GNEP Deployment Studies

Overall Summary Report

Revision 1

May 19, 2008

Prepared by

EnergySolutions

5/19/08

Submitted by Alan Dobson, Project General Manager — Date

Energy*Solutions*, LLC
2345 Stevens Dr.
Richland, WA 99354

Acknowledgement: This material is based upon work supported by the Department of Energy under Award Number DE-FC-01-07NE24503.

Table of Contents

List of Figures

List of Tables

Preface

The EnergySolutions Global Nuclear Energy Partnership (GNEP) team comprises EnergySolutions, Shaw Environmental and Westinghouse Electric Company, supported by Atomic Energy of Canada Limited (AECL), Booze Allen Hamilton, Nexia Solutions, Nuclear Fuel Services (NFS), and Toshiba. Every member of the team is focused on nuclear as its core business. We have a long term commitment to nuclear world wide and a real stake in how the industry develops. Together we have one of the largest nuclear client bases in the world and a collective commercial culture that enables us to translate invested dollars into viable commercial applications in the shortest possible time.

We have utilized this experience to identify the steps that must be taken to enable the recycling of spent nuclear fuel to be undertaken on a commercial basis near term and identify a credible technology development roadmap that will lead to the implementation of the full GNEP fuel cycle and vision.

EnergySolutions – EnergySolutions, an American owned and operated company that is committed to full engagement across the US nuclear fuel cycle. An acknowledged leader in waste management, EnergySolutions also owns exclusive rights in North America to advanced recycling and all associated waste treatment technology that can be deployed immediately in commercial facilities to meet the goals of GNEP. EnergySolutions also has extensive experience in the design, construction and operation of fuel fabrication, spent fuel recycling and waste treatment facilities both here in the US and overseas. EnergySolutions is leading this GNEP Deployment Studies Industrial Consortium. EnergySolutions is utilizing its extremely flexible but robust 'NUEX' separation technology as the basis for its Light Water Reactor (LWR) separations facility. Together with EnergySolutions' unique approach to integrated waste management, this will enable the fuel cycle to be closed in the US at the earliest opportunity on a commercial and proven basis.

The Shaw Group (Shaw) is one of the world's leading providers of engineering, design and construction services to the nuclear power, environmental, energy and chemicals industries. Shaw is an owner and the managing partner of the MOX Services LLC, responsible for design, construction and operation of the mixed oxide (MOX) Fuel Fabrication Facility (FFF) at DOE's Savannah River Site. For the initial phase of the GNEP Development Studies, Shaw performed design studies to conceptualize the Nuclear Fuel Recycling Center (NFRC) MOX Fuel Fabrication Facility. Shaw Stone & Webster Management Consultants (SWMC), as technical advisor to buyers, sellers, owners, lenders and insurance companies for over 600 plants and projects, has prepared & reviewed project financial models. These evaluations include risk assessments and sensitivity studies to evaluate key commercial variables that could impact financial projections. For the initial phase of the GNEP Development Studies, Shaw developed and modeled the GNEP business structures and identified the business arrangements and agreements required to facilitate risk sharing.

Westinghouse Electric Company (**WEC**) is one of the leading suppliers of fuel, services, technology and equipment to the worldwide commercial nuclear industry. WEC technology is the basis of nearly 50% of the worlds operating nuclear power plant and its advanced PWR design (AP600/AP1000), is being chosen by utilities throughout the world in the nuclear renaissance. WEC is the largest manufacturer of nuclear fuel in the world and it has deep experience in fast reactor design through its work on Clinch River Breeder Reactor (CRBR) and Fast Flux Test Reactor (FFTF). This capability is now supplemented by Toshiba's 4S reactor capabilities. In addition WEC has its own MOX fuel technology. WEC is leading the development and commercialization of an innovative, simplified fast reactor concept for deployment as the GNEP Advanced Recycling Reactor (ARR), all aspects of the fast reactor fuel design, and are responsible for the fuels and reactors component of the TDRM including the advanced fuels recycling facilities.

Booze Allen Hamilton (**BAH)** is a global strategy and technology consulting firm who work extensively in the private sector yet is a trusted partner of the US Government and Governments around the world. BAH has extensive experience using complex modeling and dynamic systems to develop detailed economic analysis and risk management solutions for DOE, NNSA, nuclear utilities, and nuclear fuel manufacturers. It has completed numerous reviews and analyses of market trends, risk, internal business operations and capital requirements for both private sector and government clients. BAH is playing a key role in developing the business plan for GNEP, including the steps necessary for the successful creation of FedCorp.

Nexia Solutions Ltd (Nexia) is a nuclear technology service provider which will form the foundation of the new National Nuclear Laboratory for the UK. It is part of British Nuclear Fuels plc and so has over 40 years experience in nuclear technology across the whole fuel cycle. Nexia Solutions has an in depth knowledge of reprocessing plant operation through all the stages of LWR recycling i.e. head end, primary separation, product finishing and waste treatment and storage. Nexia participation in international research programs and work for international customers means it is at the forefront of worldwide developments in recycling technology. Nexia has played a leading role in producing the GNEP Technology Development Roadmap, across the complete spectrum of aqueous and non aqueous separations, fuel fabrication and wastes. It has helped to underpin the business plan through use of its ORION fuel cycle modeling code to evaluate and quantify multiple reactor deployment scenarios that would be possible in the US when the GNEP vision is realized.

Nuclear Fuel Services (NFS) has over 50 years experience in design, qualification and manufacturing of specialty nuclear fuels, including Uranium metal, low enriched uranium (LEU) oxide, high enriched uranium (HEU) oxide, Uranium Carbide (UC), Uranium Oxycarbide (UCO), Uranium Nitride (UN), Uranium-Plutonium mixed oxide and Uranium-Thorium mixed oxide fuels. For the past 40 years NFS has manufactured fuel for the US Navy nuclear reactor propulsion systems. NFS is the leader in down blending HEU to LEU for commercial fuel. It operates a Category 1 secure area and is leading on security and safeguards aspects of the GNEP facilities for the EnergySolutions team. It is also leading the development of an innovative fuel option for burning mixed transuranic material. It is therefore also a major contributor to the GNEP Technology Development Roadmap (TDRM).

Toshiba is a household name in consumer electronics and is also a major player in nuclear reactor design and construction. It has invested heavily in research and development of advanced reactors including Advanced Boiling Water Reactors (ABWR), Fast Breeder Reactors (FBR) and fusion reactors. Together with WEC it has developed innovative reactor concepts and systems to enable the early commercial deployment of the GNEP ARR and its associated fuel fabrication and recycling facilities. The EnergySolutions team is evaluating an advanced processing concept developed by Toshiba that provides a bridge between aqueous processing of LWR fuel and electro-refining of spent ARR fuel.

Atomic Energy of Canada Limited – AECL is one of the world's leading nuclear technology companies, providing services to nuclear utilities on four continents. Established in 1952, AECL is the designer and builder of CANDU® reactor technology, including the CANDU 6, one of the world's top-performing reactors. The National Research Universal (NRU) reactor, located at AECL's Chalk River facility, is the world's primary source of radioisotopes produced for use in nuclear medicine. AECL is leading the assessment and evaluation of the CANDU reactor for burning transuranics arising from the LWR recycling program and recycling recovered uranium as primary fuel for the CANDU reactors.

1.0 Introduction

The EnergySolutions Team has prepared preliminary reports that describe:

- A credible business plan that details how the Nuclear Industry and the US Government can develop and commercialize advanced fuel cycle technologies;
- A detailed Technology Development Road Map (TDRM) which demonstrates solutions to those remaining technical issues need to support deployment of commercial GNEP facilities;
- Conceptual Design Studies (CDS) which provide scope, cost and schedule information for deployment of a commercial Nuclear Fuel Recycling Center (NFRC) and development of a commercial Advanced Recycling Reactor (ARR) together with an integrated, commercial fuel fabrication and spent fuel recycling facilities for the advanced recycling reactor;
- A Communications Plan that enables the dissemination of scientific, technical and other key information relating to nuclear energy and closing of the nuclear fuel cycle.

This report presents summary information from each of the above four preliminary reports and makes recommendations regarding the government-industry path forward that the EnergySolutions Team envisions as necessary in order to establish commercially viable nuclear fuel cycle businesses that will realize the goals of GNEP. The DOE may use this report to inform the Secretary of Energy's upcoming decision regarding whether or not the United States should close the fuel cycle and to share with the US Congress, key stakeholders and the public options for the successful implementation of GNEP.

1.1 Key Findings

1. Timely execution of an integrated nuclear waste management strategy is fundamental to supporting the global nuclear renaissance;
2. Efficient management of long term capital intensive projects (e.g. building recycling facilities and repositories) requires reliable funding planned around the project, not subject to annual appropriations, the ability to raise debt, and long term contracting authority;
3. A change is required in the way that nuclear waste is managed today. Legislative changes are required that allow the creation of a New Government Entity, The Federal Corporation (FedCorp), a non profit organization, with the authority to effectively manage nuclear fuel and nuclear wastes as a business enterprise. (TVA serves as a potential model);
4. The primary source of funds would be the waste fees and revenues generated by recycling recovered material in new fuel. The utilities would be financing the program, so not a big government project requiring massive appropriations;

5. The FedCorp would manage the Nuclear Waste Fund going forward, but would not use the existing fund. FedCorp would be responsible for waste repository construction and operation, contracting with industry (recycler) for the construction and operation of recycle facilities under a long term take or pay contract, transport of used nuclear material from reactors to the recycle facility, supporting defense and DOE legacy waste disposal, and supporting international programs through spent fuel take back;

6. Recycling Light Water Reactor (LWR) spent fuel can be accomplished today on a commercial basis using advanced aqueous processes in commercially proven equipment, without requiring government appropriations to fund either the construction or the operations of those facilities. The initial separations facility together with the associated waste treatment facilities are estimated to cost $12.6 billion and can be fully operational by no later than 2023 and possibly as early as 2020.A new MOX fuel fabrication facility to permit recycling of mixed uranium and plutonium as new fuel for LWR reactors will cost $4.0Bn and can also be operational by 2023;

7. These initial LWR recycling, MOX fuel fabrication and waste treatment facilities will substantially meet all of the goals of GNEP in an economic manner:

    a. Significantly reduce the amount and long term radiotoxity of High Level Waste (HLW) requiring disposal and therefore greatly improve repository utilization;

    b. Provide energy security by recycling valuable nuclear materials and reducing the dependency on foreign supplies;

    c. Meeting proliferation resistance requirements both intrinsically and extrinsically and being fully capable of satisfying IAEA safeguard requirements;

8. The HLW will be converted into glass and delayed stored for 70-100 years. This allows the high heat generating isotopes cesium/strontium to decay sufficiently to remove the initial heat problem for the repository; greatly simplifying disposal.

9. Most importantly no pure plutonium will be separated or produced. It will be co-extracted with either uranium or neptunium or both. There will be no accumulation of civil plutonium in the United States as a result of commercial recycling;

10. The US can demonstrate world leadership by using proliferation resistant technologies that enable the US, should it choose to do so, to participate in an international framework to provide reliable fuel services and used fuel take back. This removes the desire, but not the right for countries to develop sensitive technologies by providing them with an attractive alternative for fuel cycle services;

    By closing the fuel cycle and proceeding with LWR recycling, taking advantage of successful technology from around the world, the United States would be able to participate in the international framework as a full player, properly equipped to be a world leader in GNEP.

Without this capability, the USA will not be in a true leadership position.

11. Support exists in the US nuclear utility community today to establish the FedCorp and to implement LWR spent fuel recycling as soon as possible. Moreover a number of Utilities have acknowledged and accept that an increase in the nuclear waste fund fee is required to help generate the funding required. It should be noted that inflation since 1982, based upon US Bureau of Labor, data has been 114% which means that the nuclear waste fund fee should be adjusted to 2.1 mil/kwh just to keep up with inflation;

    Two cases are evaluated with regard to use of the existing nuclear waste fund. In the first case, which is this teams recommended approach, the existing fund is not used to fund the construction of the recycling facilities. In the second case the existing fund remains unused through 2016, but is then incrementally used over a 25 year period to supplement the ‘new’ fund managed by FedCorp.

12. The EnergySolutions team estimate that the fee will need to be increased to 1.95 mils/kwh starting in 2010 and can be held at this level throughout this century, providing for significant growth of nuclear power and construction and operation of commensurate expansion of recycling, fuel fabrication and associated waste treatment facilities. All things considered this is a modest increase and the estimates take no credit for reducing the liability of the US Government for not taking title to the used nuclear fuel. No credit is taken for repository avoidance costs, nor is any credit for carbon avoidance factored in to the equation, although the EnergySolutions team feels strongly that the nuclear power plant operators deserve such a carbon credit. All of these factors would reduce the necessary increase in the waste fund fee born by the rate payers;

    The EnergySolutions Team recognizes that there are both advantages and disadvantages with respect to not using the existing body of the nuclear waste fund. Obviously if the existing waste fund were to be used then the level of debt is incurred by FedCorp is much lower and the need to increase the waste for going forward is dramatically reduced. We estimate that a fee of 1.25 mil/kwh will suffice throughout this century.

13. If the FedCorp is created and LWR recycling undertaken promptly (by 2025) then the effective capacity of the geologic repository can be increased by at least 5 or 6 fold and it may even be that only one such repository is required ever;

14. FedCorp will generate revenues by recycling both recovered uranium and plutonium/uranium mixtures into new reactor fuel;

15. Significant legislative, policy and regulatory changes are required to permit recycling and waste disposal through existing disposal routes. For example, in order to achieve the

target hot start dates for recycling LWR spent fuel it will be necessary to expedite creation of a suitable regulatory framework requiring new rule making by the NRC. The view of the EnergySolutions team and other prominent industry members is that LWR recycling should be licensed under a revised part 70, with part 50 also suitably revised to accommodate this change. A combined construction and operating license would be sought. Another example is the legislative and regulatory changes that will be necessary to permit disposal of transuranic wastes arising from commercial recycling to be disposed of in the WIPP facility in New Mexico;

16. Sodium cooled fast reactor technology is not sufficiently developed for burning transuranic fuels to proceed with commercial deployment of the ARR today. A commercially sized prototype ARR , however, deploying several extremely innovative features that improve safety and reduce capital and operating costs, can be operational by 2025 and commercial licensing by 2031.

17. The EnergySolutions Team proposes that 'recycling reactor campuses' which deploy 4 ARR units, delivering approximately 1650 MWe total power output, are built and estimates that the first suite (a module of 4) of fully commercial ARRs can be brought on line in 2045;

18. ARR spent fuel recycling and new fuel fabrication can be accomplished using equipment and non aqueous processes very similar to those that have been proven on engineering scale, hot, demonstration facilities. The EnergySolutions team recognizes, however, that further development work is required before those processes could be fully deployed commercially;

    We have also incorporated advanced processes (Aqua-EW) in our long-term scheme that link LWR and ARR recycling. Through deployment of Aqua-EW, our proven aqueous processes are utilized to retrieve the transuranic material from recycled LWR and feed them into the ARR fuel facilities that utilize the electro-winning process.

19. The EnergySolutions team proposes that each ARR campus will have an integral fuel fabrication and recycling facility. The design , licensing and construction of the first, prototypical, ARR fuel recycling and fabrication facility is estimated to be 13 years and hot operations can commence in 2022;

20. The DOE would retain responsibility for research and development of the advanced recycling reactors and the advanced separations technologies required to process used fast reactor fuel. Industry would be heavily involved and lead certain phases;

21. The estimated cost for the development and construction of the first of a kind (FOAK) ARR is $4.4Bn. Fuel development costs are anticipated to be a further $670M; the estimated cost of the first fast reactor fuel recycling and fabrication facility is $1.2Bn. All costs are in 2007 dollars;

22. The cost of the first campus module of 4 commercial reactors is estimated to be $7.5Bn in 2007 dollars. Comparisons with the anticipated costs of Advanced Light Water Reactors (ALWR) shows that the ARR costs /kwh are still slightly higher and the EnergySolutions team proposes that the utilities be incentivized by discounting the fast reactor fuel at least through 2070. The ARR's will attract no waste fee. Additionally the FedCorp will make construction loans at competitive rates. These incentives recognize the ARRs crucial role in destruction of the transuranic waste and strategic role in increasing US energy security. No increase will be required in the waste fee of 1.95 (or 1.25) mil/kwh;

23. Execution of the integrated nuclear waste management strategy results in reuse of valuable nuclear resources, significant non proliferation benefits, effective management and disposal of 'real' nuclear waste.

24. This approach will require significant legislative change to amend the Nuclear Waste Policy Act (NWPA) and create the FedCorp. The US utilities would be major members of the FedCorp Boards of Trustees & Management and would provide the necessary commercial oversight to ensure efficient use of funds. Through the establishment of long term commercial contracts for spent nuclear fuel recycling and waste management, FedCorp would instill confidence in both the public and the nuclear industry. This would lead to:

    a. New reactors and fuel cycle facilities being built

    b. Enhanced energy security

    c. Would make significant reduction in greenhouse gas emissions achievable

    d. Safe and responsible management of nuclear waste.

2.0 Business Plan Overview

2.1 Introduction

The Business Plan demonstrates the feasibility of a new fuel cycle for the US. It is set against a backdrop of global energy needs, energy security for the US and climate change providing the major drivers for nuclear and fuel recycle. The feasibility of the Plan depends upon the ability of nuclear generally and fuel recycle in particular to clear certain significant hurdles and barriers. This ability in some important areas depends on changes to national energy policy/legislation as it relates to nuclear power, the fuel cycle and the related issues of waste disposition, and the provision of the requisite infrastructure.

The EnergySolutions Team's analysis shows that the there are four principal drivers which requires the US to take urgent action and proceed to close the nuclear fuel cycle and shift towards an era in which nuclear power is sustainable and its benefits fully realizable:

The realities of world energy needs and climate change, and their effect on US energy security;

Facilitating new nuclear build and moving spent fuel away from operating reactors sites;

Reducing the environmental burden and increasing the life and capacity of the repository;

Decreasing US dependency on foreign sources of supply and technology by establishing a new indigenous and revitalized US nuclear infrastructure.

In its simplest form the consequences of not taking urgent action are that the pace of new nuclear construction in the US will be slowed; the US will nevertheless be competing for shrinking supplies of uranium(and other sources of energy) in a global nuclear market that is expanding; and the US will miss the opportunity to take a technological leadership role in conservation and more efficient use of nuclear fuel supplies and raw materials that can lead to a significant reduction of carbon emissions at home and abroad.

2.2 Immediate action – create a new baseline for growth

Technology is available for commercial deployment today that means it is possible to take an incremental step on the pathway to full realization of the GNEP vision. The EnergySolutions team has set out a new baseline system for nuclear growth in the US. The key elements of the baseline are:

A. Timely execution of an integrated nuclear waste management strategy;

B. Creation of a New Government Entity, The Federal Corporation with authority to safely effectively manage used nuclear fuel and nuclear wastes as a business enterprise;

C. Implement LWR recycling as an interim step towards fully closing the fuel cycle;

D. Generation of revenues from the recycling of recovered uranium and MOX fuel.

FedCorp would be chartered to optimize the use of the Nuclear Waste Fund for the disposition of civilian spent nuclear fuel and to own and operate the recycling facilities. It would have the authority to let contracts for the construction and operation of facilities and make Waste Fund moneys available to finance the debt for capital expenditures and pay waste processing/recycling costs. FedCorp would also have the authority to collect disposal fees from nuclear utilities based on mils/kwh rates set by an independent board. It would also be able to issue Government-backed bonds to raise additional capital as needed to support debt financing and/or operations. It would coordinate all of the resources necessary to put the new program into place and to achieve safe disposition of spent nuclear fuel from US reactors. Because this organization will also be able to generate revenue from the sale of recycled spent fuel, it must also have a Federal Government component, since title for spent fuel in the US lies with DOE.

The Federal Corporation would be formed as part of a legislative package that includes provisions for eliminating restrictions on reprocessing and recycling of SNF in the US. As the financiers of the proposed Corporation, the Board of Directors for the company should consist predominantly of nuclear-industry representatives. An oversight Board would be established to independently monitor the actions of the company to assure that it meets its charter obligations. The financial affairs of the corporation would be subject to government audit at an appropriate frequency.

The business relationship and key interfaces of FedCorp together with the principle cash flows are depicted in Figure 2.1.

2.3 The initial phase through 2029

The emphasis in this initial phase will be deployment of commercially proven technology to close the fuel cycle in order to reduce overall costs. Key features of this interim phase are:

a. New reactor build proceeds at a rate to ensure that the nuclear contribution in the US does not fall below 20%

b. All commercial spent nuclear fuel generated after 2010 is recycled;

c. Construction of a 1500 MT/yr LWR spent fuel recycling facility(s) and associated waste treatment facilities, to commence hot operations no later than 2023;

d. Start to ship 2000 MT/yr LWR SNF from reactor sites to the recycling facility in 2020;

e. Construct and start to operate a 300 MTHM/yr MOX fuel fabrication facility(s) on the same timescale;

f. Vitrify the High level Liquid Waste immediately and delay store canisters of glass in an ever safe, naturally convected air cooled store for 80-100 years;

g. Alternate disposal sites for vitrified waste are evaluated;

h. Development of Advanced Recycling Reactors and Advanced Fuel Separations is conducted by the National Laboratories supported by Industry and the Universities;

i. The DOE funds and constructs the Advanced Fuel Cycle Facility (AFCF)

It is vital that the DOE proceed with the AFCF in a timely manner since it is critical to the commercial deployment of the Advanced Recycling Reactors in the second interim phase.

An important point to note at this stage is that the aqueous recycling facility process has three primary products: uranium; the transuranic group of elements – plutonium, neptunium, americium, and curium; and the highly radioactive fission products containing cesium and strontium. The ultimate design intent is to convert the transuranic group, which are major contributors to the long term radiotoxicity of the waste, into fuel for the ARR.

The transuranics are also the principal long term heat generators in the repository. By removing them from the waste intended for the repository that limitation on repository capacity is greatly reduced. The short term heat generators, the cesium and strontium, are not separated but incorporated in the HLW glass. It is delay cooled for about 100 years, in which time the Cs/Sr also cool and cease to be a capacity limiting factor for the repository.

The ARRs, however, will not be ready for commercial deployment until at least the middle of this century and therefore the EnergySolutions Team proposes to configure the primary separation process to produce either a mixed uranium/plutonium or uranium/plutonium/neptunium product for inclusion in mixed oxide fuel (MOX) for LWR reactors. The americium and curium can either be fabricated into targets for burning in CANDU reactors, or stored pending feeding to the ARRs, or for a limited period not separated from the HLW and disposed of with the glass. Although Am/Cm are one of the long term heat generators that reduce repository capacity it should noted that their adverse impact is greatly reduced when separated from plutonium. [Calculations indicate there is only an incremental 10-20% benefit in removing the Am/Cm from the stand point of heat limit at the repository once the plutonium has been removed.]

The EnergySolutions Team has only identified the disposal of Am/Cm via targets as an alternative to burning in the ARR, pending availability of ARRs, as a backstop and will conduct a more detailed cost benefit analysis in Continuation I or II to confirm the most appropriate way forward. Our estimates, however, have made provision for the capital and operating expenses associated with fabricating and burning targets.

2.4 Economics evaluation using Cash Flow Modeling

Based in inputs such as the estimated annual quantities of spent nuclear fuel, estimates of capital and operating costs of the recycling facilities and price estimates for recycle products a cash flow model was developed and used to evaluated the financial viability of different business cases. In setting the price of the recycled products significant discounts are included compared to the current price of uranium oxide fuel used in both the LWR and HWR fleets.

Revenue generated from the sale of recycled fuel products would fund operation and repay debt obligations. The sale of Recycled Uranium for use in CANDU reactors plus the sale of MOX fuel for LWRs will provide the bulk of the revenue needed to operate the recycling facilities. The cash flow model tracked the contributions of nuclear utilities into the waste fund, the repayment of debt obligations to the fund as well as reprocessing payments out of the fund and the loans used to finance the capital expenditures. Utility contributions were varied to indicate the level of utility support in mils/kwh charge necessary to keep the fund in the black while providing financing to the facilities required.

The model was also used to identify the number and size of recycling facilities and the timing of their construction and operation that were necessary to meet the GNEP goals of the business plan. Timing of facilities and utility fee contributions to the fund were adjusted to maintain the liquidity of the fund for current and future operations.

Capital and operating costs were developed by the EnergySolutions team for the recycle facilities, MOX fabrication plant, associated waste facilities, the ARR, and ARR fuel fabrication and recycle.

The business relationships are illustrated in figure 2-1 below.

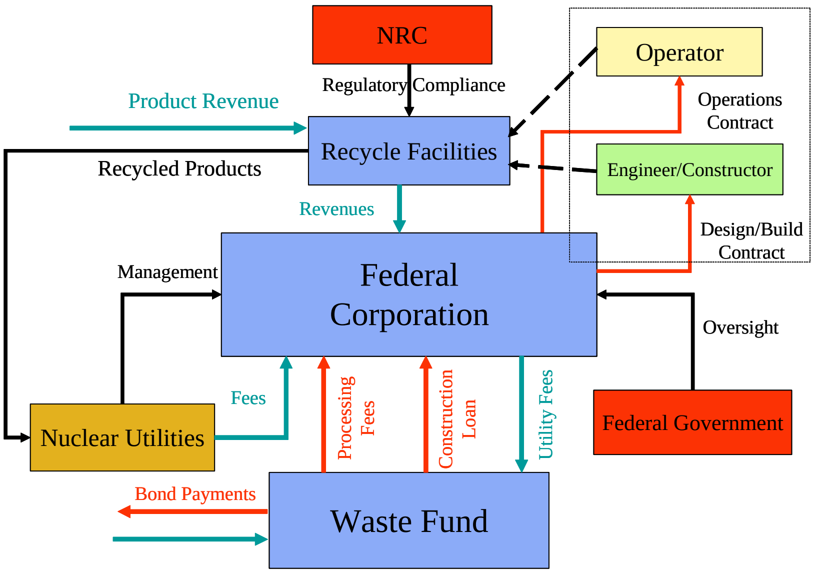

Figure 2-1. Federal Corporation Business Relationships

The FedCorp would be responsible for:

- Waste repository construction and operation;
- Contracting with industry (recycler) for the construction and operation of recycle and fuel fabrication facilities under long term, take-or-pay contracts;
- Transport of used nuclear fuel from reactors to recycle facility;
- Supporting defense and legacy DOE waste disposal;
- Supporting international programs through spent fuel take back.

The DOE retains responsibility for research and development of

- Advanced recycling reactors;
- Advanced separations technologies.

2.5 The interim phase 2030 through 2049

In this period advanced recycling reactors will transition from full scale, first of a kind, demonstration to commercial scale deployment as power reactors. Aqueous LWR recycling and fuel fabrication facilities will be expanded to cater for the significant quantities of high burn up

(HBU) and MOX fuel being discharged from the LWR fleet. The first integrated ARR fuel separations and fabrication facility using advanced non-aqueous processes will be commissioned and produce metal fuel for the first commercial ARRs. The key features of this period are:

New reactor build proceeds at a rate to ensure that the nuclear contribution in the US does not fall below 20%

No commercial spent nuclear fuel sent to Yucca Mountain repository;

Construction of a 3000 MT/yr expansion aqueous LWR spent fuel recycling facility using existing waste treatment facilities, to commence hot operations in 2035;

Approximately 4500 MT/yr of LWR SNF is shipped from reactor sites to the recycling facility, commencing in 2035;

Construct and start to operate a 500 MTHM/yr expansion of the MOX fuel fabrication facility on the same timescale;

Approximately 2000 MWe of commercial ARR capacity is brought on line, comprising an initial 410 MWe unit in 2033 followed by the first commercial 4 unit module of ARRs giving 1640 MWe output in 2045.

The cash flow modeling shows that the investment in new recycling and fuel fabrication facilities is completely funded by the FedCorp which raises additional capital through bond issue.

2.6 The final phase 2050 through 2100

This phase is characterized by growth in the ARR fleet, particularly in the period 2070 -2100. A total of approximately 96GWe installed ARR capacity is on line in 2100.

Replacement of aqueous LWR recycling is also required to replace the first two facilities which reach the end of life and proceed into deactivation around 2065 and 2075 respectively. The estimate show however that the fourth facility capacity requirement is only 1500 MTHM/yr, reflecting the reduced amount of LWR fuel being generated towards the end of the century as the ARR fleet grows.

The total number of reactors brought on line through 2100 is depicted in figure 2-2.

.

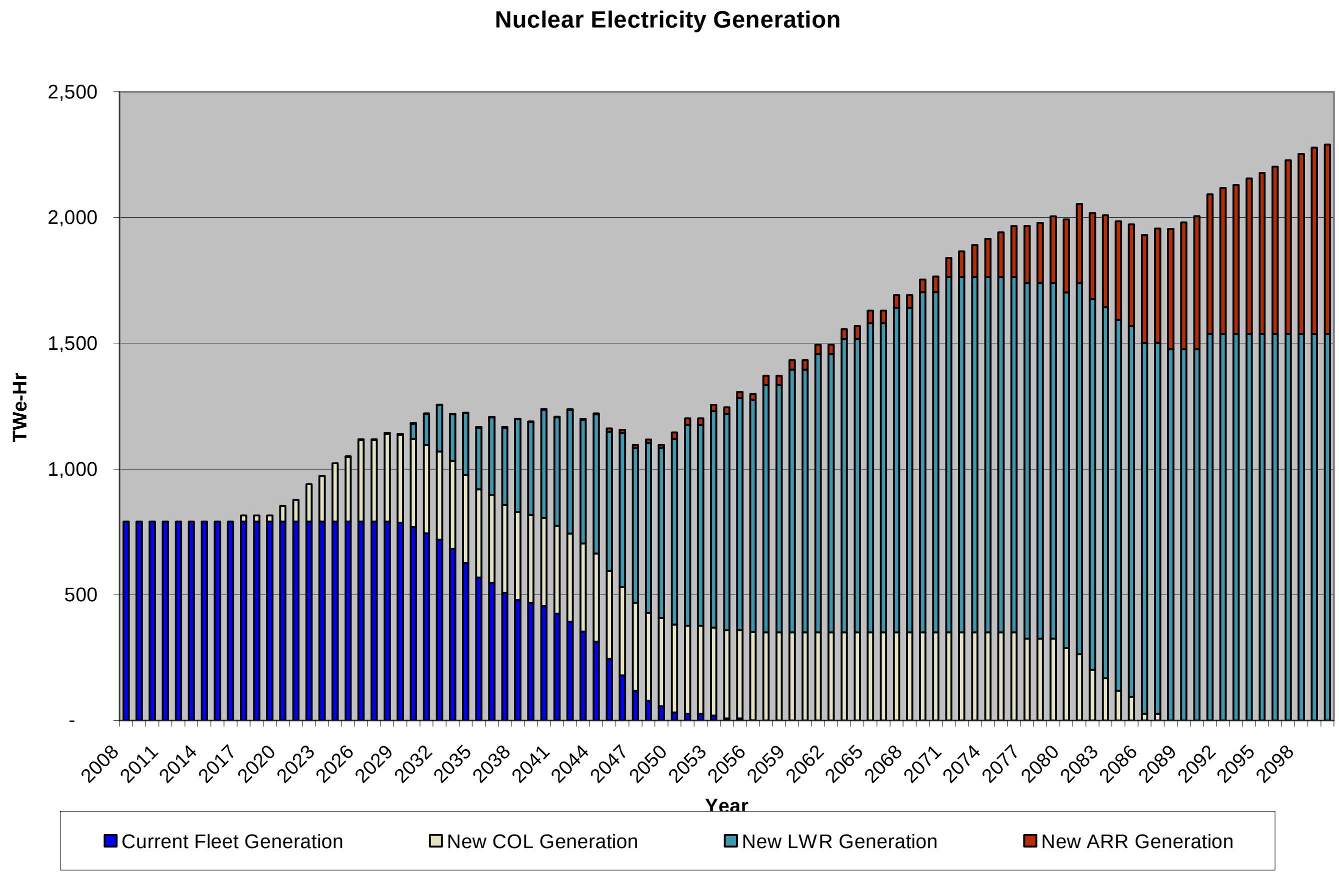

Figure 2-2 Electrical generation by reactor type

The EnergySolutions Team modeled two primary scenarios. In the first scenario the existing body (corpus) of the nuclear waste fund is not utilized; in the second scenario the existing fund is used incrementally over a 25-year period starting 2017.

The EnergySolutions Team's modeling shows that

a. When no use is made of the existing waste fund, all capital and operating costs for the recycling and fuel fabrication facilities are paid for by the fee at 1.95 mil/kwh. Sufficient funds are generated to repay all bonds and loans and to provide construction incentives for the ARR fleet and reduce the waste fund fee to the LWR fleet operators;

b. If the waste fund is used from 2017 then the fee required is reduced to 1.25 mil/kwh;

c. All plutonium generated is consumed either as MOX or metal fuel for the recycling reactors;

d. Capacity exists to convert existing stocks of foreign owned civil plutonium into either LWR or ARR fuel, subject to establishing suitable international agreements;

e. The stocks of spent fuel at reactor sites start to decrease around 2035 and are significantly reduced by the end of the century despite the substantially increased rate of arisings;

f. No commercial spent nuclear fuel is sent to the geologic repository in Yucca Mountain. No HLW has been consigned to the repository but the first shipment is anticipated in 2105.

2.7 Financing

FedCorp will provide 100% of the capital required for the engineering, licensing, design, construction and start-up of all four CFTC facilities using the Waste Fund. The Fed-Corp will also use the Fund to pay an O&M contractor to operate the facilities for the Fed-Corp. No Government involvement or support is required to get any of the CFTC facilities built and operational.

Cash flow analyses for each of the facilities were developed and all were linked to a central cash flow sheet for the Fund. Estimates of Fund contributions to completion of a repository and spent fuel transportation requirements are included in the master cash flow spreadsheet. It should be noted that even when the current body of the Nuclear Waste Fund (approximately $21Bn) is not used, the increase in the waste fee is < 1 mil/kwh which is less than that required to match inflation since 1983.

Several analyses of options of funding the construction and operation of the facilities were conducted with the models. The primary variables used in all of the analyses were the mil-rate fees charged to the utilities. The mil-rates are applied to different classes of reactors: the current fleet of 104; the 31 announced COL reactors; advanced LWRs expected to come on line after 2030; and the ARRs. In all cases, the goal was to keep the mil-rates as low as possible.

EnergySolutions believes that construction, ownership and operation of the four LWR recycling facilities should remain solely with the Fed-Corp without any private equity participation. Although the projects may be attractive to some investors, the return to any equity partner will ultimately come out of the utilities. The utilities therefore deserve full benefit of the Fund without dilution by others.

An attractive method of keeping the mil-rate low is to borrow against future revenues, utility contributions and interest. A practical way of achieving this is through the issuance of a bond instrument. As a TVA-like Authority, the FedCorp will issue 30-year bonds to raise capital for major construction efforts. To support the capital needs of the four LWR recycling facilities that are required, the FedCorp will need two bond issues: one in 2027 for $30 billion and a second in 2056 for $18 billion. The second bond is partially to assist extending the burden of the first 30 year bond an additional 30 years.

To fund the construction of the first two facilities, the mil-rate fee charged to nuclear utilities for disposal of spent fuel must be increased from its current rate. A cash flow analysis shows that the rate should increase from 1 mil/kwh to 1.95 mil/kwh by 2010, or as soon as possible if the existing body of the waste fund is not used. When the waste fund is used the increase is reduced to 0.25 mil/kwh and the new rate would be 1.25 mil/kwh.

3.0 Hurdles

3.1 Demonstration of Technical Feasibility

The Business Plan is based on the baseline technical approach contained in the technical volumes of our submission. The feasibility of this approach may be measured by the degree and nature of technical/technology work that needs to be carried out to allow deployment. In addition feasibility in the sense of a given technical approach being ready to deploy may be a time dependent attribute.

This is the case with the approach to the fuel cycle on which this plan is based and there are different timeframes on which the deployment of the two critical elements of the fuel cycle is deemed to be feasible.

The initial LWR spent fuel recycle aspect is based on technology and processes that are to the greatest extent proven at commercial scale, that is, at the scale demanded by the new fuel cycle envisioned by the GNEP. Design work can and has been started and reasonable estimates of cost and schedule have been developed. The outstanding key technology requirements driven by gap analysis have been defined in the technology roadmap and it is clear that the Technology Readiness Levels (TRL's) are consistent with a ready to deploy approach with low technological risk.

The new reactor and fuel designs and advanced fuel recycle necessary to safely and economically provide the dual functionality required of the Advanced Recycle Reactor (ARR) in a large new system require much technology development and demonstration. This is laid out in the Technology Roadmap. For the ARR, fuel and advanced fuel recycle technology, TRL's are low for all key aspects. As a result a significant demonstration phase is recommended to demonstrate fuel performance, safety, functionality and economics to the extent necessary for US utilities to be willing to deploy the ARR's commercially to burn down TRU while efficiently generating electricity. Similarly, significant work is necessary before the deployment of an advanced fuel recycle facility can be deemed as technically feasible.

In conclusion, the major technical feasibility hurdles are associated with new reactors, new fuel and advanced recycle and our deployment plan, technology roadmap, design work and business plan reflect that.

3.2 Proliferation

Probably the most prominent issue associated with the expansion of nuclear power generation is that of proliferation potential, i.e. the ability of rogue factions to produce weapons grade nuclear materials ("Big P"). Traditionally, this would have focused on high yield precursors such as enriched uranium or plutonium from the uranium (or thorium cycles). With the changing face of the world, post the cold war, proliferation concerns now extend to lower yield options and even the security of non-fissile materials for dirty bombs.

There are three approaches that are necessary in order to deal with the proliferation issue:

- Leading nuclear nations need to control the spread of front-end enrichment and recycling processes which could lead to materials being diverted to non-fuel activities. At the same time, leading nuclear powers need to make sure that diversity of fuel supply exists for all nations that wish to have nuclear power. This is the heart of the GNEP concept;
- IAEA, in concert with national nuclear regulatory bodies, needs to ascertain that there is clear and sufficient oversight to safeguard from diversion activities and any and all opportunities for nuclear materials proliferation; and
- The international community, international bodies and national regulatory agencies need to require transparent flow-sheets and processes that eliminate the options to separate the target nuclides that represent a proliferation concern.

At a different level than the "Big P" of the proliferation of key nuclear technology across international borders are the key requirements for state-of-the-art, world class approaches to Safeguards and Security ("Small p") of materials. Energy*Solutions* will implement a non-proliferation/safeguards and security program that is commensurate with the risks associated with each step in the recycle process. The front end (spent fuel receipt and storage and the backend (waste stream management) are not major concerns from the standpoint of diversion of strategic Special Nuclear Materials (SNM). The spent fuel storage and waste processing areas will therefore be Category III facilities. The sensitive segments of the process are the spent fuel separations and potentially ARR fuel manufacture areas.

The first line of defense against diversion of plutonium is the design of the process which never separates pure plutonium. The second line of defense is the plant configuration and controls (barriers, access controls, monitoring, personnel security, training etc.) in conjunction with nuclear material accountancy and safeguarding under the auspices of the IAEA. Additionally physical security (guards and guns) will be deployed in accordance with facility security category. In short, the global deployment of the GNEP concept coupled with the type of plant, system, component design and control features of today's facilities can minimize proliferation risks on the global front and render them effectively impossible here in the USA..

3.3 Financial Hurdles

The projects necessary to establish the new GNEP fuel cycle are enormous by any standards and the associated timeframes are very long. The projects considered will be up to 20 years in design, construction and commissioning with operational phases of up to 60 years. It follows then that there are significant financial hurdles both in terms of risks that must be appropriately analyzed and allocated in ways that ensure support for and success of this monumental endeavor and the expected financial returns. This is the primary driver towards creation of the FedCorp.

We have therefore based our initial business planning on an approach that utilizes contributions by nuclear utilities into a new Fund managed by the FedCorp. In future work we will perform analysis of sensitivity to different degrees of private versus public investment.

3.4 Regulatory Hurdles

The principal regulatory hurdle is the establishment of a suitable regulatory framework in time to prevent delays to the construction and operation of the initial recycling and fuel fabrication facilities. As currently written 10 CFR part 50 applies to the licensing of the LWR recycling facility (a ‘production’ facility). However its provisions are outdated and no longer appropriate regarding reprocessing/recycling plants, it was last used to license a reprocessing facility almost 40 years ago.

The EnergySolutions team believes that 10 CFR part 70, recently revised to address the requirements of the MOX processing facility at Savannah River, together with 10 CFR part 52 for a single step Construction and Operation License (COL) are more appropriate for licensing the LWR recycling facilities. The new regulatory framework would therefore require suitable modifications to these parts 70 and 52 to include the LWR recycling facilities and attendant changes to part 50 to remove the elements related to reprocessing facilities. Additionally assessments and possibly changes may be required to parts 73, 74, & 75 to address security and safeguards requirements. (The fuel fabrication facilities would be licensed under part 70.)

The “one-step” licensing process requires a new paradigm regarding the performance of the design to support the safety analysis. This new paradigm will require the scheduling and execution of the conceptual and preliminary design with the objective of supporting the safety analysis first and foremost, and to meet the construction schedule second.

All of these changes will require rule making by the NRC and that will require both budgetary provision in 2009 budget cycle and resource allocation to implement at a time when the NRC resources are being increasingly focused on supporting the new nuclear build. If the program schedule of bringing recycling facilities on line by 2023 is to be achieved then rule making will need to be largely or predictably complete by 2010/2011.

The Advanced recycling reactor will be licensed using parts 50 and 52. Modifications may be necessary to reflect the fast reactor aspects but this is not seen as a particular hurdle, given the additional time available before the ARR will need to be NRC licensed for power generation.

Amendments will be required to existing LWR licenses to allow the use of plutonium bearing fuels and recycled uranium.

These facilities will need to be comply with emission controls, which will present specific challenges with respect to specific isotopes. Krypton 85, Iodine 129 and tritium are of particular concern. The EnergySolutions team has identified design features to ensure that discharges of these isotopes meet the environmental limits. It should be noted however that none of the currently operating commercial recycling facilities trap and isolate these isotopes and the design provisions identified by the EnergySolutions team are not therefore fully commercially proven.

A full analysis of the regulatory requirements and considerations is given in Attachment 14 to the Conceptual Design Studies Report.

3.5 Policy and Legislative Hurdles

The key approaches outlined in this business plan and the implicit GNEP objectives will not be accomplished without an adequate level of support from this and future Administrations and from Congress. This support must be tangible and manifest itself in the form of new legislation, revised legislation, the development of new rules and clarification of the applicability of existing rules.

3.5.1 New Enabling Legislation

The principal act that legislates for the disposition of used nuclear fuel is the Nuclear Waste Policy Act (NWPA) of 1982 and in particular the provision it makes for the establishment and use of a Nuclear Waste Fund (NWF).

We recommend that this legislation be changed to achieve four key objectives:

- To provide the capital necessary to establish a closed fuel cycle in the USA
- To ensure that future contributions into the fund are dedicated to the establishment and operation of fuel recycle facilities
- To make an adjustment to the “mil-rate” to account for the erosion of purchasing power of the fee since 1982, and
- To establish a new entity (FedCorp) responsible for and accountable to Congress for the management and disbursement of the NWF

3.5.2 Revision of Existing Legislation

In addition to the changes driven by the recommended enabling legislation above we also recommend the following three additional revisions to the NWPA.

1. The siting criteria for the repository should be simplified to minimize the sort of protracted legal battles that have plagued the existing repository program
2. The revision should clarify any limit on capacity by waste form and the capacity set at an amount sufficient to cater for the needs of the nations new fuel cycle.
3. Restrictions on the siting, construction and capacity of interim storage should be removed and the construction and operation of interim storage facilities should be de-coupled from the licensing, construction and operation of the geologic repository.

Over and above the NWPA we recommend that the Land Withdrawal Act that governs the use of the Waste Isolation pilot Plant (WIPP) be revised to allow disposal of certain of the wastes that will arise from GNEP facilities and processes.

3.5.3 Development of New Regulations and Applicability of Existing Rules

NRC does not currently have a program set up specifically for the regulation of GNEP recycle technologies and facilities. Development of design and engineering information relating to safety related structures, systems and equipment will be critical to the establishment of a risk based regulatory approach by NRC.

Should it prove sensible to shift the location of the geologic repository from Nevada to another location, then CFR Chapter 10 Part 63 would need to be revised accordingly. In addition it may be that the Standard Contract for Disposal of Spent Nuclear Fuel and High level Waste embodied in CFR Chapter 10 Part 961 will need to be revised so that utilities will have a relationship with the FedCorp rather than DOE.

Finally, the legislation that establishes FedCorp would need to incorporate a number of requirements relating to the change in responsibilities from DOE to FedCorp and resulting replacement by NRC regulations of certain DOE requirements for transport and other operational aspects.

3.6 Public Acceptance

The growth of the nuclear power option is impeded in many countries by public concerns over the safety and environmental consequences of producing electricity by means of nuclear reactors. Historically, the main components of this public concern have been the potential for serious accidents at nuclear facilities, the day-to-day operational safety of nuclear reactors, the association in the public's mind between nuclear power and nuclear weapons, and the question of what to do with radioactive waste.

At the US national level, the importance of the GNEP mission to national and economic security cannot be overstated. The national debate over closing the nuclear fuel cycle could strongly affect the quality of life that this generation leaves for future generations.

GNEP is a complicated technical and controversial issue that is an easy target for emotional, simplistic opposition. As in most situations like this, it is easier to oppose than it is to advocate and the GNEP program has seen its fair share of that fact since its inception.

Nevertheless, the EnergySolutions team believes that a unique opportunity is being presented to the nuclear industry by the public's recognition of the importance safe, secure and economic energy supplies together with the need to reduce carbon emissions. It therefore behooves the entire industry to find a way of growing support for GNEP and in particular taking the important first step of closing the fuel cycle on the road to a new generation of nuclear power in which the problem wastes are not only eliminated, they extend our indigenous supplies of energy significantly and potentially in an unlimited manner.

4.0 Key factors to emerge from the deployment studies

Listed below are just a few examples of the factors & messages that have been identified during the execution of these studies that have a direct bearing on the process to educate key stakeholders regarding GNEP. They speak directly to some of the fundamental concerns expressed by key stakeholders such as Members of Congress regarding GNEP. They and the supporting information should be used as part of a pro-active ‘sharing what we know’ exercise that the Industrial Consortia, DOE, and other Nuclear Industry Groups should conduct in the coming months and years.

4.1 Key Factors and Messages

This is not a complete listing. In fact the key findings presented in section 2 of this report represent a complete set of the key messages to emerge from the studies and indeed should be used as such in the right circumstance. The messages presented here are shorter and more to the point. They have been selected because they reflect hot buttons with some of the key stakeholders.

4.1.1 Technology

A. Commercially proven, advanced technology is available and ready to deploy to day to close the fuel cycle for LWR fuel.

B. Technology exists today to process and dispose of the ‘real’ HLW (and other waste streams) that would arise from recycling LWR waste fuel.

C. HLW can be vitrified and delay stored for about 80 years, at which point its heat content is greatly reduced and disposal in a repository simplified.

D. That technology is configured to significantly reduce the risk of proliferation. There would be no pure plutonium separated;

E. Facilities can be built today that have negligible impact on the environment;

F. Significant technological advances have been made in the last twenty years that simplify processes, reduce capital and operating costs, and further improve safety;

G. Advanced Recycling Reactor Technology and processes to fabricate and recycle transuranic fuel for those reactors is not yet ready for commercial deployment but a number of viable reactor and fuel processing concepts exist;

H. Well structured technology development for the ARR and ARR fuel processing should enable commercial deployment within about 25-30 years.

4.1.2 Business planning and economic viability

A. Recycling spent fuel is commercially viable;

B. A change is required in the way nuclear waste is managed today. Legislative changes are required that would allow the creation of a federal waste corporation –FedCorp, a non profit organization, with the authority to effectively manage nuclear fuel and nuclear wastes as a business enterprise;

C. The primary source of funds would be the nuclear waste fees and revenues generated by the sale of recycled nuclear fuel. The utilities would be financing the program and be members of the Board of FedCorp, providing oversight. LWR recycling can be implemented now and it would not be a big government project. There would be no need for huge appropriations.

D. FedCorp would manage the waste fund in the future but would not need to use the $20 billion currently raised;

E. Two scenarios have been evaluated.

F. FedCorp would manage the waste fund in the future but would not use the $20 billion currently raised. In this case the fee would be increased to 2.0 mil/kwh starting in 2010.

G. FedCorp would manage the waste fund in the future and use the existing fund over a 25 year period commencing in 2017. In this case the fee would be increased to 1.25 mil/kwh starting in 2010.

H. If legislation was enacted to create FedCorp, LWR spent fuel recycling could begin in 2023

4.1.3 Public acceptability

A. By enabling the growth of nuclear power, closing the fuel cycle will create over 250,000 ‘good jobs’ in the US alone. Many of these will be in the manufacturing sector and will directly benefit the American work force, helping to stem the outflow of ‘middle class’ jobs from the United States;

B. Recycling and closing the fuel cycle reduces the long term toxicity of the high level waste;

C. The amount of high level waste requiring disposal is significantly reduced and repository utilization improved by a factor of at least 5, and potentially 50 times.

D. There would be no pure plutonium separated or produced;

E. US energy security is improved, carbon emissions will be reduced significantly;

F. All of this can be done economically, with no additional burden on the taxpayer and with just a small increase to the rate payer.

4.2 Information gathered during the Siting Studies

EnergySolutions participated in the GNEP Siting Studies and for each of the three sites studied, public meetings were held to understand public input to the process. Much of the information gathered was fairly predictable. Those people opposed to nuclear in general or recycling in general were generally well prepared and spoke to the emotional issues such as leukemia clusters near nuclear installations. They were not interested in hearing the counter arguments.

The rest of the audience, however, listened intently to the response given. Some of them followed up with questions or comments afterwards. Generally most such people were positive and appreciated the balanced response.

- Key lesson: it is absolutely imperative that the counter argument is made, clearly, concisely but not aggressively. The audience is not the anti nuclear folks but the undecided or pro nuclear people who are at the meeting or who might be listening to the radio or who read the newspapers etc. Media representatives know who the 'antis' are and it is vital that they hear the rebuttal.

Most general members of the public, including pro nuclear and undecided wanted to know ' How does it affect me?' The answer has to be unequivocal, factual and positive but not patronizing. Brevity is good! The EnergySolutions team conducted Siting Studies in three states, all for private sites.

- Key lesson: Multiple media contacts are vital, even if they appear unfavorable or ask awkward questions. The exposure is an opportunity.
- Key lesson: Local area research from multiple sources in advance to find the local flavor of issues; they vary from location to location even in the same region. Tailor information but always deal with core fundamentals of safety and impact on environment.

Most members of the public are more concerned today for the environment. The environmental benefits of nuclear present an opportunity therefore and it has to be taken, again unequivocally and positively. Nuclear's environmental baggage has to be dealt with and must not be dismissed.

- Key Lesson: disclosure is better than having to answer why you didn't disclose.

It is vital to engage the support of key local stakeholders. If they advocate positively, especially in person at meetings, huge benefit accrues. Having and keeping their support is essential but it doesn't guarantee that the public or other stake holders will follow. Not having their support, however will almost certainly guarantee not having the public's support

- Key lesson: Seek and secure support from key stakeholders, keep them informed, keep them engaged.

There are many other similar lessons to be learned but these give a flavor of some of the important issues and lessons that need to be built into the on going plans to build support for GNEP and closing the fuel cycle.

4.3 Feedback from Congress

Some members of Congress and their staff have been supportive of GNEP. However, many are not and there concerns are driven by different factors. They include:

- Proliferation
- Costs
- GNEP program ill defined
- Mixed messages, inadequate information from DOE
- Technology not ready
- Big government project, will overrun on cost etc
- Recycling not needed

The Deployment Studies have generated material that enables most if not all of these concerns to be addressed. It is important that the results of the deployment studies are presented to members of Congress and their staff in a structured and targeted manner. Several of the key findings described in section 1.1 above can form the basis of focused presentations. This should be done in both an informal and formal manner. It is important that the material used is not too technical unless that is specifically requested. It should just focus on two or three of the key issues, say proliferation, costs, and technology readiness.

Given the negative publicity that surrounded the recent National Academy of Sciences Report, which was echoed by members of congress, together with the criticism leveled at GNEP when the 2008 Budget was finally resolved, and the impending 2009 budget cycle, the EnergySolutions team believes this is the key area to focus on in the short term and recommends that a group be created from across all four consortia completing the GNEP deployment to studies to urgently address the task of sharing information with members of congress and their staff. The aims of that group will be to:

- Gather information regarding specific concerns held by members of congress regarding GNEP.
- Present feedback on the results of the deployment studies.
- To determine what additional information the member or their staff requires.
- To seek their advocacy for closing the fuel cycle.
- Establish follow up opportunity.

5.0 Preliminary Technology Development Roadmap

The roadmap describes the areas of technology development required to enable potential commercialization of the nuclear fuel recycling as an integral component of the GNEP vision. The current state of multiple technology options for each component of the fuel cycle is described and discussed in detail. An assessment made of the level of technical maturity, based upon the EnergySolutions team's corporate and considerable industrial experience has enabled the EnergySolutions team to recommend the preferred deployment approach. In some instances the level of maturity is such that multiple pathways are still required to be pursued concurrently in order to mitigate high technical risks. Notwithstanding this the roadmap identifies precise objectives and helps focus resources on the critical technologies that are needed to meet those objectives. This focusing is important because it allows limited development investments to be used most effectively.

In summary each Section of the Overall Technology Roadmap:

- Assesses current status of knowledge, technical maturity and readiness for deployment & assign TRLs (NASA Technology Readiness Levels)
- Analyses gaps between this current status and the knowledge/data required to support fully the facility design
- Produces a listing of all technology needs to support the project
- Produces a Technology Acquisition Plan to fill the gaps and provide the technology backing to the project
    - This includes a listing of testing & development requirements and when they are required for the design to proceed to schedule
- Uses the above as the basis of the Technical Risk Register and later develop Risk Mitigation Plans for the project.

As required the EnergySolutions team has utilized the NASA scale of Technology Readiness Levels, but has adapted and modified some of the definitions to better reflect recycling, nuclear fuel and reactor technology. This is illustrated in figure 5.1 below.

TRL	Definition	Description
1	Basic principles observed & reported	Lowest level of technology readiness. **Scientific research** begins to be translated into applied research and development.
2	Technology concept and/or application formulated	**Invention begins**. Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis
3	Analytical and experimental critical function and/or proof of concept	**Research and development is initiated**. This includes analytical studies and laboratory studies to physically validate predictions of separate elements
4	Component and/or assembly validation in laboratory environment	Basic technological components are integrated to establish that they will work together. "Low fidelity" compared to the eventual system. **Typically inactive or trace active lab testing**
5	Component and/or assembly validation in relevant environment	Higher fidelity. The basic technological components are integrated with more realistic supporting elements so they can be tested in a simulated environment. **Typically glovebox testing with "spiked" radionuclides.**
6	System/subsystem model or prototype demonstration in a relevant environment	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. **Typically large scale low active pilot plants**
7	System prototype demonstration in an operational environment	Prototype near planned operational system. Represents a major step up from TRL 6, requiring demonstration of an actual system prototype in an operational environment. **Typically fully-hot testing at small to medium scale**
8	Actual system completed and qualified through test & demonstration	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. **Typically would be completion of cold commissioning of a system before going hot**
9	Actual system proven through successful mission operations	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. **This would typically be initial hot operation of a recycling facility**

Figure 5-1. The modified NASA Technology Readiness Scale

The principal results of our assessments are given in figures 7 and 8. These figures describe the technology readiness for different aspects of the nuclear fuel cycle associated with both Light Water and Advanced Recycling Reactors. They are discussed in turn below.

5.1 Technology for recycling LWR Spent Nuclear Fuel & manufacturing MOX.

Figure 7 shows clearly that over 90 % of technology required is available today at TRLs7-9, is commercially proven and can be deployed immediately to design, build and operate LWR recycling facilities. A small number of areas associated with the separation and finishing of the americium & curium and removal of iodine 129 and krypton 85 require development work. It should be noted that the flowsheet TRLs are for the process that EnergySolutions is proposing to use on these facilities which in some cases is an improvement over alternative processes that are more mature. The removal of iodine and krypton are excellent examples. Processes have been fully demonstrated at large scale under fully radio-active conditions, but have not been chosen because more attractive alternatives, with less total risk or cost are available, but have yet to be demonstrated at industrial scale. By definition these more attractive alternatives have to be rated lower on the NASA TRL scale. Another example is uranium purification. This aspect of the process has been conducted very successfully for over 40 years on fully commercial facilities. In this instance however the EnergySolutions team will implement a significant process improvement and by strict adherence to the rules of the NASA assessment we must rate that flowsheet at TRL 8.

The spent nuclear fuel receipt, process storage, and 'Head End' facilities will all use fully commercially proven processes and equipment to deliver clarified dissolver liquor to the aqueous based separations process. The EnergySolutions team proposes to utilize the NUEX flowsheet to recover and make available for new fuel manufacture uranium and the transuranics. Over 99% of the fission products will be recovered in the liquid HLW stream which will be vitrified in the well proven Joule Heated Ceramic Melters.

The primary separations process in NUEX is extremely flexible and can be configured to deliver pure uranium and a mixture of plutonium and neptunium, or pure uranium and a mixture of uranium, plutonium and neptunium, or pure uranium and a mixture of uranium and plutonium using proven chemical control in the same commercially proven extraction equipment. Indeed The EnergySolutions Team proposes to take advantage of this flexibility in the initial phase of commercial operations before the Advanced Recycling Reactors are on line when it will initially offer MOX fuel and recovered uranium for recycle into LW and HW reactors.

In the NUEX process the americium and curium is recovered from the HLW using the TRUEX/TALSPEAK processes. Although these processes have not been deployed commercially the EnergySolutions Team has reviewed the work to date and determined that the process technology readiness is such that design work can commence and the requisite development work will be completed on a timescale that will not delay construction. This assessment is based on experience of completing similar design driven development programs in parallel with commercial recycling facility design and construction. The risk associated with this strategy is not therefore considered very great but a mitigation plan has been prepared and is very simple and straightforward to execute. The design of the initial LWR recycling facility incorporates features that are thoroughly tested and proven which enable the EnergySolutions team to incorporate process modifications at any stage, even after the facility has started full commercial operations. These are discussed more fully under and in Volumes I & II of the preliminary Conceptual Design Studies Report.

Technology Area		TRL	
		Equipment	Flowsheet
Head-end	Fuel Receipt & Storage	9	9
	Fuel Prep & Feed Pond	9	9
	Shearing	9	9
	Dissolution	9	9
	Feed Clarification	9	9
Primary Separation	U/Pu/Np Separation	9	9
	U Separation from Pu/Np	9	7
	U Purification	9	8
	Pu/Np Purification	9	9
Am/Cm Separation	TRUEX	7	7
	TALSPEAK	7	5
Product Finishing	Uranium	9	9
	(U)/Pu/Np	9	6
	Am/Cm	5	5
Solid Wastes Processes	HLW Vitrification	9	9
	Super Compaction	9	9
	Grout Encapsulation	9	9
	RH Tru & CH Tru	9	9
	LLW & MLLW	9	9
Liquid Effluent Treatment	Evaporation	9	9
	Actinide Removal	9	9
	Ion Exchange	9	9
	Solvent Treatment	9	9
Aerial Effluent Treatment	Particulate Removal	9	9
	General Fission Products Removal	9	9
	C14 Removal	9	9
	I129 Removal	8	6
	Kr85 Removal	6	6

Figure 5-2: LWR Spent Fuel Recycling Technology Readiness Levels

An extremely important aspect of closing the fuel cycle is dealing with wastes and emissions. The TDRM assesses technology requirements for clean up of liquid and gaseous effluents and packaging and preparing for disposal solid wastes. The roadmap shows that technology is available at TRL 9 for treating, packaging and preparing for disposal all of the anticipated solid waste streams from the initial aqueous LWR fuel recycling facility (and the associated fuel fabrication plants). The key challenge with respect to disposal of solid wastes is legislative not technical, with the principal concern being an authorized and practical disposal route for transuranic wastes, including RH TRU. These issues are discussed under 'Necessary Regulatory & Legislative Changes" in the business plan. The fuel cladding debris is an excellent example. The residual small amount of undissolved fuel remaining means that it exceeds GTCC limits. (The TDRM shows that enhanced dissolution technology, which would obviate this problem, is not yet ready to deploy in the first facility) The plutonium and other transuranic content means that it needs to be disposed of as RH TRU. The performance assessment of the salt repository, WIPP, in Carlsbad, NM, would cover this waste form but current legislation restricts the use of WIPP to Defense Waste.

The evaporation, trace actinide removal, ion exchange and solvent destruction processes required for treating liquid wastes are all well-proven and are available at TRL9. The LWR Recycling facility will be a zero or near-zero liquid discharge facility with water recycled to reagent make up and the removed contaminants encapsulated and/or packaged as solid waste.

The technology roadmap highlights one potentially significant gap and that is regarding tritium removal. Abatement technology exists at proof of principle levels but is not commercially deployed in nuclear facilities today. Technology to initially treat the spent fuel and drive the tritium off as a gas (voloxidation) as well as tritium –hydrogen exchange in 'end of pipe' solutions have been evaluated. The EnergySolutions team considers that neither of these options are viable for the first recycling facility but will be implemented in the expansion facility taking advantage of the voloxidation process that will be used to enhance dissolution. With respect to the initial facility a simpler option, based upon solidification of tritiated effluent, resulting from water recycling is being examined.

In commercial reprocessing plants in Europe and Asia aerial effluents are cleaned up using a variety of technologies, including wet scrubbers, condensers, electrostatic precipitators and absolute filters. This ensures that emissions are extremely low and comprise principally the volatile/gaseous fission products of iodine 129, krypton 85, and carbon 14. Carbon 14 removal technology exists and is deployed very successfully on the Thorp facility in the UK. Iodine capture technology also exists but is not deployed currently on commercial facilities but will be deployed on the initial and subsequent LWRRC facilities. Krypton capture technology exists and has been proven at proof of performance level (TRL7) in Karlsruhe, Germany, but is not deployed at any of the commercial reprocessing plants. In one of those plants the regulatory authorities determined that the greater risk to the operators presented by capturing and concentrating the Kr 85 significantly outweighed the risk to the general population or critical group by dispersing the gas as it was released during fuel shearing. The EnergySolutions team therefore proposes to deploy capture technology for all three isotopes, subject to the proviso that a risk informed assessment and cost benefit exercise be completed for the krypton removal.

The uranium product will be converted into uranium trioxide powder by a well-proven process with a TRL of 9. Conversion of this recycled uranium to uranium dioxide fuel and the processes for making mixed uranium plutonium oxide (MOX) fuel are also well understood and commercially established. The TRL is 9. The technology assessment shows that MOX incorporating neptunium requires certain physical test work to be performed primarily to underpin the fuel qualification process.

5.2 LWR SNF Recycling Technology Gap Analysis and Approach to Gap Closure

Given the status of each technology summarized above, the ES Team analyzed the gap existing between current status and that desired for deployment to proceed with confidence. Gaps are classified in terms of flowsheet, process or equipment.

The predominantly more mature technologies have gaps largely in the flowsheet areas, reflecting incremental evolutions of currently deployed technology but with chemistry adjustments to improve them for GNEP application. Flowsheet confirmation for uranium separation from Pu/Np and subsequent uranium purification falls into this category at TRL7&8. These gaps are characterized by a desire for the technology suite to be demonstrated over broad operational and feed envelopes in coupled end-to-end demonstrations. These demonstrations are not typically required for process design purposes. However, the knowledge gained by these demonstrations is beneficial in reducing the schedule and costs associated with plant commissioning and for business, technical and environmental confidence in the flowsheet.

Less mature technologies have gaps largely in the process and particularly equipment areas. However, the ES Team believes these gaps can be filled after design is initiated because initial design studies can be based on published development work and the team’s own knowledge. The americium /curium separation and finishing processes fall in this category. Additionally, all SNF recycling processes are envisioned performed in industrially proven equipment and configurations. The ES Team has selected a technology suite that requires no inventions so that design can be immediately implemented.

Technology needs are identified based on the gap analysis. These needs are largely for flowsheet demonstration for the mature technologies and equipment or process demonstration and optimization for those less mature. Development requirements indicate that most technology needs can be satisfied with small-scale prototypic test equipment using simulated feed material and computer-based modeling. The ES Team is confident that all technology needs for the LWR recycling can be satisfied while design proceeds (i.e. no development is required before commencing design).

5.3 Linking LWR and ARR Spent Fuel Recycling

An Aqua-ElectroWin (Aqua-EW) recycling process will be considered for introduction to the overall scheme and may replace one or more of the standard NUEX Expansion facilities. Aqua-EW combines a modified NUEX front end aqueous solvent extraction separation of uranium only, with oxalate precipitation of the fission products from the TRUs & rare earths (lanthanides), followed by non-aqueous molten salt electro-winning separation of the rare earths from the transuranics. The RU produced will be burned in CANDUs, formed into MOX or re-enriched for LWR use. A product of plutonium/neptunium, americium/curium is produced at the Electro-Win (EW) cathode that is fabricated into metal fuel for the ARRs. This Aqua-EW process, with a conventional Head End to expose and dissolve the fuel, will allow LWR SNF to be processed through to ARR fuel. It will also allow Pu/Np/Am/Cm product oxides from LWR aqueous recycling to be introduced directly into the EW process. By this means, the ARRs can progressively take over the burning of the TRUs.

6.0 Technology for Americium, Curium Target Fabrication

One of the options for the spent fuel processing / recycling for the GNEP program is to separate the americium (Am) and curium (Cm) from the fuel stream and burn the Am/Cm in separate target rods / assemblies. There are many advantages for this approach:

- The main fuel fabrication processes are cleaner, easier, require less shielding and are more economic if the high dose/ high heat Am/Cm is removed from the fuel.
- Reactor core physics behavior is more predictable without Am/Cm in the fuel.
- The Am/Cm targets can be placed in designated regions of the reactor core for optimized core performance.
- The target rods / assemblies are independent of the fuel, and therefore can reside in the core longer than the fuel, if necessary, to achieve the desired burn-up.
- The Am/Cm can be incorporated into an inert matrix so no additional new transuranics are created under irradiation. After irradiation, most of the Am/Cm has been burned and the fission products remain bound in the matrix. After a cooling period, it is expected that the target rods / assemblies can be directly disposed in the geologic repository (no further separations). This approach removes Am/Cm from the fuel cycle and eliminates the continuous (and costly) cycling of the Am/Cm through the separations process, fuel fabrication, and reactor operations.

Ceramic material types are in the early irradiation test stage for use as minor actinide (MA) target host material, and testing beyond currently planned irradiation testing will be required before the burning of MAs in targets is mature enough to deploy commercially. Attractive advantages of these ceramic host oxide forms are:

1 High potential Am/Cm loading fraction to minimize the number target rods produced;

2 Stability against radiation damage which allows the targets to go through multiple irradiation cycles to reach desired burn-up; and

3 The final rock-like form after irradiation that is suitable for geological disposal after cooling without any additional reprocessing or recovery steps.

The most practiced physical fuel form for use in targets is pellet; however there is a large experimental-scale experience base for sphere-pac (SP) fuel. The SP approach offers several advantages over pelletization for remote fabrication and provides the flexibility to present the Am/Cm material to a wide variety of transmutation systems. The advantages for the SP method include significantly less dust generation during fabrication, better thermal conductivity characteristics due to not needing a pellet/ cladding gap to allow for target swelling, increased space for storage of evolved helium gas, use of improved thermal conductivity from evolved He gas, less target/cladding chemical corrosion potential, and less severe target/cladding mechanical interactions through the ability of the spheres to shift and relieve strain.

Although it is technically preferable to burn Am/Cm targets in the advanced recycle reactors (ARR); three (3) additional burner alternatives were evaluated by the ES Team for nearer term application. These are: CANDU reactors, burnable poison rod assemblies (BPRA) in light water reactors (LWR), and conversion of LWRs near end-of-licensed-lifetime (EOLL) to dedicated actinide burners (while still generating electricity). CANDU reactors provide the most efficient, flexible, and easiest of the thermal reactor concepts to license and implement:

1. Offers on-line refueling,
2. Provides a simple core bundle design,
3. Good neutron economy increases target burning efficiency,
4. A full core of inert matrix fuel (IMF) and MA targets can be used,
5. The operational and material requirements of an CANDU IMF are very similar to those for LWR thus offering additional flexibility in material pathways,
6. Advanced CANDU Reactor (ACR) design offers possible enhancements to improve actinide burning efficiencies, and
7. The CANDU is unique in that its design allows for use of alternative fuel types other than natural uranium (NU) without requiring major modifications to the basic reactor design.

7.0 Technology for recycling ARR spent fuel

7.1 ARR SNF Recycling Technology Description and Readiness

The ES Team selected an electro-winning (EW) technology for recycling ARR SNF on the basis of the significant pilot-scale demonstrations undertaken particularly at Idaho National Laboratory for recycling Experimental Breeder Reactor – II SNF. EW of irradiated metallic fuel is performed in molten LiCl-KCl salt eutectic. Batches of fuel sheared into pieces and anodically dissolved, leaving the fuel cladding hulls to be removed in a basket for disposal. The uranium is electrotransported to a solid iron cathode where it deposits in purified form and subsequently recovered. Plutonium, minor actinides (MA) and reactive fission products (FPs) convert to chlorides and accumulate in the salt. FPs, that are unreactive, generally accumulate as metallic solids in the anode baskets (anode sludge). When a number of fuel batches have been treated, the plutonium is recovered as a U-TRU alloy in a liquid cadmium cathode. The cathode and its deposited actinide metal inventory are loaded into an inert crucible and the cadmium removed by vacuum distillation. The cadmium is collected and recycled, while the actinides are further processed into fuel for the ARR.

Primary waste arisings from the EW process will comprise the fission products as metal, phosphates or captured in zeolite, anodic sludge and heavy metal waste from molten metal reductive extraction. It is proposed the heavy metal sludge will be oxidized and blended with ceramic formers and sealed in containers, which are then hot isostactically pressed (HIPped) to form a dense ceramic. This waste form also captures anodic sludge. Discharged zeolite is blended with glass and poured into containers. The filled HIP flasks are placed inside the HIP machine and converted into a glass-ceramic waste form. There is significant development work to undertake in the waste processing area before a high level of confidence in this process operation is established.

Different parts of the EW flowsheet are at differing TRLs. For example, the electrorefiner, itself, is assigned a TRL of 6 based on the significant pilot-scale work performed to date and waste treatment assigned a TRL of 4.

7.2 ARR SNF Recycling Technology Gap Analysis and Approach to Gap Closure

There are significant gaps in the process and equipment areas of the EW process, reflecting the relative immaturity of pyrochemical recycling of SNF, as indicated in the introductory remarks to section 2.1.1. In addition, gaps also exist in the material accountancy and regulatory areas, which do not exist for aqueous-based recycling approaches. Technology needs were developed from the gap analysis on a global basis. These needs show significant work is required to develop and optimize unit processes and demonstrate equipment. The technology acquisition plan will include development work to be performed by the ES Team and the national laboratories (principally ANL and INL). Technology development is expected to be complete within 15 years.

8.0 Technology for the ARR and its fuel

The technology readiness levels for the most mature technology available to implement the EnergySolutions Team's path forward to advanced recycling reactors that can burn transuranic fuels is presented in figure 8. The assessments for the interim step of fabricating Am/Cm targets and the various ways in which the CANDU reactor may be deployed in the closing the LWR fuel cycle are also presented.

Area	Sub-Area: Most Mature available Technology	TRL
Fabrication of Metal Fuels for ARR	Receipt & handling	6-7
	Slug casting & scrap recovery	5
	Slug inspection, handling & storage	6
	Fuel pin loading & sealing	6-7
	Fuel pin inspection, handling & interim storage	6
	Fuel assembly pin loading	6
	Fuel assembly fabrication	7
	Fuel assembly inspection, handling,& storage	8
Fabrication of Am/Cm targets	Target materials & Fabrication	3-4
Advanced Recycling Reactors	Electro-magnetic pump	6
	Double wall steam generator tubes: straight/helical	6/8
	Decay heat removal systems: DRACS/SCAGHRS/RVACS	8/8/6
	Core systems & Equipment (depends on equipments), Phase 1 of implementation	1 to 9
CANDU Reactors	Burning RU	7 to 9
	Burning MOX	7 to 8
	Burning Am/CM	4 to 6

Figure 8-1 Summary of TRLs for the ARR, Use of the CANDU, and fabrication of transuranic metal fuel & Am/Cm targets.

It is clear that very few aspects of the ARR fuel cycle are ready for commercial deployment. While some reactor systems are close and adjudged to be at the TRL 8 level, a number are still at proof of principle and one key core systems, the diverse shutdown system is adjudged to be TRL 1. The key features are discussed below.

9.0 Assessment of ARR Technology Readiness

9.1 Technology Readiness for Key Reactor Systems

9.1.1 Primary System Electro-magnetic Pumps

The current state-of-the art for large no moving part electro magnetic (EM) pumps is represented by the 160 m3/min EM pump build in Japan and tested in ETEC in 2001. This pump testing demonstrated that EM pumps of sufficient capacity can be built, operated, and controlled, to meet the needs of up to a 1500 MWth reactor plant. This design therefore bounds the needs for a 1000 MWth ARR. The pump configuration to be used in ARR is a double stator Annular Linear Induction Pump. The testing of the large EM pump demonstrated that the hydraulic characteristics of such designs meet the requirements for the ARR primary system pumps. In the last decade, electrical insulation systems have been developed that are capable of operating submerged in sodium, at a temperature of 600C with a life of more than 100 years. This allows the use of EM pumps operating submerged in a sodium pool at temperatures of 400C or higher, without requiring auxiliary cooling. The technology behind the improved insulation (consisting of mica and alumina cloth) is mature, and is currently being used in electrical motors intended for high temperature service.

The current state-of-the-art of EM pumps using the annular linear induction pump design is sufficiently mature to support the ARR pool plant with no additional research and development. However, the qualification (including seismic qualification) of an engineered design for the specific performance requirements of the ARR by testing will be required. Based on the NASA System, the electromagnetic pump has been demonstrated to be at the Technology Readiness Level (TRL) of 6 for use in the ARR primary system.

9.1.2 Double Wall Steam Generators

Experience with duplex tube steam generators (SG) such as in EBR-II, has demonstrated great reliability with over 30 years of service without any incidence of leaks. The EBR-II tube and shell SG design minimized the possibility of interaction between the sodium and the water/steam by using double tubes and double tube-sheets. The outer tubing was welded to the sodium tube-sheets at both ends, and the inner tubing was welded to the water/steam tube-sheets at both ends. With this design no single weld, tube or tube-sheet separates the sodium from the water/steam. Incorporating continuous leak detection using helium as a third fluid between the inner and outer tube gives an additional level of safety to the steam generator. Helical coil heat exchangers have advantages over straight tube ones in the better accommodation of stress between inner and outer tubes. The technology to form straight tubing into coils of radii needed for a helical coil steam generator design, without damage to the interface between the inner and outer tube has not been demonstrated at this time. The technology readiness for the double wall helical coil steam generator tubing (reference design for the ARR) is considered to be TRL of 6. The technology readiness for the straight double wall steam generator tubing is considered TRL of 8.

9.1.3 Decay Heat Removal Systems

The ARR may use up to three different decay heat removal systems, Reactor Vessel Auxiliary Cooling System (RVACS), Direct Reactor Auxiliary Cooling System (DRACS), and Steam Generator Auxiliary Heat Removal System (SGAHRS). Of these systems, RVACS and SGAHRS are the preferred choices for the ARR, with DRACS a backup if analysis shows that an enhanced RVACS has insufficient heat removal capability. All of these systems have been implemented in previous LMR designs; and therefore, are considered mature technologies. Based on available data, DRACS and SGAHRS have been demonstrated to be at the Technology Readiness Level (TRL) of 8 for use in the ARR. RVACS has been demonstrated in smaller reactors. For larger reactor systems such as the 1000MWt ARR, enhancements of the basic system will be required. This includes high-emissivity surface treatments or coatings on the reactor vessel exterior surface, and the interior guard vessel surface. The high-emissivity surfaces treatment need to be qualified to last for the life of the plant under normal plant full power condition, and also perform adequately for the plant accident conditions. The high-emissivity surface treatment of the vessel surfaces is a development item that has not been demonstrated. For this reason, the Technology Readiness Level for the RVACS for the ARR is estimated to be TRL of 6.

System/Component	Technology Readiness Level	Comments
Electromagnetic Pumps	6	Need qualification testing at prototypic conditions
Coiled Double Wall Steam Generator Tubing	6	Need to demonstrate manufacturability of coiled duplex tubing.
Straight Double Wall Steam Generator Tubing	8	Demonstrated by 70 MWth model manufacture and test.
RVACS	6	Need enhanced emissivity surface treatment of vessel walls.
DRACS	8	Mature technology, need engineered design.
SGAHRS	8	Mature technology, need engineered design.

Figure 9-1 - Technology Readiness for ARR Reactor Systems

9.2 Technology Readiness for Key Core Systems

Nuclear Core Design computer codes are developed for LMRs (EBR-II and FFTF). The TRL for design and safety codes is estimated to be 7 to 9; little additional work will be needed to support the ARR. Experience with irradiation performance of actinide fuels that include inventories of minor actinides is limited; and therefore, more in-core testing will be needed. The behavior of core structural materials at higher fast neutron exposure levels will also have to be demonstrated. The TRL for irradiation performance of actinide fuels and structural materials is estimated to be 3 to 7, depending on the particular material or core component. The diverse shutdown system is not mature technology and will require significant R&D. Its TRL is estimated to be 1.

9.3 Assessment of ARR Development Needs

9.3.1 Development Needs for Key Reactor Systems

The technology to manufacture straight duplex tubing for use in LMRs is a proven technology. The technology to manufacture coiled duplex tubing in required lengths (manufacturing technology issue) needs to be fully developed. Once this has been demonstrated, a “few tube” model of the ARR steam generator, with full-length duplex tubing and double tube-sheets at each end, will be manufactured. This model will be tested in a sodium test facility at rated conditions to qualify the design of the ARR steam generator.

The enhanced RVACS is dependent on two technologies; enhanced emissivity surface treatment of RV(Reactor Vessel) outer surface and guard vessel inner surface, and evaporative cooling of the guard vessel outer surface. The enhanced emissivity surface treatment must be developed and qualified by coupon testing in an environment simulating the conditions of the two vessel surfaces. The surface treatment must effectively increase the spectral emissivity to 0.8 or better for both surfaces, and maintain this emissivity for the life of the plant. The evaporative cooling of the guard vessel will be based on technology developed for the Westinghouse AP-1000.

9.3.2 Development Needs for Key Core Systems

The scope of development needs will vary. Licensing and economic performance are the main drivers for the development programs for core systems. The DOE National Laboratories will be involved in fuel and material performance programs, while industry will be more involved in system design issues and the safety and licensing of the reactor. The National Laboratories should have the lead for developing the TRU burning fuel for the ARR, which is metal fuel (with MOX as a backup). The INL has laid out a 20-year program to develop and qualify actinide fuel/targets for use in an ARR over the entire range of compositions to obtain closure of the fuel cycle. A step-wise implementation of this program limited to directly supporting licensing of the ARR fuel system is recommended.

9.4 Path to Deploy the ARR

The “bootstrap” approach is the simplest and least costly way to license the AAR plant design. It avoids building a dedicated test reactor. The first ARR may be operated on a government site by a government organization or a utility as a contractor to the government. Until the first ARR is operating, the National Laboratories, in cooperation with the future fuel supplier and core designer, would lead the development of ARR actinide fuel. This may require irradiation testing in foreign reactors, Japan and France.

This approach differs from proposals that envision National Laboratories leading ARR fuel development and building a dedicated fuel test reactor, much like EBR-II or FFTF. This more conventional approach using a dedicated test reactor would not get to a commercial deployment of the ARR as quickly as the "bootstrap" approach recommended here. If the irradiation performance of actinide fuel (including moderate amounts of minor actinides) is consistent with predictions extrapolated from the current database, then the fuel development time could be reduced because extensive testing in a dedicated test reactor would not be needed.

10.0 Technology for CANDU Reactor use

EnergySolutions has contracted Atomic Energy of Canada Limited (AECL) to contribute a CANDU specific assessment section to the overall Roadmap. The AECL study focuses on the feasibility of using alternate recycled fuels in existing and new CANDU type reactors. These alternate fuel streams are to be produced by recycling spent LWR fuel into fresh fuel bundles and/or targets for use in CANDU reactors. The main alternate fuel streams envisioned for use in CANDU reactors and assessed in this study include Recycled Uranium (RU) based fuels, Mixed Oxide fuels (MOX) based on plutonium/neptunium/uranium blends and americium/curium based fuels and/or targets. The use of recycled fuels in CANDU reactors during the short (up to 2035) and medium time frame (2035 and beyond) is in accordance with GNEP goals and methodologies.

One such method of dispositioning LWR spent fuel can be accomplished by recycling spent fuels into new fuel streams for use in CANDU and other reactors. The unique features of the CANDU reactor design (the currently operating CANDU 6 reactor and the future ACR-1000 reactor), mainly their inherent high neutron economy, on-power fuelling and flexible fuel bundle design, can be readily employed to use an assortment of different nuclear fuel-cycles.

CANDU technology was examined for GNEP application to recycle SNF and reduce the quantity of long-lived radioactive substances.
The technology readiness assessment reveals that CANDU is capable of utilizing Recycled Uranium and optionally Mixed Oxide fuels effectively because of its inherent high neutron moderation. It is concluded that the alternative fuels can be introduced to CANDU reactors either via the cold, green fuel path or the hot, irradiated fuel path without any major hardware modification to the reactor.

Also, the study shows that CANDU will be a very effective system to reduce minor actinide fuel/targets (Am/Cm) by transmutation due to the high neutron economy. The optimal neutron flux in CANDU reactor cores are maintained by on-power fuelling. This means that the rate of transmutation of Am/Cm actinide targets can be maintained at a prescribed rate. It is envisioned that significant reduction in mass of long-lived Am241 isotope can be achieved, and the Am/Cm reduction goal can be met with CANDU technology.

The study concludes that CANDU technology can be readily modified for use in the spent nuclear fuel recycling and waste reduction program envisioned by DOE with minimal technological barriers. Additional detail studies are needed including safety analysis, plant operation and plant modification plans to further reduce the gaps identified.

The full report provides detail including readiness assessments, the required testing & development activities, a technology risks register, mitigation plan and the cost and schedule estimates for each of the alternate fuel streams.

CANDU technology is a mature nuclear technology with reactors designed, licensed, built and supported by Atomic Energy of Canada Limited. Currently there are 26 CANDU type reactors operating in Canada and internationally, with extensive operating experience, including in-reactor testing of alternate fuel streams.

AECL together with CANDU utilities currently possess the capability, tools and experience required to develop the technology required to use new alternate fuel streams (Recycled Uranium, MOX, Slightly Enriched Uranium (SEU), Am/Cm targets) in current CANDU reactors.

11.0 Conceptual Design Studies

This preliminary conceptual design studies report presents scope, costs and schedule information for several sets of facilities that are required to close the fuel cycle in the United States and realize the GNEP vision. Detailed aspects of the design of those facilities are presented in Preliminary Conceptual Design Studies Report. Those conceptual designs encompass LWR SNF recycling, fabrication of MOX fuel, waste treatment facilities, an Am /Cm Target Manufacturing Facility, an Advanced Recycling Reactor and the recycling of spent ARR fuel and the production of new ARR fuel.

The degree of detail in the design support material is considerably greater for the LWR Recycling Center and its associated waste treatment plants than for the ARR facilities, reflecting both the maturity of the design concepts and the technology. The initial recycling facility, the MOX fuel fabrication facility and the waste treatment plants are all based upon commercially proven designs that can be deployed into commercial operations quickly, safely and economically. This approach enables the United States to close the fuel cycle at the earliest opportunity and take a significant step forward towards an integrated waste management strategy that will allow the US to take advantage of the nuclear renaissance and re establish its leadership position in nuclear.

11.1 Key Design & Operational Assumptions

- The initial LWR spent fuel recycling, MOX fuel fabrication facility and the associated waste treatment facilities designs are all based on existing commercially proven plants and processes that have been modified slightly to meet the requirements of GNEP and US environmental protection requirements.
- The separations flowsheet for LWR recycling is aqueous based & designed to separate and produce mixed transuranic products with or without uranium. Pure plutonium will not be separated anywhere in the process.
- The initial LWR recycling facility nominal capacity is 1500 MT/yr. Design & process improvements have been incorporated which build on the Chemical Separations Facility's proven capacity of 5 MT/day and enable a target throughput of 1500 MT/yr to be achieved for the overall facility.
- The initial recycling facility will process spent fuel with burn ups up to 50GWD/MT. Subsequent facilities will process material with burn ups up to 60GWD?MT
- The initial MOX fuel fabrication facility nominal capacity is 300 MT/year, but can be increased to match the recycling facility by implementing full shift, 24/7 working.
- The Am/Cm Target manufacturing facility has been sized to process up to 1500 kg/yr of americium/curium in the ratio of 1500/ 40 for all batches.
- The Advanced Recycle Reactor Fuel Recycling and fabrication facility design and throughput are based upon fuel processing and supply to four reactors co located at a single site. The process is a non aqueous electro winning developed from the processes deployed on the EBR II fuel fabrication facilities.

- The ARR will be a sodium cooled, pool type, generating an electrical output of 410 MWe containing several innovative features that will improve safety and reduce design, build and operating cost.
- HLW containing the cesium and the strontium along with other fission products and lanthanides will be vitrified and delay stored on site for up to 100 years. Hulls and ends will be disposed of as RH TRU.
- Liquid radioactive discharges will be as near zero as practicable.
- The facilities will be fitted with iodine 129, krypton 85 and carbon 14 removal.

11.2 Scope, cost and schedule summary

The principal parameters of scope and schedule for the initial phases of GNEP facilities are summarized in the table 15-1 below. The EnergySolutions team has also discussed expansion of facilities in its preliminary reports in order to describe and evaluate the US nuclear industry through 2100. Although cost information is not presented in this summary (for commercial reasons) it should be noted that to facilitate incorporation in the business planning models the 6/10 power rule has been used for scaling up capital costs. Operating costs for the expansion facilities were scaled up by looking at throughput related items such as materials, utilities, and labor as appropriate

.		Capacity*	Start Date
1	Initial LWR Recycling Facility	1500 MT/yr	2023
2	Initial MOX Fuel Fabrication Facility	300 MT/yr	2025
3	Waste Treatment Facilities	4500 MT/yr	2023
4	Am/Cm Target Fabrication Facility	1.5 MT/yr	2025
5	First-of-a-kind (FOAK) Advanced Recycle Reactor (ARR)	410 MW(e)	2026
6	ARR Fuel Recycling and Fabrication Facility	20 MT/yr	2022
7	N^{th}-of-a-kind (NOAK) ARR (4-unit module)	1650 MW(e)	2033

**Capacity of LWR Recycling Facility, MOX Fuel fabrication facility, the Waste Treatment Plants is based upon equivalent metric tons/year of spent nuclear fuel processed*

Table 11-1 Summary of scope, capacity, cost and schedule for the GNEP facilities

11.3 LWR recycling Key Design concepts

The initial LWR recycling facility utilizes the EnergySolutions NUEX separations process as depicted in figure 15-2. A key feature of the process is the flexibility of the primary separation process. Pure plutonium is never separated. It can be configured to co- extract uranium and plutonium or uranium/plutonium/neptunium, which is a key fraction of the transuranic fuel feed to ARRs. Our approach allows the Pu/Np mixture to be blended in the liquid phase with recovered americium and curium and/or with additional recovered uranium. This is the option depicted in figure 15-2 and commensurate with the primary GNEP goal of recovering plutonium and the minor actinides for fabrication into fuel for consumption in advanced recycling reactors.

When configured to give a U/Pu product the neptunium portion is directed to the HLW stream. The amount of uranium that can be extracted with the plutonium is limited to about the same mass as the plutonium. It is of course possible to blend in further quantities of recovered uranium in the liquid phase. In the initial period of operations before the ARRs are available the EnergySolutions team proposes to operate this latter option such that a mixed uranium - plutonium conventional product is available for MOX fuel manufacture from the outset.

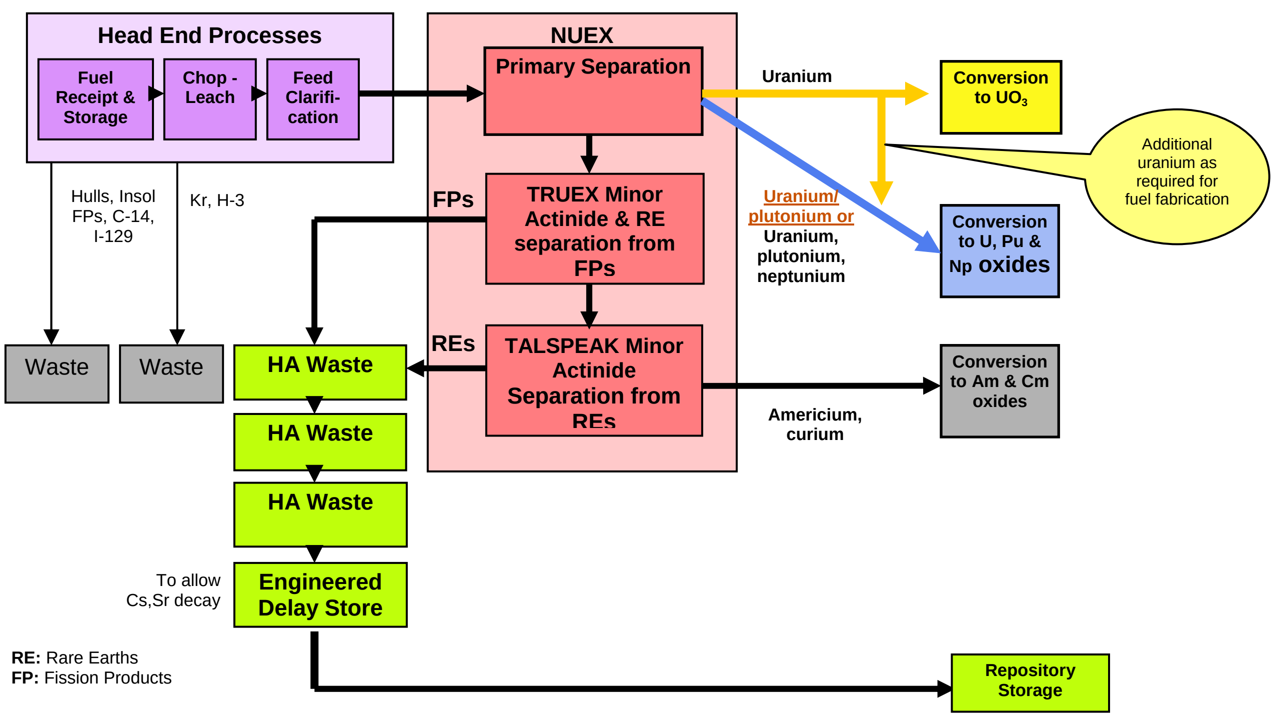

Figure 11-2 EnergySolutions NUEX primary separation process meets all GNEP objectives for a proliferation resistant flowsheet.

The first expansion LWR recycling facility (3000MT/yr) will still use the NUEX separation flowsheet but will utilize different equipment design concepts for fuel dissolution and the solvent extraction contactors in order to be able to process High Burn Up fuel (60GWD/MT) and spent LWR MOX fuels safely and at economical throughputs. The principal concern is criticality control. The EnergySolutions team believes that redesign of the key affected equipment is a fundamentally better approach than trying to extend the design concepts used for the current generation of reprocessing facilities operated in Europe and Asia. Operating experience shows that both MOX and HBU fuel can be processed through existing commercial reprocessing plants but only at low through puts or blended with LBU fuel and providing that the original design made adequate shielding provision, particularly in the downstream waste treatment facilities. This expansion facility is estimated to be available for commercial operation in 2035.

11.4 LWR Recycling wastes & effluent treatment

The waste treatment facilities at 4500MT/yr have been sized to deal with the waste from the first recycling facility and the substantial increase in process wastes when the second recycling facility is brought on line in 2035. Assessment showed that this approach was the most cost effective when considering the full life costs of recycling LWR fuel through the year 2100.

Over 99% of the fission products, including the high decay-heat isotopes of Cesium and Strontium (Cs/Sr), with negligible amounts of the actinides are recovered as liquid high-level waste, concentrated and vitrified in a borosilicate glass matrix in cylindrical stainless steel canisters. The canisters are delay-cooled in a passively cooled, engineered storage facility for up to 100 years to meet the disposal requirements prior to shipment to the geologic repository. This delay storage increases the waste loading at the repository by approximately a factor of five.

Fuel cladding hulls are roller compacted and packaged into RH-72B containers for disposal as Remote Handled Transuranic Waste (RH-TRU) assumed to be in a salt repository similar to the Waste Isolation Pilot Plant in New Mexico.

A key feature of the EnergySolutions Team approach is to reduce liquid discharges to as near zero as practicable by building on the advanced salt-free flowsheets deployed in the United Kingdom Reprocessing facilities. These flowsheets have enabled the operators of those facilities, some of which are over 40 years old and still in commercial operations, to implement and/or back fit radically new flowsheets and substantially reduce liquid discharges. See the discharge performance data that is presented in Volume II of the Conceptual Design Studies. The technology is fully commercially proven and discussed in the roadmap. In essence advanced chemistry is utilized to maximize collection, concentration and treatment of most of the aqueous effluent streams, resulting in solid wastes suitable for disposal to authorized repositories.

EnergySolutions proposes to augment these processes in two ways. Ion exchange technology will be added to the final discharge point in the LWR recycling facility and a significant proportion of the 'clean water' effluent will be recycled back into reagent make up to minimize the discharge volumes. This technology is also commercially proven and deployed widely in the nuclear industry.

11.5 ARR Fuel Fabrication & Recycling key design concepts

Spent fuel from the fast reactor will be recycled by electrolytic reduction and salt distillation. Provision will be made to take transuranic oxides from the LWR recycling facilities. They will be dissolved in hydrochloric acid and the dried, mixed chlorides fed into the electrolytic reduction process. Although the conceptual design studies report shows this step being integral to each ARR fuel fabrication facility a trade study will be performed to determine if the conversion facility should be located with the NFRC.

Uranium and the transuranic metals produced in the electro winning process will then be formed into metal slugs and processed to meet fuel standards prior to rod assembly. The facility layout is based on the EBR II fast reactor fuel fabrication and processing facility at INL. The EnergySolutions team proposes to install four electro-refiners and two metal casters, as opposed to 2 and 1 respectively on the EBR II facility. The capacity of each electro refiner is 5 MTHM/yr and the vacuum casters 10 MTHM/yr. This facility will handle the fuel requirements for the module of 4 advanced recycling reactors proposed. The current design concept is labor intensive remote manipulator based and it is proposed to examine the application of computer controlled robotic manufacturing techniques.

11.6 ARR design concepts

The primary mission of the Advanced Recycling Reactor (ARR) is to burn actinide elements that are produced in Light Water Reactors (LWRs) when neutrons are captured in fuel. A fast neutron spectrum reactor is an efficient burner of actinide elements because the ratio the captures-to-fissions for a neutron interaction event is significantly smaller at higher neutron energies than it is at thermal neutron energies. The liquid metal cooled fast reactor (LMR) is the reactor system of choice to burn excess actinides produced in LWRs. The ARR design has been driven by several design objectives that support its mission; these objectives are listed in Table 11-2 ARR Design Drivers.

Goal	Requirement	Implementation
Proliferation resistance	• TRU burning capability **Note**: TRU is fuel containing Transuranic Elements – Np, Pu, Am, Cm	Conversion ratio 0.6-0.8
Timeliness	• Early development and deployment	Utilization of proven technologies and single plant concept with different cores from test to commercial operation
Economy	• Capital cost • Plant efficiency • Refueling interval • Availability • Construction time	Competitive with ALWR > 40% 12 to 24 months 90% or higher Max 46 months (first concrete to initial criticality)
Safety	• Reactivity feedback • Shutdown system • Auxiliary Decay Heat Removal System	Negative Three shutdown systems (tertiary added for cold shutdown of ATWS) Passive system
Fuel	• Available database • Reactor performance • Recycling performance	Metal or MOX fuel

Table 11-2 ARR Design Drivers

11.7 Principal Considerations and Key Features for the ARR

The ARR must be attractive as a commercial power reactor. The capital cost and fuel cycle cost for an LMR have been generally higher than those for an LWR operating the same electrical power output. This has placed the LMR at a cost disadvantage when compared to an LWR. The ARR design uses innovative plant features (use of "pool configuration" and duplex tube heat exchangers) to reduce capital cost and make LMR produced electrical power more competitive with the cost of LWR produced power. A major capital cost item in an LMR power generating plant is the intermediate (or secondary) sodium loop that couples heat from the primary heat transport circuit to the steam-generator turbine. The secondary loop prevents a sodium water reaction with radioactive sodium in the primary system. However, the secondary sodium system adds complexity and cost to the LMR plant, making it more expensive to build than an equivalent LWR plant. A significant cost reduction is achieved through the innovative use of a double walled tubing heat exchanger to eliminate the “secondary” sodium circuit. Primary system heat is transferred directly to the steam-generating loop. The steam generator is installed inside the reactor vessel. It is a helical coil type double wall tube steam generator (DWTSG) that uses double wall tube with wire mesh between the two concentric tubes. The wire mesh allows detection of any water or sodium that may leak into the space between the concentric tubes. Four DWTSG units are installed in the ARR primary vessel.

A simple proliferation resistant fuel fabrication recycling process has been selected to control the cost of manufacturing actinide fuel. Uranium-plutonium alloy metal fuel developed for the EBR-II by the U.S. Department of Energy at the Argonne National Laboratory under the IFR (Integral Fast Reactor) program is particularly well suited for LMR fuel recycling at low cost.

A summary of key plant parameters is given in Table 11-3, Major Plant Parameters.

Item	Plant Parameters	Note
Reactor type	Pool type without IHTS	
Thermal power	1000MWt	
Power output (net)	410MWe	
Plant life	60 year (target)	
Core	Homogeneous core with two radial fuel zones	
Fuel	Metal (or MOX: option)	Cladding: HT-9
Sodium temperature reactivity coefficient	Zero, or Negative (target)	
Core shield circumscribed diameter	Core barrel diameter: 3.5m	
Average fuel burnup	88,000MWD/T	
Conversion ratio	0.6-0.8	
Primary sodium Temp	550/395 degC	
Primary flow	$4.58 \times 10^3 \times 4$ t/h	
Water/Steam Temp.	240/497 degC (268/500 degC)	
Main steam pressure	175 atm	
Feed water flow	1.61×10^3 t/h (1.72×10^3 t/h) (/plant)	
Intermediate Na/Na heat transport system	Eliminated	

Item	Plant Parameters	Note
Turbine generator	TCDF turbine (38")	
Decay heat removal system	PRACS or RVACS	
DHRS pipe	6BSch20S	
Fuel Treatment system	Refueling interval: 12 to 24 months, 3 batch core	
Spent fuel storage in sodium	Ex-vessel fuel storage system (1 core +) ~ 400 assy.	
In-vessel fuel transfer system	Rotating plug and a variable arm length type FHM	
In-, and Ex-vessel fuel transfer	In-vessel transfer port + Ex-vessel Transfer machine	
Spend fuel storage in water	None	
Reactivity control	24 primary system assemblies	
Shutdown system	3 systems: 24 primary, 6 secondary, plus tertiary at center of the core equivalent to up to 7 assemblies	
Primary pump	EMP. 89 m3/min x 4	
Steam generator	Double wall SG with continuous leak detection: 250MW x 4	
Reactor support type	Top support flange	
Reactor cover	Hot deck structure	
Reactor vessel	RV(10.5m ID, 20.5m L)	
Containment vessel	Steel containment vessel: Top dome and Bottom Cylinder	
Reactor building	Horizontally Seismic Isolated (50mx50mx66mH) (center)	

Table 11-3 Major Plant Parameters

The ARR must have enhanced safety characteristics. Using the “pool configuration” for the ARR plant provides added thermal inertia to mitigate off-normal reactor transients due to increased primary system sodium mass associated with this configuration as compared to a “loop configuration” plant. The ARR core is designed with reactivity coefficients that support passive safety characteristics of the reactor. The ARR core has a third diverse shutdown system to assure safe shutdown under any condition. The ARR has decay heat removal systems that assure adequate cooling of the core even if all station power is blacked out.

The safety of ARR plant is based on the Defense-in-Depth concept used in the design earlier fast reactors. The first level of safety in the Defense-in-Depth prevents accidents by inherent and basic characteristics. The second level of safety protects against anticipated and unlikely events. The third level of safety mitigates radioactive materials release to environment during anticipated and unlikely events. The fourth level of safety uses countermeasures to control and suppress pressurization of containment during a hypothetical extremely unlikely event. Containment pressure control is essential to assuring containment integrity.

The following key safety features are adopted to assure ARR safety within the framework of the Defense-in-Depth concept.

- Reactor core: Designing for a void reactivity coefficient that is less than zero to prevent the core damage due to a gas void in the primary sodium coolant.
- Reactor shutdown system: Installation of a diverse tertiary reactor shutdown system.
- Decay heat removal systems: Four passive PRACS (Primary Reactor Auxiliary Cooling System) and RVACS (Reactor Vessel Auxiliary Cooling System) augmented by natural circulation cooling by primary/secondary coolant loops.
- Counter measurement for sodium leak: For the Primary system, a guard vessel around the Primary System Vessel will prevent loss of primary coolant and an inert gas atmosphere to exclude oxygen from these spaces. For the secondary sodium system, catch pans, fast drain systems, burning suppression panels, and pressure relief disks will be installed.
- Suppression of sodium-water reaction: A continuous leak detector system will provide early warning of a leak in the double-wall helical coil tube steam generator.
- Containment Integrity: Primary isolation valves on the steam system at the outer boundary of containment. The boundary of reactor cover gas is the inner side of tube walls of the double wall steam generator. The integrity of this boundary will be continuously monitored by helium-gas leak detection system.

The ARR design must be flexible to accommodate a variety of core configuration and fuel forms. The ARR reactor core can irradiate minor actinide (isotopes of Np, Am, and Cm) targets while burning actinide fuel. This provides an option to burn excess minor actinide inventories that may result from recycling MOX fuel in LWRs. The ARR can also use MOX fuel without any significant alteration to the core or other plant systems. The ARR core can also irradiate blanket assemblies to moderate the rate of reduction of the overall plutonium inventory if that were needed in the future. The ARR will be able to transition from “full burner reactor mode” to a more “neutral” burner-breeder as actinide inventories are reduced to a minimal level.

The ARR design is “scalable” to allow larger plants of this type to built in the future without requiring new research and development programs or costly “retooling” of manufacturing facilities. The initial ARR plant size (1000MWth) has been selected to take advantage of factory fabrication of major reactor plant components as proposed for the Advanced Liquid Metal Reactor (ALMR) and PRISM (Power Reactor Inherently Safe Module or Power Reactor Innovative Small Module). Larger ARR plants may be more attractive economically in the future.

The ARR design has a path to be licensed by the NRC. This will require demonstrating performance of core and plant components in an early prototype plant built at a government site and operated by a utility operator for the Department of Energy. This early plant will provide fuel performance experience for the prototype ARR fuel and target assemblies as well confirming operation of plant system features such as passive decay heat cooling and duplex tube sodium-to-water heat exchangers.

A “bootstrap” approach is proposed to attain NRC licensing of the ARR. This approach is implemented through three phases using a “first-of-a-kind prototype” ARR. This 1000 MWt commercial power plant will be used to qualify ARR actinide fuel and verify plant safety features. In Phase 1, the ARR will be fueled with a fuel form that is already proven, e.g., binary alloy metal fuel or uranium oxide. Lead Test Assemblies (LTAs) of actinide fuel and actinide simulant fuel will be included as irradiation demonstration tests. In Phase 2, the core will transition to actinide fuel and continue to irradiate lead assemblies in order to develop a licensing database for actinide fuel. In Phase 3, the ARR will operate as a commercial power plant and “burner reactor” with a full load of LWR generated actinide fuel. The phases and their associated key operating conditions are described in the Table 11-4 ARR Operating Phases.

	Phase 1	Phase 2	Phase 3
Specifications	Initial Core	Reference Core	Burner Core
Fuel	Proven metal fuel MOX as backup	Proven metal fuel and transition to metal fuel from LWR and ARR recycle with TRU	Metal fuel from LWR and ARR recycle with TRU
Reactor ownership and placement	Government on government site	Government on government site	Government on government site
Operation	By Government laboratory or utility for government	By Government laboratory or utility for government	Utility operation
Purpose of operation	Shake down ARR with proven technology and include lead test assemblies	Transition to TRU fuel cycle	Demonstrate fuel recycle fuel and TRU operation with licensable fuel
Fuel	Proven metal fuel MOX as backup	Proven metal fuel and transition to metal fuel from LWR and ARR recycle with TRU	Metal fuel from LWR and ARR recycle with TRU
Lead test assemblies	With LWR recycle with and without TRU	With LWR recycle with higher TRU enrichment	No interruption of operation by test assemblies

	Phase 1	Phase 2	Phase 3
Core outlet temperature	530 °C	550 °C	550 °C
Conversion ratio	Not a criteria	Transition to burning TRU	0.6 – 0.8
Conversion ratio	Not a criteria	Transition to burning TRU	0.6 – 0.8
Fuel assembly (FA)	Standard FA	Improved FA for reducing peripheral flow rate	Improved FA for reducing peripheral flow rate

Table 11-4 ARR Operating Phases

Note: TRU is fuel containing Transuranic Elements – Np, Pu, Am, Cm4.3.3

11.7.1 ARR Conceptual Design Features that Reduce Costs

The ARR plant design will use a "pool" configuration. The pool configuration was selected because it reduces plant capital cost. Locating major primary system components (Pumps and Heat Exchangers) in one large vessel avoids plant capital costs associated with separate vessels and guard vessel for each primary pump and heat exchanger as well as the additional piping and inert cells needed to connect these components outside the reactor vessel. The pool configuration also provides added thermal margin to mitigate off-normal operation because the primary vessel contains about three times the mass of sodium than in a comparable "loop" plant; thus, providing more thermal inertia for in the primary system. The pool configuration also cuts capital costs by simplifying the cover gas system needed for the primary system.

A major capital cost item in an LMR power generating plant is the intermediate (or secondary) sodium loop that couples heat from the primary heat transport circuit to the steam-generator turbine. The secondary loop prevents a sodium water reaction with radioactive sodium in the primary system. However, the secondary sodium system adds complexity and cost to the LMR plant, making it more expensive to build than an equivalent LWR plant. A significant cost reduction is achieved through the innovative use of a double walled tubing heat exchanger to eliminate the "secondary" sodium circuit. Primary system heat is transferred directly to the steam-generating loop. The steam generator is installed inside the reactor vessel. It is a helical coil type double wall tube steam generator (DWTSG) that uses double wall tube with wire mesh between the two concentric tubes. The wire mesh allows detection of any water or sodium that may leak into the space between the concentric tubes. Four DWTSG units are installed in the ARR primary vessel.

Using Electro-magnetic (EM) pumps instead of mechanical pumps to pump primary system sodium coolant is another cost reduction feature of the ARR. The pump configuration to be used in ARR is a double stator Annular Linear Induction Pump (ALIP). The testing of this type of large EM pump has demonstrated hydraulic characteristics that meet the requirements for the ARR primary system pumps. Electrical insulation systems and materials have been developed that are capable of operating submerged in sodium, at a temperature of 600C with a life of more than 100 years. This allows the use of EM pumps operation submerged in a sodium pool at temperatures of 400C or higher, without requiring auxiliary cooling. A comparison of a cost comparison of operating electromagnetic and mechanical pumps for the ARR plant is presented in Table 11-5 Cost of Operating EM and Mechanical Pumps. Using the power generation loss of mechanical pumps as a base line, the power generation loss for the electromagnetic pumps is approximately 140 k$/year due to a lower pumping efficiency; however, mechanical pumps need argon cover gas that costs approximately 330 k$/year, which is not needed for electromagnetic pumps. Mechanical pumps require inspection of lubricating system, disassembling and inspection of main motor; the cost of periodical inspection of the mechanical pumps is estimated to be approximately 330 k$/year (estimated from MONJU Plant experience). Electromagnetic pumps require only electrical inspection; the periodical maintenance cost is estimated to be 20 k$/year. Based on these estimates, the use of electromagnetic pumps instead of mechanical pumps results in an annual cost savings of 560 k$/year.

Economic efficiency	Mechanical pump	Electromagnetic pump
Power generation loss	Baseline	-140 k$/y
Consumables (Argon gas)	-390 k$/y	0 k$/y
Periodical inspection	-330 k$/y	-20 k$/y
Total	-720 k$/y	-160 k$/y

Table 11-5 Cost of Operating EM and Mechanical Pumps

Metallic fuel was selected as the preferred actinide fuel form for the ARR to reduce fuel costs. The fabrication of actinide fuel requires special measures to assure radiological safety of workers and to protect the special nuclear materials in inventory. The metal fuel fabrication process is simpler than that for MOX and has a lower risk of contamination outside of the isolated spaces where fuel pins are produced. The metal fuel recycling and fabrication system has been demonstrated at the Argonne National Laboratory in Idaho. Four recycling passes of EBR-II metal alloy fuel were processed on-site at ANL-West (now part of the INL). This fuel was irradiated in EBR-II, transferred to the Fuel Cycle Facility at ANL-West, where it was processed using pyroprocessing technology. The recovered plutonium and uranium was cast into “new” EBR-II fuel pins. These pins were clad in EBR-II stainless steel tubes and bonded to the cladding with sodium. The re-fabricated fuel assembly (91 fuel pins / assembly) was transferred back to the reactor core and irradiated. This process was repeated four times; in all, about 400 fuel assemblies were reprocessed and fabricated, and returned to the reactor.