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OFFICE OF FUEL CYCLE TECHNOLOGIES, USED FUEL DISPOSITION CAMPAIGN OBJECTIVE, MISSION, PLANS, AND ACTIVITY STATUS

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ABSTRACT

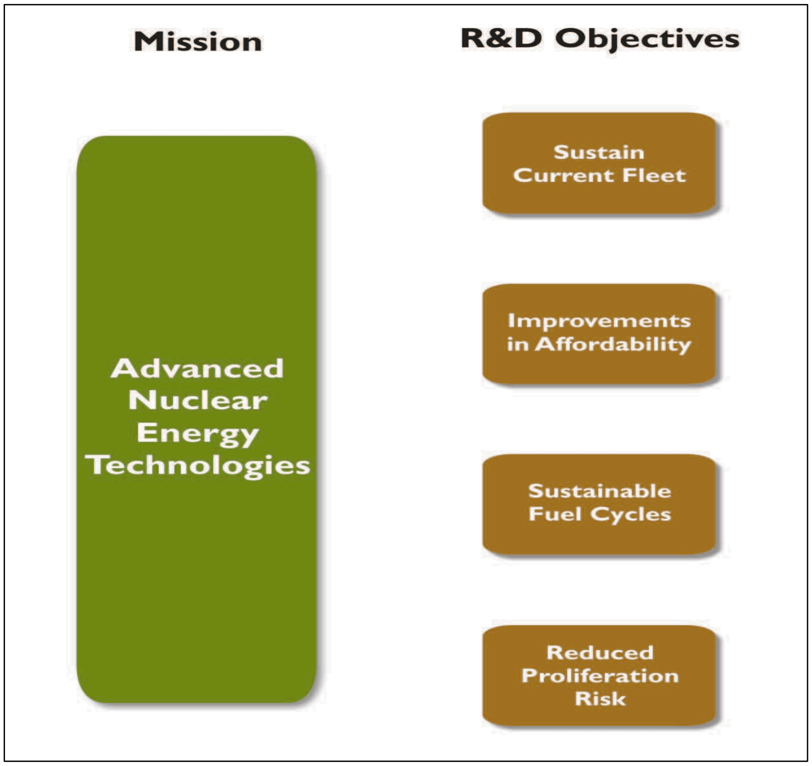
The safe management and disposition of used nuclear fuel and/or high level nuclear waste is a fundamental aspect of the nuclear fuel cycle. The United States currently utilizes a once-through fuel cycle where used nuclear fuel is stored on-site in either wet pools or in dry storage systems with ultimate disposal in a deep mined geologic repository envisioned. However, a decision not to use the proposed Yucca Mountain Repository will result in longer interim storage at reactor sites than previously planned. In addition, alternatives to the once-through fuel cycle are being considered and a variety of options are being explored under the U.S. Department of Energy's Fuel Cycle Technologies Program.

These two factors lead to the need to develop a credible strategy for managing radioactive wastes from any future nuclear fuel cycle in order to provide acceptable disposition pathways for all wastes regardless of transmutation system technology, fuel reprocessing scheme(s), and/or the selected fuel cycle. These disposition paths will involve both the storing of radioactive material for some period of time and the ultimate disposal of radioactive waste.

To address the challenges associated with waste management, the DOE Office of Nuclear Energy established the Used Fuel Disposition Campaign in the summer of 2009. The mission of the Used Fuel Disposition Campaign is to identify alternatives and conduct scientific research and technology development to enable storage, transportation, and disposal of used nuclear fuel and wastes generated by existing and future nuclear fuel cycles. The near-and long-term objectives of the Fuel Cycle Technologies Program and its' Used Fuel Disposition Campaign are presented.

I. NUCLEAR ENERGY RESEARCH AND DEVELOPMENT

To achieve energy security and greenhouse gas emission reduction objectives, the United States must develop and deploy clean, affordable, domestic energy sources as quickly as possible. Nuclear power will continue to be a key component of a portfolio of technologies that meet our energy goals. The U.S. Department of Energy's Office of Nuclear Energy (DOE-NE) recently developed a roadmap of its research, development and demonstration (RD&D) activities that will ensure nuclear energy remains a compelling and viable energy option for the United States.



As shown in Figure 1, DOE-NE has organized its RD&D activities according to four R&D objectives that address the challenges to expanding the use of nuclear power. The four R&D objectives are:

(1) Develop technologies and other solutions that can improve the reliability, sustain the safety, and extend the life of current reactors;

(2) Develop improvements in the affordability of new reactors to enable nuclear energy to help meet the Administration's energy security and climate change goals;

(3) Develop sustainable nuclear fuel cycles; and

(4) Understand and minimize the risks of nuclear proliferation and terrorism.

Figure 1. Four R&D objectives for nuclear energy technologies

A principal challenge for the government in the third objective, achieving sustainable fuel cycles, is to develop a suite of options that will enable future decision-makers to make informed choices about how best to manage the used fuel from reactors. To achieve sustainable fuel cycles there are three primary aspects that need to be considered:

1. Availability of fuel resources;
2. Adequate capability and capacity to manage all the nuclear wastes produced by the fuel cycle; and
3. Improving utilization of fuel resources while minimizing the generation of nuclear waste.

An expansion of nuclear power in the United States will result in a growth of the used nuclear fuel inventories. The Nuclear Waste Policy Act of 1982 gave the U.S. Government the mission to safely manage the used fuel from these nuclear power plants. This management will require the safe storage and transportation of used fuel for some length of time prior to disposal or treatment. The extent to which the used fuel is further processed to remove key elements from the waste for reuse will define the nuclear fuel cycle and the wastes that will require disposal. In addition to the used fuel and high-level waste that will contain most of the highly-radioactive elements, secondary waste or byproducts including low-level waste, and depleted uranium will require safe management and disposition.

The DOE-NE RD&D approach for used fuel management is to investigate the technical challenges that would be encountered in each of three fuel cycle strategies that may be deployed in the future and develop technologies that could demonstrate the best approach within each of these strategies. These three potential fuel cycle strategies for used fuel management are defined that together encompass the totality of potential fuel cycle options.

- **Once-Through Fuel Cycle** – Nuclear fuel makes a single pass through a reactor after which the used fuel is removed, stored for some period of time, and then directly disposed in a geologic repository for long-term isolation from the environment. Less than one percent of the mined uranium is utilized in the present once-through fuel cycle. The developments of high burnup fuels to increase resource usage and reduce waste generation are potential options for this strategy. The addition of thorium as a fertile component to the fuel to minimize the production of higher actinides is a potential consideration. In this strategy, used fuel will not undergo any sort of treatment to alter its form prior to disposal, eliminating the need for separations technologies that may pose proliferation concerns. It is envisioned that current or next generation LWR will be used to implement this option.
- **Modified Open Cycle** – The goal of this strategy is to develop fuel for use in reactors that can increase utilization of the fuel resource and reduce the quantity of actinides that would be disposed in used fuel. In this strategy, used fuel is recycled to produce energy and result in "spent" nuclear fuel (i.e., there is no additional economic benefit in attempting to extract more energy from the fuel) and other radioactive wastes that must be disposed of in a repository. This strategy is "modified" in that some limited fuel processing technologies, perhaps including separation, are applied to the used LWR fuel to create fuels that enable the extraction of much more energy from the same mass of material and improve waste management characteristics. The options may include, but not limited to, very high-burnup fuels in advanced systems (such as traveling wave reactors), a one-step treatment of the fuel after LWR discharge to remove the fertile materials for subsequent deep burn using fertile free fuels in various thermal or fast spectrum systems, mechanical reconditioning of the fuel (without chemical separations) for limited recycle until fission product built-up prevents further recycling, etc.
- **Full Recycle** – In a full recycle strategy, all of the actinides important for waste management are recycled in thermal- or fast-spectrum systems to reduce the radiotoxicity of the waste placed in a geologic repository while more fully utilizing uranium resources. In a full recycle system, only those elements that are considered to be waste (primarily the fission products) would be disposed, not used fuel. Implementing this system will require extensive use of separation technologies.

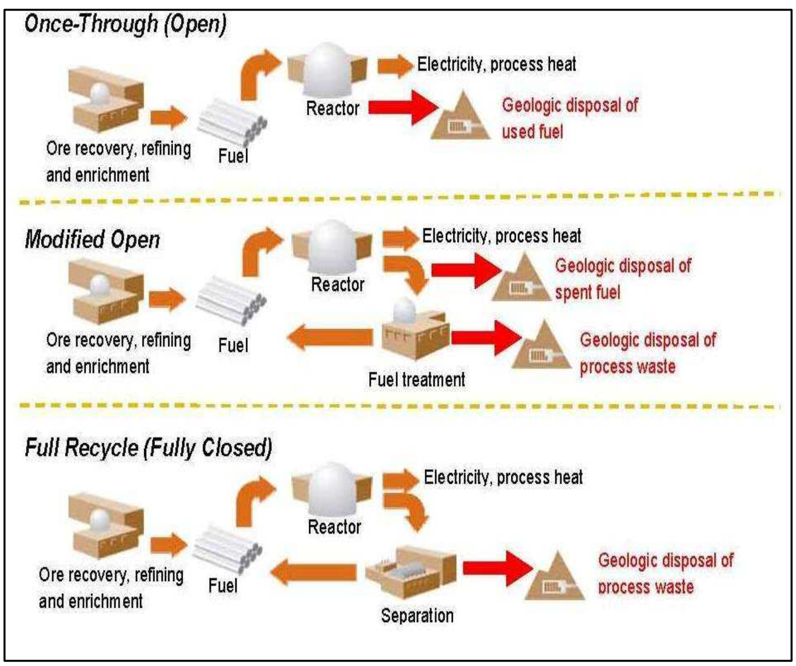


Figure 2. Fuel cycle approaches

In all of these fuel cycle strategies, depicted in Figure 2, new reactor technologies may be introduced that would appreciably alter the sustainability of the strategy. Once the RD&D is sufficiently advanced, perhaps twenty or thirty years from now, decision-makers will have sufficient information to decide which of the approaches are best suited for demonstration. As a target, the DOE-NE RD&D effort is guided by the goal of enabling a national decision to deploy a chosen waste management system by 2050.

II. FUEL CYCLE TECHNOLOGIES

The DOE-NE Office of Fuel Cycle Technologies (OFCT) is investigating future nuclear fuel cycles, in particular sustainable fuel cycles. Work conducted within the OFCT will provide a more complete understanding of the underlying science supporting the development of advanced fuel cycle technologies and provide a sound basis for any future decisions on the U.S. nuclear fuel cycle.

The Mission of the OFCT is:

> *To research, develop and demonstrate options to the current U.S commercial fuel cycle to enable the safe, secure, economic and sustainable expansion of nuclear energy while minimizing proliferation and terrorism risks.*

Sustainable fuel cycle options are those that improve uranium resource availability and utilization, minimize waste generation, and provide adequate capability and capacity to manage all wastes produced by the fuel cycle. The key challenge for the government is to develop a suite of options that will enable future decision-makers to make informed choices about how best to manage the used fuel from reactors. The overall goal is to have demonstrated the technologies necessary to allow commercial deployment of solution(s) for the sustainable management of used nuclear fuel that is safe, economic, secure and widely acceptable to American society by 2050.

To achieve this mission the following objectives have been established:

- In the near term, define and analyze fuel cycle technologies to develop options that increase the sustainability of nuclear energy
- In the medium term, select the preferred fuel cycle option(s) for further development; and
- By 2050, demonstrate the selected fuel cycle options at sufficient scale to enable commercialization

Developing options in each of the three fuel cycle strategies described previously will require development of technologies in eight major critical technical areas (referred to as research pathways). Each of these can also have enabling technologies that will have to be developed. Most of these research pathways apply to all three fuel cycle strategies (even though specific technologies will be different for the different potential options within each of the strategies) but some only apply to one or two of the options. For example, separations technology clearly does not apply to the once-through fuel cycle strategy. The research pathways are:

- Fuel Cycle Systems Analysis
- Fuel Resources
- Fuels Technology
- Separations Technology
- Waste Forms Technology
- Storage, Disposal and transportation
- Transmutation Technology (including advanced reactors)
- Materials, Protection, Control and Accountability Technology

Working in an environment of limited resources and aging infrastructure, a new approach to research and development is being used with new partnerships allied with new methods and new technologies. Taking advantage of recent advances and experiences in government and industry in the use of modeling and simulation (including high-performance computing) and small-scale experiments, the OFCT will conduct goal-driven science-based research and development that integrates theory, experiment, and high performance modeling and simulation to develop the needed technologies. These technologies must exceed current safety and security standards; minimize the long-term environmental and proliferation risks of used fuel, and ultimately support the electric utility industry as they deliver economic electrical power to competitive markets.

A goal-driven, science-based approach is essential to achieving the stated objectives while exploring new technologies and seeking transformational advances. This science-based approach, depicted in Figure 3, combines theory, experimentation, and high-performance modeling and simulation to develop the fundamental understanding that will lead to new technologies. Advanced modeling and simulation tools will be used in conjunction with smaller-scale, phenomenon-specific experiments informed by theory to reduce the need for large, expensive integrated experiments. Insights gained by advanced modeling and simulation can lead to new theoretical understanding and, in turn, can improve models and experimental design. This R&D must be informed by the basic research capabilities in the DOE Office of Science.

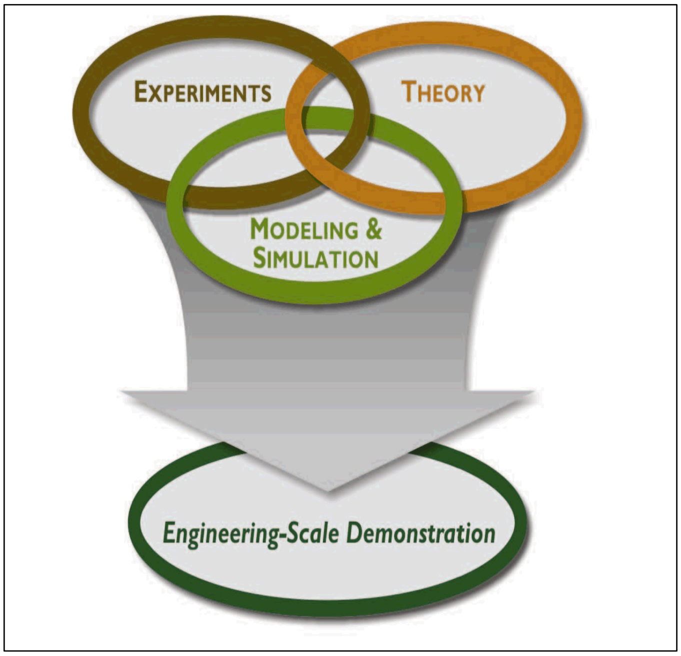


Figure 3. Major elements of a science approach

III. THE USED FUEL DISPOSITION CAMPAIGN

The OFCT has established the Used Fuel Disposition Campaign (UFDC) to conduct the R&D activities related to storage, transportation and disposal.

The Mission of the UFDC is

To identify alternatives and conduct scientific research and technology development to enable storage, transportation and disposal of used nuclear fuel and wastes generated by existing and future nuclear fuel cycles.

The Grand Challenge for the UFDC is:

To provide a sound technical basis for confidence in the safety and security of long-term storage, transportation, and disposal of used nuclear fuel and wastes from the nuclear energy enterprise.

The safe storage, transportation and disposition of used nuclear fuel and/or high level nuclear waste is a fundamental aspect of the nuclear fuel cycle. The United States currently utilizes a once-through fuel cycle where used nuclear fuel is stored on-site in either wet pools or in dry storage systems with ultimate disposal in a deep mined geologic repository envisioned. However, a decision not to use the proposed Yucca Mountain Repository will result in longer interim storage at reactor sites than previously planned. In addition, alternatives to the once-through fuel cycle are being considered as discussed above. These two factors lead to the need to develop a credible strategy for managing radioactive wastes from any future nuclear fuel-cycle in order to provide acceptable disposition paths for all wastes regardless of transmutation system technology, fuel reprocessing scheme(s), and/or the selected fuel cycle. These disposition paths will involve the storing and transportation of radioactive material for some period of time and the ultimate disposal of radioactive waste. As disposition paths evolve from the continuing research and development process, it is important that storage options for fuel cycle materials remain as flexible as possible in order to facilitate selected disposal options.

While considerable progress has been made in the development and optimization of storage systems for managing used nuclear fuel used in the current light water reactor (LWR) fleet, the investment in additional research and development could lead to more robust systems having improved security aspects, resulting in further improvements in the management of LWR used nuclear fuel. The OFCT has been directed to assess such alternative technologies. Advanced transmutation systems will utilize fuels, and possibly targets, that are quite different than LWR fuel. Research will be needed to identify and develop practical storage systems for these materials, leveraging on the experience gained for developing LWR used fuel storage systems.

The disposal of radioactive waste of all classifications (low-, intermediate-, high-level waste, and used nuclear fuel) has been investigated world-wide since the inception of nuclear power. While significant progress has been made regarding disposal, the routine disposal of used nuclear fuel and radioactive waste remains problematic. Experience with the Yucca Mountain Project has illustrated the challenges of siting, characterizing, designing, and licensing a geologic repository. Progress has been demonstrated by the deployment of near-surface disposal facilities for low level waste and the Waste Isolation Pilot Plant for the disposal of defense-related transuranic wastes. However, the capacity for disposing of low level wastes is limited, potential disposal pathways for Greater Than Class C low level waste (which is essentially intermediate level waste) have yet to be identified, and the disposal of used nuclear fuel and high level waste has not been demonstrated. An expansion of nuclear power in the United States, and world-wide, and the closing of the nuclear fuel cycle would increase the amount of all classes of waste and requires the availability of routine disposal pathways.

Recognizing that the current system for managing nuclear waste is viable for several decades, the UFDC has established five near-term objectives and four long-term objectives; in turn, these objectives support achievement of OFCT objectives stated above:

III.A. Near-Term Objectives

1. Provide technical expertise to inform policy decision-making regarding the management of used nuclear fuel and radioactive waste that would be generated under existing and potential future nuclear fuel cycles, in collaboration with the DOE offices of Civilian Radioactive Waste Management and Environmental Management
2. Develop a comprehensive understanding of the current technical bases for storing used nuclear fuel and high-level nuclear waste to identify opportunities for long-term research and development

3. Develop a storage roadmap that provides viable options to long-term storage of used nuclear fuel and high level nuclear waste that incorporates a systems perspective of fuel cycle alternatives
4. Develop a comprehensive understanding of the current technical bases for disposing of used nuclear fuel, low-level nuclear waste, and high-level nuclear waste in a range of potential disposal environments to identify opportunities for long-term research and development
5. Model development for the evaluation of disposal system performance in a variety of generic disposal system concepts.

III.B. Long-Term Objectives

1. Develop a fundamental understanding of the performance of potential storage system concepts over many decades for a variety of used nuclear fuel types and radioactive waste forms based on simulation and experiment.
2. Initiate long-term storage strategies through a small-scale demonstration project that incorporates the technologies identified and developed from the near-term storage objectives.
3. Develop a fundamental understanding of disposal system performance in a range of environments for potential wastes that could arise from future nuclear fuel cycle alternatives through theory, simulation, testing, and experimentation.
4. Develop a computational modeling capability for the performance of storage and disposal options for a range of fuel cycle alternatives, evolving from generic models to more robust models of performance assessment. Ensure Nuclear Energy Advanced Modeling and Simulation (NEAMS) activities are well-integrated so that improved system level models are realized.

Within the OFCT, the UFDC is intimately linked with the Separations and Waste Form Campaign because that campaign is investigating the possible waste forms that could be used to isolate wastes generated under alternative fuel cycles and developing modeling capabilities for their long-term performance in disposal system environments. The UFDC is also linked with the Systems Analysis Campaign by providing that campaign with information for evaluating waste management impacts within fuel cycle system analyses. Lastly, as discussed above, the UFDC will work in collaboration with the Nuclear Energy Advanced Modeling and Simulation program in the development of advanced modeling tools for evaluating disposal system performance.

The UFDC will interface with the DOE office of Environmental Management because there is considerable commonality in issues and needed modeling capability among the three organizations.

The UFDC will collaborate with universities, the U.S. Nuclear Regulatory Commission, and the nuclear industry. Their experience, knowledge, and expertise is essential in establishing future strategies and approaches for the management of nuclear wastes in the U.S.

The management of nuclear waste has also been investigated internationally. A wealth of information and knowledge is available, in particular regarding disposal environments that have not been under consideration in the U.S. for a number of years. The UFDC will participate extensively with international working groups and already collaborates with Japan through a bilateral agreement. Additional international collaborations will be pursued through existing and potential future frameworks.

IV. KEY BARRIERS AND TECHNICAL CHALLENGES

IV.A. Storage

Neither wet nor dry storage systems offer a permanent solution for managing used nuclear fuel or high level nuclear waste. Rather, they are designed to be temporary with plans for the ultimate removal of the material and subsequent disposition (i.e., disposal). The unavailability of disposition options, such as a permanent disposal facility, has resulted in the potential for needing an extended storage period. Dry used fuel storage systems are typically licensed by the U.S. Nuclear Regulatory Commission for a 20-year period, although extended storage for periods of up to 60 years has been licensed. Storage for even longer may be viable, although research and development is needed to determine how long storage may be technically feasible.

Current storage policy is that the status quo is acceptable for long-term storage pending a decision on fuel cycle alternatives and final disposal. This is a reasonable approach based on current economics, a stable regulatory environment, and sufficient land space to expand the on-site storage footprint, as needed. From a longer term strategic perspective, several issues arise that will need to be addressed:

- As UNF continues to be stockpiled in long-term storage, on-site storage space may become limited and there may be a drive to interim storage of UNF at one or more consolidated, independent used fuel storage facilities,
- The NRC is going into rule-making regarding security requirements for UNF storage,
- There is a general security concern regarding this increasing stockpile of stored UNF at many different reactor sites,
- Stranded fuel (i.e., fuel that is stored at shut-down reactor sites) will need to be managed from a more unified perspective, as opposed to the current ad hoc manner, and
- Utilities are going to higher burnup fuels that will require additional safety and security assessments to verify their compatibility for storage under current regulatory and operational regimes, and validation requirements for UNF integrity for shipment after long term storage need to be developed.

IV.B. Transportation

Significant R&D and operational experience exists related to the transportation of LWR uranium oxide (UOX) used fuels. However, higher burnup fuels and advanced fuels developed as part of future fuel cycle options will likely require development of a materials properties database and may require new technologies to support their transportation. The following are the R&D topics associated with Safe and Secure Transportation activities:

IV.B.1 Risk-informed Qualification.

As the nuclear fleet evolves and new fuel types are used, new approaches are possible for cask qualification that would protect the public and possibly be more cost effective. Such approaches would require the development of advanced modeling capability supported by experimental data to predict the response of the shipping cask and its contents to accident conditions.

IV.B.2 Radiological Consequences.

The potential environmental consequences from intentional destructive events on shipping containers require complex characterization, in particular regarding how irradiated fuel will disperse following an attack. Existing R&D has focused on LWR UOX fuels, and much is known about their behavior under these conditions. Additional research is needed, however, for higher burnup fuels and advanced fuels to develop the fundamental data on damage and dispersal phenomena, and scaled-experiments can capture the effects of the coupling of the fuel-clad system. In addition, an evolving threat environment points to the need to improve analytical capabilities to support the estimation of potential consequences resulting from intentional destructive acts. The dynamics and extreme nature of these events dictate the use of unique experiments to support the development and validation of engineering consequence models.

IV.B.3 Secure Transportation.

There is currently no commercial capability in the U.S. to transport Category I and II materials that require enhanced security. The DOE Safeguards Trailer (SGT) has been used on some shipments (e.g., Eurofab MOX fuel) in the U.S. However, the SGT cannot be relied on once routine commercial transport operations are required for Cat I/II shipments. As advanced fuel cycles are evolving in this country, there is a need to begin the development of a commercial capability to ship NRC-licensed Cat I/II nuclear and radioactive materials.

IV.C. Disposal

When considering the safety of disposal systems, the fundamentals of radiation protection are translated to two primary considerations.

- Completely isolating disposed wastes for as long as possible, after which;
- Limiting radionuclide releases to the accessible environment where radiation exposure could occur.

The long-term radionuclide isolation capabilities and characteristics of a waste disposal environment are dependent on the details of the site and the form and contents of the wastes to be disposed.

Geologic disposal concepts are typically complex systems with couplings between the disposed waste, engineered barrier materials, and the natural system. Disposal facilities can be geographically large and the distance over which materials could potentially migrate can be long. Understanding how disposal systems could evolve over very large time scales, considering chemical and physical couplings and large length scales, is somewhat *uncertain. Quantifying this uncertainty, reducing this uncertainty, and propagating this uncertainty through the safety case have been and continue to be the challenge in demonstrating the viability of geologic disposal.

It must be recognized that uncertainty will never be eliminated, or may not even be reduced to a small level, due to the complexity of the disposal systems and the long time frames involved. However, research and development can be completed to understand a disposal system well enough to forecast with reasonable assurance that it would be protective of public health and safety. Research and development focuses on gathering sufficient data (laboratory and field) and the development of computational models such that long-term disposal system performance can be estimated.

V. USED FUEL DISPOSITION RESEARCH AND DEVELOPMENT ACTIVITIES AND GOALS

V.A. Near Term: Five Years

The focus during this period is on the development of the science-based tools for evaluating storage, transportation, and disposal system performance using theory, experiments, and modeling. The tools will aim at understanding the fundamental processes in a variety of disposal environments, relying on information and data currently existing in the United States and international waste management programs. Improvements in storage and transportation systems for used LWR fuel will be explored and developed. Concepts will be developed for storing and transporting used fuels and waste generated from a range of advanced fuel cycles. The objectives for 2010 – 2015 are:

1) *Develop a storage roadmap that provides a systems perspective of alternatives that address safety, security, and flexibility to accommodate the evolution of disposal options*
2) *Develop a plan for a demonstration storage facility*
3) *Develop recommendations for advanced analytical approaches that can be applied to safety and security scenarios for storage*
4) *Identify and develop criteria for verification of fuel integrity prior to shipment after long-term storage.*
5) *Develop a technical basis for licensing transportation systems designed to ship high burnup fuels*
6) *Develop a framework of computational models, validated by experiments, for evaluating disposal system performance*
7) *Develop a "catalog" of potential disposal systems that could be utilized*

V.B. Long Term: Five - Ten Years

The focus during this period is primarily on continued development of the capability for understanding of disposal system performance through modeling and simulation and focused experimentation in the laboratory and field (i.e. underground research laboratories [URLs]). The URLs used will either be existing or constructed in the United States or those that could be accessed through international collaborations (for example, the Japanese, Chinese, and European URLs), or a combination. Storage and transportation concepts for used fuel and wastes for an advanced fuel cycle will be selected and regulatory approval of these concepts will be initiated. The objectives for 2015 – 2020 are:

1) *In collaboration with the DOE Office of Civilian Radioactive Waste Management (OCRWM), field an NRC-licensed storage facility to demonstrate long-term storage capability that addresses strategic goals*
2) *Develop advanced analytical approaches for evaluating storage options based on the five-year recommendations*
3) *Working with DOE and industry, develop a plan to field a commercial-scale long-term interim storage facility*
4) *Complete the technical basis for licensing transportation systems designed to ship high burnup fuels*
5) *Continuation of the development of the modeling capability for evaluating and demonstrating disposal system performance, validated by experiment.*

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