chemical energy flow of burning coal to achieve a revolutionary transition away from centuries of reliance on water wheel and animal power to coal-fired steam engines. The exploitation of the factor of a million between renewable and chemical energy density achieved by changing over to a *stored* (coal) resource – *when enabled by re-engineering the architecture of production (factories, division of labor, etc.)* – led to the first Industrial Revolution. Over the

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[1] STAR = Secure, Transportable, Autonomous Reactor. The reactors are referred to a "Batteries" because they store 20 years worth of heat and they load follow by passive means – delivering heat when it is requested by the Balance of Plant and passively shutting off when the request stops.

> ensuing one and a half centuries this revolution literally changed the Western world [technically, institutionally, and socially] and finally broke the Malthusian regression to unchanging GDP/capita.

He concluded:

> "One must be prepared for evolution or even revolution when *real* nuclear power [frees itself from the architecture optimized for fossil, and] brings the factor of a million between nuclear and chemical bond energies to the surface – *one cannot treat nuclear power like chemical power, -- uranium like yellow coal, so let us not loose our perspective*."

Nuclear energy's current configuration has left its most important innate features unexploited; its economically harvestable resource base good for a millennium of global energy supply by closing the fuel cycle; its capacity to service the *entire* primary energy market by manufacturing hydrogen; its capacity to break the energy security/nonproliferation dilemma by exploiting its incredible energy density – serving as a long distance energy carrier to fuel long refueling interval reactors supported by regional fuel cycle centers operating under international oversight, and its ability to achieve neutral radiological exchange with the ecosphere in the long term by self consuming its very long lived radioactive waste.

The objective of the work reported here has been to exploit these features to propose a re-engineered world energy supply architecture optimized for nuclear rather than fossil. It is intended for global energy supply in the market conditions of mid 21st century and beyond where 80 percent of the world's population of ~10 billion people reside in cities; where electricity and hydrogen serve as complementary energy carriers replacing fossil; and where ecologically-neutral closure of the world's energy supply chain is attained by eliminating carbon from the chain and by sending only fission products to waste. This nuclear-based architecture is intended to fuel a transition to global sustainable development.

Although it is revolutionary in concept, it is aimed to gradually displace the fossil architecture and manage the back end of the current nuclear infrastructure over a four or five decade evolutionary market penetration process. Just as was the case for the Industrial Revolution, technology by itself it not sufficient; the transition will require institutional as well as technological innovations to achieve market penetration.

2 MID CENTURY ENERGY NEEDS

Global energy demand forecasts for the 21st century project massive growth in demand for energy services, and they show that the dominant capacity additions by 2030 and beyond will occur in the currently developing economies. They predict that demographic migrations will lead to a majority of global population living and working in urban centers by mid century. Thus, the global reach of the nuclear client base must be expanded to include cities in developing countries. The range of demanded energy products will also expand; an emerging need for process heat conversion of water or hydrocarbon feedstocks to hydrogen is foreseen. Manufacture of potable water may also be needed as cities increasingly outsource municipal water supply contracts to profit-making entities.

Developing economies enjoy the opportunity to "leap frog" to new sustainable energy infrastructures which meet their special needs. Population and economic activity which is focused primarily in cities will require an energy supply architecture having high energy density. Rapid economic growth rates will require emplacement of energy infrastructures having a short energy payback period. These two requirements preclude a major role for renewables for the clients targeted here, but are well suited to the innate features of nuclear.

3 RECONFIGURING THE WORLD'S ENERGY ARCHITECTURE TO EXPLOIT NUCLEAR'S INNATE FEATURES

Nuclear has much to offer to fuel a sustainable development [2] revolution on the scale of the Industrial Revolution, but to do so it must be reconfigured to meet the 21st century market situation. The fact that much of future growth will be in cities of developing nations means that market conditions facing future nuclear deployment will be different from historical conditions where deployment occurred primarily in industrialized countries under regulated electricity market conditions. The proposed STAR-H2 energy supply architecture has been optimized to exploit all of nuclear's innate features for the new market situation. STAR-H2 power plants are 400 MW_{th}, turnkey plants which manufacture hydrogen and electricity as energy carriers and potable water. They are targeted for worldwide deployment and especially for urban centers in developing countries. To break the energy security/nonproliferation dilemma, they are designed with 20 year refueling interval and they fit within a proposed hierarchical hub-spoke energy supply architecture using regional fuel cycle centers; using nuclear fuel and hydrogen as the long distance energy carriers – and supporting distributed electricity generation as the local energy carrier. In that way the new architecture will *mesh seamlessly with existing and imminent urban energy distribution infrastructures using grid delivery of electricity, hydrogen, potable water, and communications (and sewage return) through a common grid of easements.* This will facilitate incremental market penetration. The small sizing and outsourced fuel cycle and waste management configuration allows for plant deployment at modest initial capital outlay for the client. Turnkey plants are transported to the client's site and rapidly connected to a pre-constructed non nuclear safety grade balance of plant to achieve a rapid start of the revenue stream.

Figure 1 illustrates the proposed hierarchical energy delivery infrastructure at an abstract level. The "hubs" represent where one energy carrier (nuclear fuel, hydrogen, electricity) is converted into the successive energy carrier along the supply chain – a carrier better suited to the required function. The "spokes" represent the transmission channels of the energy carrier from its source point to its point of use. The ordered sequence of energy carriers (nuclear fuel shipped from the regional centers to the Battery nuclear power plants; hydrogen and water piped from the STAR nuclear plants to the district load centers; and electricity wired from distributed production center to end use) *are organized sequentially (hierarchically) in the order of their energy density and their associated power carrying capacity through practical-sized conduits (e.g., ships/trains; pipelines/trucks; wires, respectively).* The widths of the spokes in Fig. 1 suggest the power carrying capacity of practical conduits for each energy carrier; the fractal-type expansion of the architecture as it progresses from the uranium ore energy resource to the point of end energy use reflects the diminishing energy carrying capacity and corresponding multiplicity of carrier conduits in the hierarchical sequence of energy carriers.

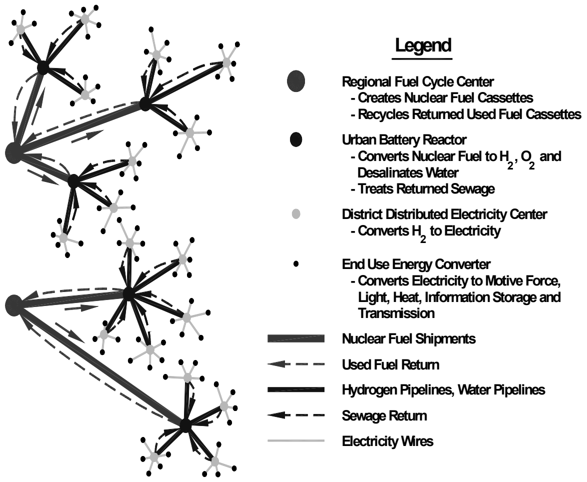

Figure 1. Hierarchical Hub/Spoke Energy Architecture

For example, e.g., a two-week voyage to deliver a single 400 MW_{th} whole core fuel cassette good for 20 years (at a capacity factor of 0.9) in a STAR-H2 power plant represents a 188 GW_{th} power transmission conduit. A single ship carrying ten cassettes on an itinerant one month delivery voyage from a regional center could supply nearly 1000 GW_{th} (1 terawatt years/year) to its service region. A fleet of 10 ships could provide 10 $terawatt_{thermal}$ years/year (which rivals the entire current world primary energy use of 12 $terrawatt_{thermal}$ years/year).

Marchetti has observed [3] that the economical scale of equipment sited at the "hubs" will expand to match the energy demand in the geographical area circumscribed by the spokes. Because of the enormous energy density of nuclear fuel contained in the refueling cassettes, the "reach" of the nuclear fuel supply "spokes" through practical sized transport conduits (ships) (i.e., the energy demand met in the area circumscribed by the spokes) can be thousands of miles and as a result the fuel cycle facilities at the regional centers can (must) be sized for economy of scale to service the very large demand arising from a significant global region. Even if providing for a plausible world demand (~50 terawatt$_{thermal}$ years/year) by mid century, no more than a dozen such fuel cycle centers could meet the world's *entire* needs. In that sense they could be viewed as the 21st century analogue to the oil fields of the twentieth century.

The "reach" of the next link in the supply chain – the hydrogen pipeline "spokes" – would reflect their several gigawatt carrying capacity [4] and would service regions of several hundred mile dimension though pipeline grids such as are currently used to distribute natural gas to load centers. Pipeline grids would carry hydrogen (and water) to district centers scattered throughout the city and its surrounding population region. At a primary energy use rate of 4 toe/capita/year[2] (i.e., ~5.5 kw$_{th}$ day/person day) a five and a half gigawatt hydrogen pipeline could service a city and its environs with a population of a million people.

After manufacture at a STAR-H2 power plant located at the margins of the city, the hydrogen and water will be piped or trucked to city districts through a grid of distribution conduits. At district level distribution hubs, the hydrogen will be partitioned to meet society's energy service needs:

- A third will be dispensed for hydrogen-fueled transportation services
- A third will be distributed by pipe throughout the district for heating homes, apartments, offices, and factories, and
- A third will be converted in fuel cells and/or microturbines to electricity for distribution throughout the district.

The "reach" of the electricity distribution wires starting at district microturbine or fuel cell converters of hydrogen to electricity and taking the electricity to final use in lighting, motors, and information management would be of the scale of city districts and skyscrapers – as is the current usage. This last stage of distribution would use the existing electrical and water distribution network (where it already exists) and *would thereby make the conversion to the new energy architecture nearly transparent to the end user of energy services.*

District-level conversion of hydrogen to electricity – as opposed to conversion of heat to electricity at the STAR reactor – is envisioned for several reasons. The first – and the one which is already driving a transition – is supply reliability. Microturbines and (imminently) fuel cells can provide secure electricity at a district level, even if the broader grid suffers a shutdown, because they run on a storable supply – currently natural gas, but eventually hydrogen. Some planners believe that distributed generators will, in fact, eventually *drive* the grid.

The second driver is that the hot water produced as the "waste" from conversion of hydrogen to electricity at district hubs can be used in support of the city's hot water needs. This will increase billable product for the owner of the conversion equipment but more importantly, it will reduce the water vapor and thermal plume ecological footprint of the conversion step. *This sets the scale of electricity production at a district level because of the limited "reach" of hot water distribution spokes.*

The overall conversion efficiency of nuclear heat to district-level reconversion of hydrogen to electricity, [fission heat → hydrogen → electricity] would be about 0.45 x 0.80 = .36 which is already better than current LWR's. The overall conversion efficiency of nuclear heat to district level *energy products* [fission heat → hydrogen → electricity + hot water] would be about 0.45. When potable water manufacture from the STAR-H2 process plant is included, the overall conversion [nuclear heat → energy services] reaches 85%.

The proposed hub/spoke energy architecture optimized for nuclear thus envisions a worldwide total of a dozen or less regional fuel cycle centers each servicing thousands of long refueling interval STAR Battery heat source reactors which individually or in clusters service cities and their surrounding regions with hydrogen and potable water. Hydrogen substitutes for fossil fuel in the transportation and heating sectors. Electricity and hot water are produced from hydrogen at distributed district centers and electricity reaches its final point of use through wires.

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[2] 4 tons of oil equivalent per capita year (toe/capita year) is the average current primary energy use rate in Europe.

Carrier conduit cross connections of the user hubs to multiple supplier hubs (not shown in Fig. 1) and *energy storage buffers* provided by the storable nuclear fuel and hydrogen energy carriers would provide for robustness of energy security at both the national and the individual user levels – and for protection against monopolistic pricing.

Over time, in a transition lasting of the order of a century, the hydrogen would gradually displace oil, gas, and coal and the new sustainable, nuclear-based architecture would gradually replace the current fossil-based world energy supply infrastructure. The resulting fission based energy supply architecture will provide centuries of energy on the Known plus Speculative ore base recoverable at $\leq \$130$/kg U.

4 BREAKING THE ENERGY SECURITY/NONPROLIFERATION DILEMMA

Long (20 year) refueling interval and full core cassette refueling supported from consortia-owned Regional Fuel Cycle (front and back end including waste management) Service Centers, operating under international oversight are intended to make nuclear-based energy supply available in countries which don't wish to emplace an indigenous front-to-back fuel cycle infrastructure – and to do so without jeopardizing their energy security posture. Consortia of client nations exercising ownership and control of the center under international law – when combined with 20 year fuel cassettes installed on sovereign territory – could provide high assurances for a nation's energy security. At the same time, the regional centers, infrequent cassette refueling and full transuranic recycle (such that both reload and spent fuel cassettes meet the spent fuel standard of self protection and no fissile material ends up in waste) are intended to provide appropriate barriers to misuse of materials and facilities for military purposes.

This proposed architecture meets the criteria recently specified by M. ElBaradei for an enhanced nonproliferation regime [5].

5 SUSTAINABILITY AND ECOLOGICAL COMPATIBILITY

Full transuranic multi-recycle is employed to extract full energy content from the uranium ore, and to consign only fission products (and trace recycle/refab losses) to waste. *A millennium of global energy supply can be supported by the currently Known plus Speculative uranium resource base recoverable at <130 \$/kg.*

The architecture employs non carbon emitting technology throughout the entire supply chain. With nuclear fuel recycle, this architecture achieves sustainable ecological closure – no carbon emissions anywhere in the supply chain; recycle of oxygen and water via nature's cycles; and radioactive waste stewardship reduced from thousands to a few hundred years at which time neutral radiotoxic exchange is attained between ore withdrawals and fission product waste return to the earth's crust.

If successfully deployed such a nuclear-based global energy architecture can meet all elements of the broad definition of sustainability for global energy supply[2.]

6 THE REACTOR HEAT SOURCE [6]

STAR-H2 is a Pb-cooled, fast neutron spectrum, 400 MW_{th} reactor operating at a power density similar to LWR's. It employs natural circulation cooling at full power and passive load following and passive safety response characteristics. The 400 MW_{th} sizing is optimized to retain a rail shippable reactor vessel size while allowing for natural circulation heat removal. The neutronics properties of lead coolant enable a high coolant volume fraction fuel pin lattice so that natural circulation will remove heat at full power. Its neutron reflection properties and hard neutron spectrum permit fissile self regeneration in the core lattice itself which achieves zero burnup reactivity loss over the 20 year burnup interval and minimal reactivity vested in control rods – which is the key to enable passive load following/passive safety. Passive safety/passive load follow in turn enables use of a balance of plant having no nuclear safety function; *this allows for indigenous construction and operation of the Balance of Plant, using the local work force and institutional conditions prevalent during the initial stages of industrialization, providing local jobs for economic growth.*

Mid-sizing of the STAR-H2 power plant is targeted for incremental deployments where capital financing is dear and/or indigenous infrastructure is at an early stage of development. Modular construction, factory fabrication, and delivery of a turnkey heat source reactor to the client's site *where a non safety grade balance of plant has already been emplaced* will facilitate rapid assembly and initiation of revenue generation – strategies intended to achieve economy of mass production to replace historical economy of scale.

The reactor is refueled on a twenty year refueling interval with very short on-site cooling period. Whole core cassette refueling is conducted by Regional Fuel Cycle Center personnel using equipment brought to the site and returned to the Regional Center with the spent fuel cassette.

The concept employs an ambient pressure primary and extensive levels of passive safety [7] to be consistent with a worldwide deployment of many thousands of STAR-H2 plants; to remove all nuclear safety functions from the balance of plant; and to facilitate siting near urban centers. The reactor is located in a silo under an earthen berm to protect the reactor from external hazards including those posed by the co-sited hydrogen production plant. (See Fig. 2)

A conceptual design of the reactor has shown that it can meet its long life, natural circulation cooling, and passive safety/passive load follow requirements.

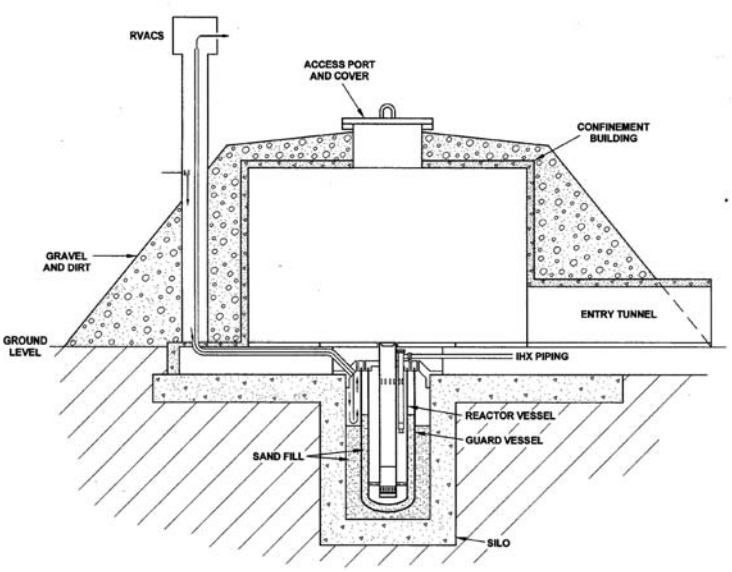

Figure 2. STAR-H2 Heat Source Reactor Sited in a Silo

7 THE BALANCE OF PLANT

The STAR-H2 balance of plant (BOP) is comprised of three cascaded cycles (Water Cracking; Brayton Cycle; Desalination) operating at successively lower temperatures – and with the heat rejected from each cycle used to drive the succeeding cycle (See Fig. 3). The reactor supplies 400 MW_{th} of heat between 800ºC and ~650ºC to the BOP through an ambient pressure flibe (fused salt) intermediate loop. The strategy for BOP plant design is to use as much of the heat as possible to maximize hydrogen production; use only as much heat to make electricity in the Brayton cycle as is required to run the BOP; and use whatever heat is finally left over to desalinate water. The ecological thermal footprint is minimized by converting as much as possible of the low grade heat to potable water, and the brine tailings are rejected only slightly above ambient seawater temperature.

The Ca-Br water cracking cycle [8] has three main segments: an endothermic "water cracking" segment where $CaBr_2$ and steam react at 750°C to make HBr and CaO; an exothermic Ca rebromination segment where CaO and bromine react at 600°C to regenerate $CaBr_2$ for recycle and release heat and oxygen; and a plasma chemistry HBr cracking segment where electrical driven (RF frequency) energy cracks HBr at 90°C to regenerate bromine for recycle and to release hydrogen. The plasmatron is followed by a pressure swing absorption cascade which cleans and pressurizes the hydrogen to meet pipeline delivery specifications.

Heat at 600ºC is rejected in the segment for regeneration of $CaBr_2$ from CaO. It is used to help drive the SC-CO_2 Brayton cycle [9]. After expansion in the Brayton cycle turbine, the SC-CO_2 passes through a high temperature and then a low temperature recuperator. It exits the low temperature recuperator at 125ºC. Heat is rejected from the SC-CO_2 to seawater in the Brayton cycle cooler which cools the SC-CO_2 from 125°C to 31ºC in preparation for its compression.

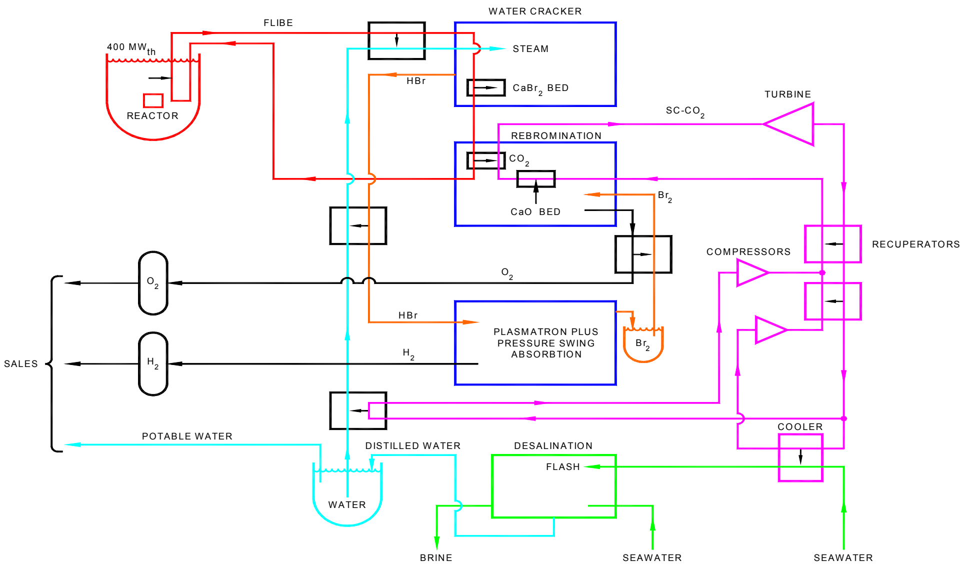

Figure 3. Process Heat Cascade: Water Cracking ⟶ Brayton Cycle ⟶ Desalination

The 100ºC seawater exiting from the Brayton cycle cooler delivers heat and seawater feedstock to the desalination plant. The desalination plant is a feed forward Multi-Effect-Distillation (MED) design [10] which produces 8000 m^3/d of potable water. Finally, heat at temperature slightly above ambient exits the plant in the form of heated brine tailings from the desalination process – minimizing the thermal plume ecological footprint of the plant. Alternate bottoming cycles have been identified for use at landlocked sites.

The BOP has been designed at the conceptual level and shown to achieve about 44% conversion of heat to H_2 (LHV) – making 160 MW_t days/day of H_2 (LHV) and 8000 m^3/day of water – enough to support all primary energy and water needs for a city of 25,000 using energy at 4 toe/capita year and water at 300 liters/day/person. All the electricity produced by the Brayton Cycle is consumed on site (and is figured into the 44% heat to H_2 conversion). Overall, 85% of the reactor's 400 MW_{th} is converted to energy products; 15% is rejected in the form of heated brine.

8 THE FUEL CYCLE

The reactor uses uranium/transuranic N-15 enriched nitride fuel and operates on a 20 year whole core cassette refueling interval; it is fissile self sufficient with an internal core conversion ratio of one. The fuel recycle technology is based on electrometallurgical recycle and remote vibropack refabrication of the uranium/transuranic nitride fuel. The recycle technology produces a commixed stream of all transuranies and achieves incomplete fission product removal such that the transuranic materials during processing and during fresh and used cassette shipping are always at least as unattractive for military use as is LWR spent fuel.

All fuel cassette shipments, refueling operations and used cassette returns are conducted by Regional Center personnel who bring the refueling equipment with them and take it away with the spent cassette. No refueling equipment remains at the site. The cassette and the cask are massive (each ~200 tonnes)[3] and are

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[3] Note that crawler cranes in use for LWR construction have capacities in excess of 600 tonnes.

amenable to GPS monitoring for item accountancy providing resistance to diversion. Shipping is done with the cassette entombed in frozen Pb as a precaution against loss at sea. A whole core cassette refueling operation using relocatable Regional Center equipment is illustrated in Fig. 4.

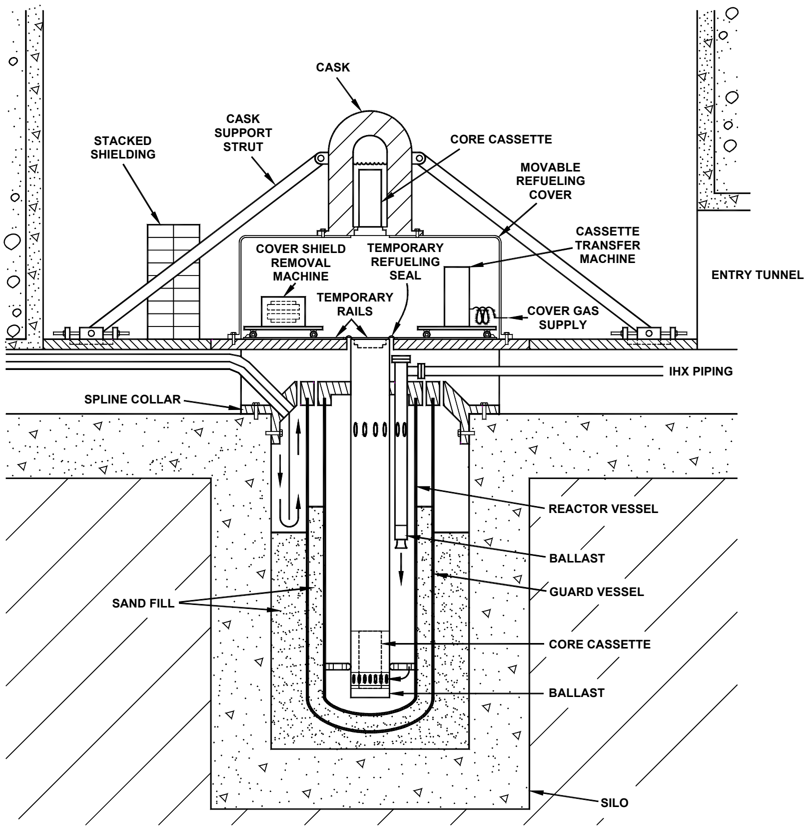

Figure 4. Whole Core Cassette Refueling Using Relocatable Equipment from the Regional Center

The fuel cycle feedstock is natural or depleted uranium, and multi recycle through sequential cassette reload cycles achieves total fission consumption of the feedstock; only fission product waste forms (and trace losses of transuranics) go to a geologic repository operated by the Regional Center. These waste forms decay to the equivalent radiotoxicity levels of the original ore within 200-300 years.

Working inventories for STAR-H2 deployments will initially come from LWR spent fuel reprocessing. This symbiotic fuel cycle allows for incremental market penetration by beneficially managing the “waste” from the current once-through cycle (such that only fission products go to a repository) while simultaneously beneficially providing fissile transuranic feedstock for initial working inventories of STAR-H2 deployments. (Once deployed, each STAR is fissile self sufficient.) Eventually, fast breeder reactors will be sited at the Regional Fuel Cycle Centers to manufacture excess fissile material to fuel new deployments in a growing economy after the source of fissile from LWR spent fuel becomes exhausted. The heat from their operation is converted to hydrogen for shipment to regional consumers.

9 BUSINESS PLAN INNOVATIONS AND MULTI DECADE MARKET PENETRATION

A growing market can be foreseen for secure energy supply at moderate buy-in cost and with outsourced fuel cycle and waste management support; the STAR concept is designed to meet this need. The nuclear industry will have to undergo significant structural changes in order to support an expanding STAR-H2 segment of nuclear energy supply; the business will likely become one analogous to the airplane and automobile sales businesses where risk is transferred from client to supplier; where customers receive a commodity product delivered turnkey and ready to use; and where suppliers make significant upfront investments in factories and fuel cycle facilities to attain economy of mass production and to spread their investment cost over a large volume of sales.

The proposed architecture is scalable. It need not be deployed all at once and is suitable for multi decade incremental market penetration of both power plants and regional fuel cycle centers. STAR-H2 can be preceded in deployment by sister concepts in the STAR family such as STAR-LM [11,12]. In most respects STAR-LM and STAR-H2 are similar and they rely on the same institutional arrangements for regional fuel cycle centers and the same business strategies. However STAR-LM is less aggressive in core outlet temperature – using traditional structural materials and producing electricity from a SC-CO_2 Brayton cycle operating at 565°C. It will be ready for market earlier than STAR-H2, but fits into the same Regional Fuel Cycle Center infrastructure.

10 INSTITUTIONAL INNOVATIONS

Global deployment of STAR-H2 reactors meeting Gen-IV goals for sustainability, safety, energy security and nonproliferation rests on the use of Regional Fuel Cycle Centers owned by consortia of clients and operating under international nonproliferation oversight. National membership in the regional center consortium and receipt of services for a nation's clients would be contingent on the nation's legal commitment to regulate its nuclear deployments in conformance with international norms on safety, radiological control, mutual assistance and early notification of emergencies, nonproliferation treaty provisions, etc., etc. A supplement to the NPT could be considered in which a nation agrees to forego an indigenous fuel cycle infrastructure in exchange for legally binding access to services from the Regional Center. Additionally, licensing reciprocity agreements among supplier and client regulatory authorities will have to be emplaced. *The emplacement of such a supranational legal regime will build on the substantial ensemble of legal norms already emplaced by the IAEA, EU, and NEA. However, full ratification and execution of all necessary provisions will require substantial further efforts in the international community.*

11 SUMMARY

The outcome of the research on the STAR-H2 concept is a proposed nuclear-based energy supply architecture which employs nuclear fuel, hydrogen and electricity as the energy carriers. Fuel is delivered in 20 year whole core refueling cassettes to STAR-H2 plants placed near cities in both developed and developing countries. The STAR-H2 plant is a small, (400 MW_{th}), long refueling interval fast neutron spectrum reactor which provides fission heat to manufacture hydrogen and potable water sufficient to meet the entire energy and water needs of a city of 25,000 in a developing country. STAR-H2 operates fissile self sufficient; employs passive safety response; couples to a non-nuclear-safety-grade balance of plant and follows BOP heat requests using passive means. The STAR-H2 fuel cycle is based on full transuranic multi-recycle performed at Regional Fuel Cycle Centers – achieving a proliferation-resistant nuclear-based energy supply which is sustainable for many centuries and is suitable for deployment worldwide. The Regional Fuel Cycle Centers also will eventually site breeder reactors whose function is to convert fertile U238 to fissile transuranics to fuel initial working inventories for a growing deployment of STAR's. The fission heat from the breeders is converted to hydrogen for shipment to regional customers.

Over time the proposed nuclear-driven energy supply architecture would displace fossil and provide energy to support a global energy infrastructure meeting all aspects of sustainable development – secure longevity, ecological compatibility and social acceptability [2]. With concomitant institutional innovation it might succeed to fuel an increase in GDP/capita for the 80% of humanity which was not reached by the Industrial Revolution.

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