A Non-Proliferating Fuel Cycle: No Enrichment, Reprocessing or Accessible Spent Fuel-12375

Frank L. Parker, Ph. D.
Vanderbilt University

ABSTRACT

Current fuel cycles offer a number of opportunities for access to plutonium, opportunities to create highly enriched uranium and access highly radioactive wastes to create nuclear weapons and 'dirty' bombs. The non-proliferating fuel cycle however eliminates or reduces such opportunities and access by eliminating the mining, milling and enrichment of uranium. The non-proliferating fuel cycle also reduces the production of plutonium per unit of energy created, eliminates reprocessing and the separation of plutonium from the spent fuel and the creation of a stream of high-level waste. It further simplifies the search for land based deep geologic repositories and interim storage sites for spent fuel in the USA by disposing of the spent fuel in deep sub-seabed sediments after storing the spent fuel at U.S. Navy Nuclear Shipyards that have the space and all of the necessary equipment and security already in place. The non-proliferating fuel cycle also reduces transportation risks by utilizing barges for the collection of spent fuel and transport to the Navy shipyards and specially designed ships to take the spent fuel to designated disposal sites at sea and to dispose of them there in deep sub-seabed sediments. Disposal in the sub-seabed sediments practically eliminates human intrusion. Potential disposal sites include Great Meteor East and Southern Nares Abyssal Plain. Such sites then could easily become international disposal sites since they occur in the open ocean. It also reduces the level of human exposure in case of failure because of the large physical and chemical dilution and the elimination of a major pathway to man-seawater is not potable. Of course, the recovery of uranium from sea water and the disposal of spent fuel in sub-seabed sediments must be proven on an industrial scale. All other technologies are already operating on an industrial scale. If externalities, such as reduced terrorist threats, environmental damage (including embedded emissions), long term care, reduced access to 'dirty' bomb materials, the social and political costs of siting new facilities and the psychological impact of no solution to the nuclear waste problem, were taken into account, the costs would be far lower than those of the present fuel cycle.

INTRODUCTION

The world's population is increasing rapidly having just reached 7 billion and projected to reach 10 billion by the year 2083 (1). Further, as the economies of China, India and Brazil, in particular, grow, their demand for more goods, alternative higher energy input foods and, due to globalization, increased transportation costs will require more energy including electricity. (2) Though in the long run the world will have to depend upon renewable energy, for the present energy from carbon fuels and nuclear fuels are the only alternatives that have the capability to meet these demands. Nuclear energy use can be limited by the fear of proliferation of nuclear weapons, accidents in nuclear facilities, fear of 'dirty' bombs and fear of a lack of a solution to the disposal of radioactive wastes. The environmental consequences of each of these limitations need to be taken into account. Only fear of potential proliferation of nuclear weapons by rogue states and terrorists and fear of a lack of a solution to the disposal of nuclear wastes will be addressed here. Accidents in nuclear facilities should be addressed by nuclear and safety engineers and development of ‘dirty’ bombs should be addressed by the National Security Agency and other intelligence and security associated organizations. Figure 1 shows the potential of proliferation sources exist and where radioactive waste is generated.

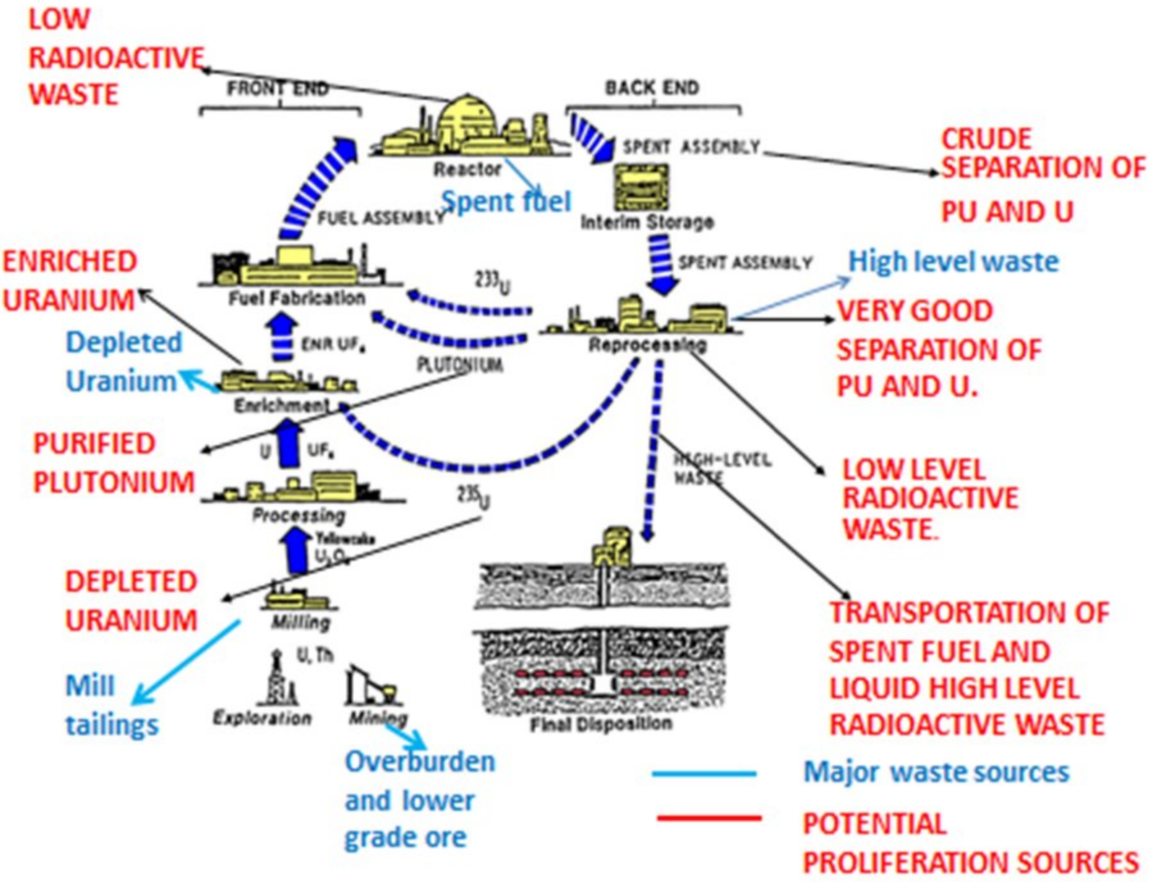

Figure 1 Nuclear Fuel Cycle with Waste Generation and Potential Proliferation Sites

Prevention of proliferation of nuclear weapons would be improved if the availability of enriched uranium and fissile plutonium were reduced. Further, if spent nuclear fuel were not easily available and were more securely guarded, then potential sources of radioactive materials for ‘dirty’ bombs would be reduced.

Problems with the disposal of radioactive wastes would be reduced if the amount of wastes was limited, the potential of their causing harm when released was minimized and the likelihood of the wastes being retrieved was negligible.

RESULTS

Front end of the fuel cycle

The generation of radioactive waste will be followed through the fuel cycle and then techniques to reduce their generation and impact will be presented. At present uranium for nuclear power plants is obtained from underground and surface mining, in situ leaching of uranium ores and from surplus enriched uranium from surplus nuclear weapons or research reactors. Smaller amounts of plutonium from surplus stocks can also be utilized for MOX (mixed plutonium and uranium oxides) fuels. It is estimated that 20,000 tonnes of 1% uranium ore are required to fuel a 1,000 MWe reactor for 1 year and after milling and processing would yield 239 tonnes of uranium oxide concentrate.(3) In the USA, there are 8 licensed uranium recovery facilities, 7 in-situ leaching and 1 conventional mining- not all are operational.(4) In addition, there are 25 sites undergoing or having undergone decommissioning, 11 under license to the U.S. NRC and 14 under state licenses.(5) The estimated cost of remediation of these sites is approximately 500 Million Dollars (6) Actual costs for decommissioning projects have greatly exceeded these amounts. For example, the decommissioning costs for WISMUT, the Soviet Union's large uranium mining site in the Deutsche Demokratische Republik, was estimated in 2008 at 6 billion Euros and an additional 12 percent (worst case) for monitoring and care for 30 years after closure. At the approximate dollar conversion rates at that time, 1.5 to 1, the cost for remediation of this complex, only one of many in the former Soviet Union, would be 10.8 billion dollars. (7) This cost ignores the likelihood of cost overruns in most nuclear activities.

In addition, these wastes are very long lived and 3.7 E10 Becquerel (1 curie) of pure U-238 will increase in radioactivity 12 fold beyond a few hundred thousand years. (8) The overburden and the lower grade ores will have to be handled as well. Further, the lixiviants, dissolving fluids used in in-situ solution mining, will need to be better contained than they are now. In some situations the lixiviants, typically an oxidant such as oxygen and/or hydrogen peroxide mixed with sodium carbonate or carbon dioxide, injected through wells into the ore body in a confined aquifer to dissolve the uranium could pollute ground waters.

In addition, the ores are also chemical and biologic hazards, in some cases greater than the radiologic hazards. Finally, uranium ores are a diminishing resources and this is one of the reasons for an interest in breeder technologies. However, breeder technologies increase the production of plutonium which increases the opportunity for diversion to nuclear weapons.

Is there a way to overcome these problems? Yes, the Japanese have developed a method of extracting uranium from seawater and have field tested it. (9) They have been working on such techniques since the early 1980s. The President's Council of Advisors on Science and Technology has recommended that the USA investigate such processes in a 1999 report (10) Though the uranium concentration in sea water is low (3 ppb) there are 4.5 billion tonnes of uranium in seawater (about 700 times more than known terrestrial resources recoverable at a price of up to \$130 per kg). If only half of this uranium could be recovered, it could provide nuclear fuel for 6,500 years for 3,000 GW of nuclear power on a once-through fuel cycle. The estimated price for the uranium, as U3O8, recovered from the sea in 2009 was \$96/lb. (9) It is expected that the cost could be reduced substantially with further development.

If the non-proliferating cycle were adopted, as shown in Figure 2, there would be no need for exploration, increasingly in more distant and demanding environments, because the uranium in the sea is almost uniformly distributed.

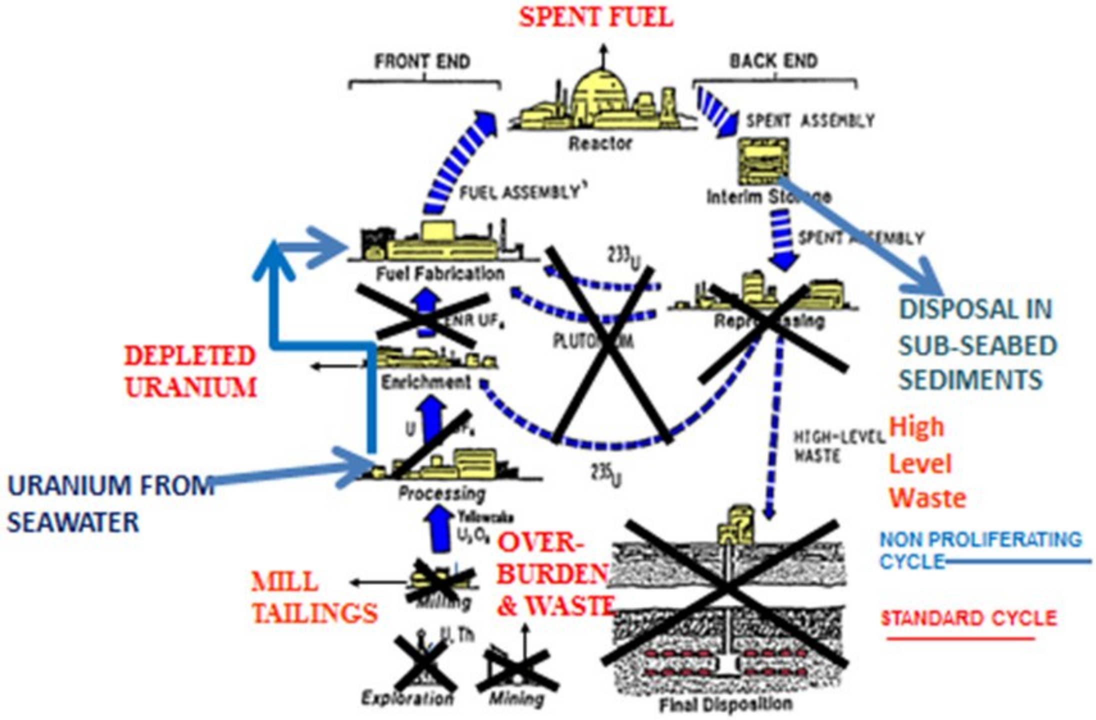

Figure 2 Simplified Fuel Cycle with Reduced Opportunities for Proliferation of Nuclear Weapons and Permanent Disposal of Radioactive Wastes

There would be no more boreholes that need to be backfilled perfectly so that leaks through them could not contaminate ground waters. There would be no need for mining, 2nd highest fatal injury rate in the USA, transport, 4th highest, (Agriculture, Forestry, Fishing and Hunting highest and Transportation and Warehousing 3rd highest). (11) There would be no mountains of overburden to remediate. There would be no destruction of the environment to get at the ores. There would be no production of mill tailings and the need to care for them, even in remote locations, for many thousands or millions of years. (7) Attempting to provide care for such long periods is Don Quixotic.

No one can accurately predict what the human condition will be in the near future, never mind the distant future. No one can predict accurately what and when exogenous events will occur. It can be seen from Figure 2 that the processing to separate the uranium ores from the host rock would not be necessary. (Ore concentrations of recovered uranium range from 20 to less than 1 percent.) No processing slimes would be generated.

However, in the Japanese system the free-floating amidoxime uranium absorbing fabric would be placed in the sea and then retrieved and the uranium eluted by 0.5 M hydrochloric acid. Since the absorbing time is not crucial, the fabric can be placed and retrieved in calm seas. Since uranium is contained in such low concentrations, there is essentially no change in the chemical composition of the seawater after removal of the uranium.

It can further be seen from Figure 2 that no enrichment would be required if the Canadian CANDU type reactors that use naturally occurring uranium were used. Therefore, no stocks of depleted uranium would be produced. There are approximately 10 times the mass of depleted uranium as there is of spent fuel in the USA. (12) The depleted uranium will remain hazardous for the same length of time as the mill tailings. (8) With the elimination of enrichment facilities, the means to achieve quantities of nuclear weapon level concentrations of uranium 235, even by signatories to UN convention to eliminate nuclear weapons will have been removed.

The uranium from the sea and that obtained by mining will require the same methods of fuel fabrication. The fuel will then be inserted into reactors. The enriched uranium will be used in the light water reactors while the fuel using natural occurring uranium will be used in heavy, Canadian type, water reactors. The spent fuel from CANDU reactors has U235 at a concentration of approximately 0.2 percent and plutonium about half of that in spent fuel from light water reactors. (13) CANDU reactors have been operating in Canada since 1962 and 48 heavy water moderated reactors based on the CANDU design are in operation, under construction, or under refurbishment worldwide.(14) There are 12 CANDU reactors in India and Pakistan, Argentina, China, Romania, and South Korea. (15) The technology and design of the Enhanced CANDU reactors have evolved with the experience in building recent Korean and Chinese units,– built as twin units – with a capacity increase to 750 MWe and flexible fuel options, plus 4.5-year construction and 60-year plant life (with mid-life pressure tube replacement). It is assumed that these changes will overcome the previous problems of pressure tube corrosion. AECL built the two-unit Qinshan Phase III plant on schedule and under budget and estimates that it could be replicated for 25% lower cost. The Enhanced Candu-6 is undergoing Canadian Nuclear Safety Commission review with the first phase, initial design approval, granted in March 2010. (16) The concentration of U-235 in spent fuel from CANDU reactors is 0.2 percent. To obtain enough plutonium for a nuclear explosive device, over 100 irradiated CANDU fuel bundles with a total mass of over two tons would be required. It is not technically impossible, given sufficient ingenuity, expertise, expense, personal health risk, and luck, to make an explosive device from the plutonium present in spent CANDU reactor fuel (or any spent power-reactor fuel). However, it is technically difficult.

In mid-2011 AECL sold its reactor division to SNC-Lavalin's CANDU Energy subsidiary with the Canadian government retaining intellectual property rights for the CANDU reactors.

It can be seen in the front end of the nuclear fuel cycle that the operations that allow possible diversion of highly enriched uranium for weapons or plutonium, enrichment and spent fuel from light water reactors have been eliminated. In addition, no overburden and lower grade ore waste piles are generated no depleted uranium streams are generated and no mill tailings generated and thus the operations in the front end of the fuel cycle have lower impact on the environment. The only wastes generated are low level, short-lived wastes from operations. There already exist disposal sites for such wastes. There is minimal transportation requirements-just point to point transport of product.

Backend of the fuel cycle

The back end of the fuel cycle includes the spent fuel discharged and its disposal. Reprocessing of CANDU spent fuel is not useful as the U-235 and plutonium in the spent fuel is of such low concentration that it is not worth recovering. The reprocessing facility is eliminated. Without reprocessing there is no store of plutonium to be diverted for proliferation of nuclear weapons. The spent fuel would stay for some time in the spent fuel pool in the Service building at the reactor. The spent fuel would then be transported to a preparatory building for disposal. The main decision then is where to store the spent fuel and how to dispose of it.

Perhaps the most comprehensive study of the storage of spent fuel was the Report of the Monitored Retrievable Storage Review Commission (17) The Commission found "that while no single factor would favor an MRS (Monitored Retrieval Storage facility) over the No-MRS option, cumulatively the advantages of an MRS would justify the building of an MRS if …the restrictions imposed on its construction were removed."

The MRS Commission "decided that some limited interim storage facilities would be in the national interest to provide for emergencies and other contingencies." The Commission recommended "a Federal Emergency Storage facility with a capacity limit of 2,000 metric tons of uranium (and) a User–Funded Interim Storage facility with a capacity limit of 5,000 metric tons of uranium." Especially needed was centralized storage for spent fuel from inactive reactor sites.

The Draft Report of the Transportation and Storage Subcommittee of Blue Ribbon Commission on America's Nuclear Future (BRC) quotes much of the findings of the MRS Review Commission report. (18) In order to locate the interim storage facilities for spent fuel and high level waste, the probable location of the disposal sites must be estimated.

Attempts to locate deep geological repositories in salt, granite, welded tuff, basalt and clay have failed for a number of reasons. Since the landmark National Academy of Sciences report, the Disposal of Radioactive Waste on Land in 1957, there has been near unanimous agreement that disposal in deep geological formations is the best solution for spent fuel and high level radioactive waste. (19) Since that time there have been many attempts to site and operate repositories in deep geological formations.
To date, 55 years after the recommendation, no deep geological sites for disposal of spent fuel or high level wastes are in operation. A short review of the history of attempts to build a repository in the USA will lead to some general recommendations on how to proceed.

Nuclear Waste Policy Act, Section 112, laid out the site screening process intended to help choose the repository sites. The legislation noted that no formal analysis can account for all the factors important to a "decision as complex as recommending sites for characterization" the process would not form "the sole basis for the decision." (20)

The health and safety impacts of the repository and transportation and the environmental, socioeconomic and economic impacts were abstracted from the Environmental Assessments of each of the sites to determine composite utilities and fraction of EPA radionuclide limits for the first 10,000 years after repository closure. If one assumes identical waste-transportation and repository costs for all sites, then the composite utility for all sites with 100 percent weighting on the preclosure factors ranged from 97.5 to 100 and for 100 percent weighting on the postclosure factors, the composite utility ranged from 98.5 to 99.3. (21) In other words, considering the accuracy of calculations and the uncertainty in the input data, the composite utility for all sites was the same as shown in Table I.

Table I. Computed Base-Case Expected Releases and Postclosure Utilities

SITE	EXPECTED POSTCLOSURE UTILITIES	EQUIVALENT RELEASES PER 10,000 YEARS a.
SALT		
Cypress Creek Dome, Louisiana		
Richton Dome, Mississippi	99.99	1.10x10E-4
Vacherie Dome, Louisiana		
Deaf Smith County Bedded, Texas	99.98	2.23x10E-4
Swisher County Bedded, Texas		
Davis County, Bedded, Utah	99.99	1.09x10E-4
Laveder County, Bedded		
WELDED TUFF		
Yucca Mountain, Nevada	99.98	2.23x10E-4
Basalt		
Hanford Washington, State	99.76	2.41x10E-4

a. Fraction of EPA limits for the first 10,000 years after closure

These results were predictable because the sites were selected based on their meeting EPA's site criteria. In other words, it was a circular exercise-the sites were selected based on the likelihood of their meeting the EPA site criteria and when the calculations were made, not surprisingly they did. It was a waste of time, energy and money to do EAs of nine sites. It would have been possible to eliminate four sites from consideration by a simple comparative analysis. The requirement to study a diversity of geological formations should be eliminated. Looking for the 'best' sites could include a diversity of geological formations.

These results argue for a much simpler screening method for preliminary site selection similar to that used to select sites for the National Priority List 40 CFR 300 - -- Uncontrolled Hazardous Waste Site Ranking System (HRS) (22). The HRS serves as a screening device to evaluate the potential for releases of uncontrolled hazardous substances to cause human health or environmental damage. The HRS provides a measure of relative rather than absolute risk. It is designed so that it can be consistently applied to a wide variety of sites. The preliminary choices for the back end of the fuel cycle could be made with a much lower effort and far lesser cost and with equal validity. Of course, the new screening tool should be tested against the results of the EAs and for ease of calculation.

Despite all of these difficulties in the USA and many other countries SKB Sweden has submitted, March 2011, applications for a permit to build a final repository at Forsmark for spent nuclear fuel, and an encapsulation plant.(23) If successful the facilities are scheduled to open in 2025. Finland, the only other country so far advanced, is scheduled to submit applications in 2012 for construction permits to build a repository in Olkiluoto at Eurajoki to submit applications for the operating license in 2018 to open in 2020. (24)

There is general agreement what procedures and attributes are necessary for a disposal site that will likely be acceptable to the host region population. It requires a management system that works cooperatively with its many publics, is responsive to changing conditions in geology of the site, technology and legal requirements and is open, trustworthy and involved with its community.(25) Because of the number of attributes, it is impossible to determine the 'best' solution even if we could agree on what 'best' means. As shown in the results from the EAs in Table 1 and known from many studies, the results of the calculations, the response surface is likely to be relatively flat so that achieving the 'best' is not necessary. In these studies it is necessary to distinguish between present deaths and those that could occur far in the future and to distinguish between observed deaths and those calculated based upon probable, even possible, events. It is also necessary to distinguish between deaths based on present demographics, lifestyles and medical knowledge, as required in USA regulations and those that could occur far in the future taking into account the then existing demographics, lifestyles and medical knowledge. Attempts have and are still being made to establish multi-national and or international repositories.

One approach that has been widely studied is the disposal of spent fuel and high level waste in sub-seabed sediments. There is no excavation involved, there is no closure involved, it is international and it is almost impossible for rogue nations or terrorists to retrieve the radioactive material. Further, if radioactive and/or hazardous material should leak from the canisters containing the wastes, much of the material would captured by absorptive sediments and they would be highly diluted physically and chemically in the open ocean. Finally, seawater is not potable so one of the hazardous paths to human exposure from radioactive material would be eliminated.

Major studies of the potential of deep sea disposal of radioactive material in sub-seabed sediments have been carried out by the Nuclear Energy Agency, the European Union, and the U.S. Department of Energy in the 1970s and 1980s.

All of the radioactive material that would have been put into Yucca Mountain is more than an order of magnitude less than what is naturally in the ocean and if disposal is delayed for 300 years the radioactivity would be 3 orders of magnitude less, as shown in Table II. It should be noted that Becquerels (curies), amount of radioactivity, do not equal sieverts (rems) the radiological impact. The mobility and bioavailability of the radionuclides must be considered in determining the human and environmental impact.

Table II. Amount of Radioactive Material in the Oceans

RADIOACTIVITY IN THE OCEAN	BECQUERELS
Natural	1.50E+22
Directly Dumped	8.50E+16
Fallout	1.5 E+18
Reprocessing Plant Effluent	1.00E+17
Yucca Mountain when full 70,000 MTHM	8.00E+20
Yucca Mountain after 300 years	1.8 E+19

The Nuclear Energy Agency studies concluded that "the disposal of high level waste in sub-seabed sediments could be radiologically a very safe option." (26) The input data were 3,000 GW (e) years (100,000 MTHM burnup) The main dose is equally from mollusk consumption and external exposure from beach sediments. The Commission for the European Community found that "Individual doses are at all times less than 10E-6 mSv/y". (27) The DOE studies concluded "All analyses to date indicate that subsea bed disposal would be a safe and economical method of HLW disposal and that predictions could be made with a high degree of confidence" though they acknowledged that the technical feasibility study is not complete, and there are still some uncertainties in the SDP (Sub-seabed Disposal Project) performance assessment. (28) The reference sub-seabed disposal project has spent fuel and/or high level waste coming from a reprocessing plant, utility or MRS by truck, barge or train to a port facility where the waste is loaded on the specially designed ships that transport the wastes to designated disposal areas where waste is released in free fall penetrometers or into the drill stem for guided emplacement into the sub-seabed sediments, as shown in Figure 3.

In the Atlantic Ocean, suitable disposal locations were located in Great Meteor East and Southern Nares Abyssal Plain. Though not as investigated to same degree, a site in the Pacific Ocean appeared suitable for a disposal site. These sites could easily become international disposal sites since they occur in the open ocean.

Only the proposed Atlantic sites are discussed. The proposed sites need port and interim storage facilities.

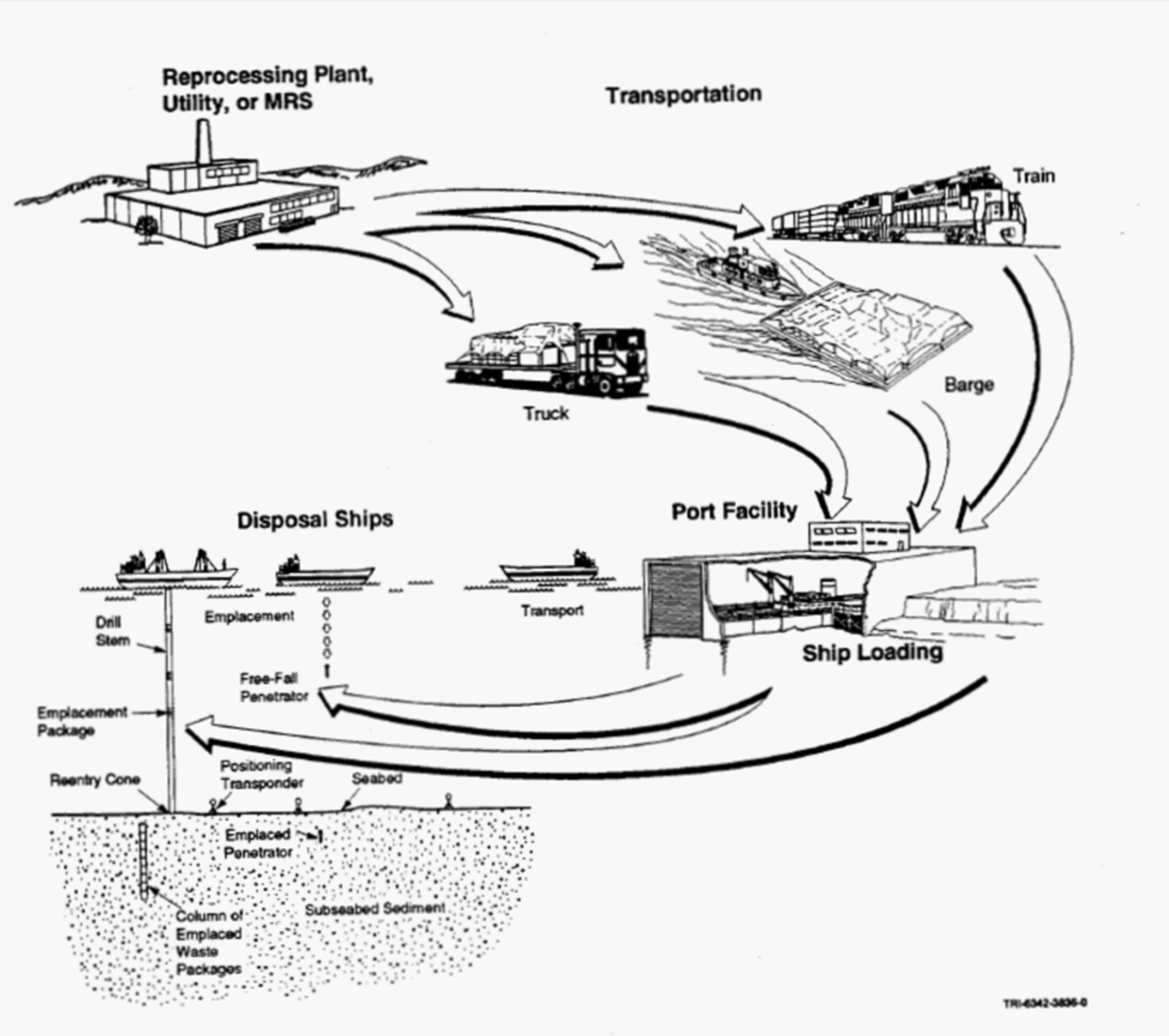

Figure 4. Reference Sub-seabed HLW Disposal System

It is easier to site new nuclear facilities where other nuclear facilities already exist. There are two nuclear navy shipyards on the East Coast of the USA, Portsmouth and Norfolk, and one on the West Coast. Nuclear maintenance and repair facilities are already in place. High capacity cranes are already in place. Enhanced security is already in place. For example, the Norfolk Naval Shipyard can accommodate any ship in the fleet. State-of-the-art technology provides capability to service nuclear as well as conventional ships of all sizes and types, from tugboats to submarines to aircraft carriers.

Their services include reactor safety and the technical aspects of all shipyard nuclear propulsion plant work involving overhaul, maintenance, conversion, refueling, testing, quality control and radiological engineering of the reactor plant. Further, security at the facility is required and with 800 acres of land, 4 miles of waterfront, 400 cranes, 19 miles of railroad tracks, its own police & fire departments and electric & steam generating plant, space for installations is available as are all essential services. Figure 4 shows the relative location of all the facilities required for the non-proliferation fuel cycle.

Figure 4. Location Of Representative Nuclear Power Plants, DOE, US Nuclear Navy and Potential Sub-Seabed Sediments Disposal Sites

Transportation

Obviously the material must be transferred from one site to another. However, there are problems without a synoptic view. For example the Transportation, Aging, and Disposal (TAD) canisters, maximum weight of 54 tons that are to be used for nuclear fuel are not truckable (29). Currently, 25 commercial reactor sites do not have rail capabilities (30) and almost one-third of the total 63,000 MTU of commercial spent that will be shipped to the proposed repository over the first 24 years would originate from sites without direct rail access. (31) DOE's transportation plans are for a multimodal system-primarily rail and truck. However, "OCRWM never prepared a description, for transportation planning purposes, of what mode each site would use for shipping and how many shipments would take place". (Janairo) DOE has given short shrift to ship/barge shipments as does the National Academies "The committee strongly endorses DOE's decision to ship spent fuel and high level waste to the federal repository by mostly rail using dedicated trains." (32) and further, does not even mention barge transport This is strange as every reactor site had barge access during construction for pressure vessel delivery.

There are major advantages to barge shipping. It is a well-established practice and all nuclear power sites at one time had barge facilities to bring in the pressure vessels and other large, heavy equipment. Barge/ship transportation will reduce the number of transfers in shipping compared with a multi-modal system. Much greater loads can be carried so that fewer shipments will be required. Therefore, there will be fewer opportunities for terrorist attacks. The heavy lifting equipment needed should be available at the sites. Many of these shipping facilities are not operational now but could be rehabilitated most likely at lower cost than a couple of hundreds of miles of new railroad track through difficult terrain as would have been required for the Yucca Mountain site. Finally, commercial shippers of hazardous materials use barges because of its greater safety. (33)

Shipping spent fuel by barge/ship is standard practice for Svensk Karnbranslehantering AB (SKB), Swedish Nuclear Fuel and Waste Management Company. SKB currently uses its M/S Sigyn vessel to transport spent fuel and waste. The 90-metre long ship is capable of carrying ten containers, was launched in 1982. They have contracted to buy a new, 99.5-metre ship that expected to be launched in 2013 that will be capable of carrying 12 containers. SKB president Claes Thegerstrom noted, "Since the early 1980s, the *M/S Sigyn* has operated in a safe and efficient manner." (34)

The Russians have purchased a new ship, Rossita, to transport submarine waste in north-west Russia. The ship, launched December 16, 2010, measures 84 metres by 14 metres and can carry up to 720 tonnes up to 3000 kilometres. (35)

The UK's Pacific Nuclear Transport Limited has completed over 170 shipments of used nuclear fuel, vitrified high-level waste, mixed oxide (MOX) fuel and plutonium since it was established in 1975. (36)

DISCUSSION

The devastation caused by an atomic bomb overwhelms all other considerations. Non-proliferation efforts should dominate all other efforts but other priorities cannot be ignored. The non-proliferation cycle outlined in this paper depends upon proven technologies and others that have undergone field testing. Of course, these are assertions and modeling and pilot testing need to be carried out to verify these claims and determine the costs. In addition, the environmental impact, including embedded emissions-emissions associated with making, installing, maintaining and decommissioning the facilities and equipment- must also be calculated.

These results must be compared with similar studies on the present fuel cycle-not on ideal fuel cycles. Externalities must also be considered. With present knowledge, the non-proliferation cycle is clearly superior. Clearly, the opportunities for diversion of plutonium and highly enriched uranium are eliminated.

If the spent fuel is considered waste, then it could be used for 'dirty' bombs but this would be difficult to do. Such attempts would be much more difficult than stealing radiation sources that are widely available. Without mining, milling, enrichment, reprocessing and opening deep geological repositories, the environmental impact of the non-proliferation fuel cycle is obviously less than the present fuel cycle. The costs of the non-proliferation fuel cycle that does not require mining, milling, enrichment, reprocessing and opening deep geological repositories and the remediation that they entail are certainly lower than the present fuel cycles.

If externalities, such as reduced terrorist threats, environmental damage (including embedded emissions), long term care, reduced access to ‘dirty’ bomb materials, the social and political costs of siting new facilities and the psychological impact of no solution to the nuclear waste problem, were taken into account, the costs would be far lower than those of the present fuel cycle.

Of course, all fuel cycles have value complexity, "presence of multiple, competing values and interests." (37) Under such conditions, most strategic problems cannot be resolved through objective analysis, management, a simple phone call, outsourcing, cost-benefit tables or mathematical "solutions. They tend to be resolved through subjectivity, human instinct, relationships, interdependence, leadership, personal intervention, and deliberative value judgments and tradeoffs. Further, “the world of science and technology is not one of safety, absolutes and hard facts, but rather one of risks, probabilities and uncertainty.” (38)

There will also be legal and cultural objections. The London (Dumping) Protocol of 1996 prohibited the disposal of radioactive materials into the sea. Lawyers have argued that sub-seabed sediments are not in the sea but below it. Further, the Protocol was modified in 2006 to allow sequestration of CO2 in sub-seabed geological formations (despite the potential of oceanic acidification). Why not for spent fuel and high-level waste in sub-seabed sediments?

Some of the island nations strongly objected to any disposal of hazardous materials at sea. However, they shall be among the first to suffer flooding from global warming and nuclear energy emits no greenhouse gases and therefore would reduce the threat from global warming.

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