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General Comment

In the last several years, there have been proposals to collocate and integrate reprocessing and repository facilities. The initial assessments suggest multiple benefits: lower costs, lower risks, the possibility of terminating long-term safeguards on the repository, and greater ease in siting a repository. The attached paper is an early description of the potential benefits--more detailed papers will shortly be published.

While the results are preliminary, the results are sufficiently encouraging that the NRC should carefully review any proposed regulatory structure or rule to be sure that it will easily allow the adoption of such an alternative combined fuel cycle facility without the need for new rule making,

Charles Forsberg

Attachments

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Collocation and Integration of Reprocessing, Fabrication, and Repository Facilities to Reduce Closed Fuel Cycle Costs and Risks

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Abstract – *In a closed fuel cycle, spent nuclear fuel (SNF) assemblies are converted into new reactor fuel assemblies and the wastes are emplaced in a repository. The reactor defines the requirements for new fuel assemblies. The requirements for the emplaced wastes include storage, transportation, and repository requirements. It is proposed that reprocessing, fuel fabrication, and repository facilities are collocated and integrated together to enable major reductions in the costs and risks of closed fuel cycles. Collocation and integration of facilities would eliminate waste storage and transport requirements for low-heat waste [All wastes except high-level waste]. This, in turn, removes most constraints on allowable low-heat waste volumes from backend fuel cycle facilities because repositories can be designed to have low disposal costs for low-heat wastes. Changing these requirements may enable simplification of the reprocessing flowsheets, direct solidification of many waste streams rather than further processing wastes to reduce volumes before solidification, use of lower-cost higher-performance waste forms (primarily cement-based waste forms), termination of safeguards for most waste streams, and improved repository performance. Collocation and integration of back-end fuel cycle facilities may also aid the siting of future repositories by creating large financial and employment benefits for communities and states accepting such facilities.*

I. INTRODUCTION

Closed nuclear fuel cycles under U.S. economic ground rules are currently uneconomic [1]. Either uranium prices must dramatically increase or radical changes in closed fuel cycles are required. This paper proposes a radical change in closed fuel cycle design—collocation and integration of reprocessing, fuel fabrication, and repository facilities. Collocation of these facilities can result in economic savings by reducing transportation requirements, common overhead functions from administration to radiation monitoring, and security needs. *While these savings may be significant, a different paradigm is proposed herein.* The reprocessing plant, the fuel fabrication facility, and the repository are integrated together on a single site to enable major simplifications in processing operations, treatment of wastes, and disposal of wastes with resultant reductions in cost and risk.

In a closed fuel cycle SNF is converted into new fuel assemblies for reactors and the resulting wastes are emplaced in a repository. Traditionally about half the costs are associated with each of these activities. The reactor defines the requirements for new fuel assemblies. The requirements for waste management have historically been determined by storage, transportation, and repository requirements. If facilities are collocated and integrated together, the waste storage and transport requirements are drastically reduced or eliminated for all waste streams except the high-level waste (HLW). High-level waste, because of its high decay-heat generation rate, may require storage to reduce radioactive decay heat levels before disposal. For all wastes except the HLW, collocation relaxes the need to minimize waste volumes. Increased waste volume should have little impact on repository costs because repositories are physically limited by heat loads. Underground volume can be inexpensive. Changing the requirements creates new options.

In the context of repository design, there are two waste classes [2]: high-decay-heat wastes and low-decay-heat wastes. High-decay-heat wastes include SNF and HLW. To avoid excessive repository temperatures that can degrade the waste form, package, and geology, high-decay-heat wastes are stored for decades to reduce decay heat before disposal. In the repository these wastes are spread over parallel tunnels to enable decay heat to be conducted from the waste form through the waste package, and through the repository environment to the earth's surface. The strategy herein does not change the treatment or disposal of HLW but does change the treatment and disposal strategy for all other back-end radioactive wastes—the low-heat wastes.

Low-decay-heat wastes can be disposed of in large engineered caverns that have relatively low disposal costs [2]. Relaxing volume requirements enables the use of alternative reprocessing flowsheets that may be more economical but that generate added waste volumes. Major simplifications in waste treatment, solidification, and disposal of low-decay-heat wastes are possible. These wastes include radioactive off gases (tritium, krypton, iodine, and carbon-14), transuranic wastes, miscellaneous low-level wastes, and failed equipment. The use of cement-based waste forms or cement-based materials for encapsulating wastes has proven to be an economically and technically feasible option. This paper examines the option of collocation and integration of all back-end fuel cycle facilities into a single facility.

II. FUEL CYCLE HISTORY

The early experience of cold-war defense SNF reprocessing facilities in the United States with on-site disposal of wastes suggested that reprocessing would be relatively inexpensive. However, methods used to process, store, and/or dispose of wastes at defense sites have led to the need for a large cleanup program [3]. In the early 1970s the Germans proposed to integrate reprocessing, fuel fabrication, and the repository at Gorleben [4] but the concept was not implemented with the decision to not adopt a closed fuel cycle. These early examples suggest that there may be large economic incentives for collocation and integration of backend closed fuel cycle facilities. However, the idea of collocated integrated facilities was never seriously investigated in the United States.

In the 1960s and early 1970s the United States government encouraged a closed fuel cycle and planned that the major industrial facilities would be built, operated, and owned by private industry. Because no repository existed, the option of collocation and integration of backend facilities was not an option. Separated reprocessing and repository facilities resulted in reprocessing flowsheets that were partly selected to minimize waste volumes. Waste forms were chosen with high waste loadings to minimize volumes and thus minimize storage, transport, and disposal costs. Waste form development was separated from repository development.

In the United States a repository may be sited and built before the adoption of a closed fuel cycle; thus, there is the potential option of collocating and integrating together reprocessing, fuel fabrication, and repository facilities. This would be similar to many other industries where industrial facilities generate byproduct wastes, the wastes are locally treated, and the wastes are disposed of on site. The acceptance of the disposal site is partly coupled to the larger benefits of the local industry. For example, coal plants do not ship ash to disposal sites.

The benefits to a community and the state government from a reprocessing plant and fuel fabrication plant are an order-of-magnitude larger than a disposal site. The historical difficulties of siting a geological repository would likely have been reduced if there were 5,000 to 10,000 direct and indirect jobs from reprocessing and fabrication facilities that would be associated with a geological repository.

III. IMPLICATIONS OF REDUCING WASTE VOLUME CONSTRAINTS

Repositories can be economically designed for large volumes of low-heat waste. In this context, there is a need to define large quantities of wastes. A large reprocessing plant processes about 5 tons of SNF per day; thus, the nuclear reprocessing definition of large quantities of waste is very small (tons or tens of tons per day) compared to the chemical plant definitions of waste volumes. If backend facilities are collocated and waste volume is not a controlling factor, a much wider choice of separations process options exist. Some examples can clarify this.

Chemical decladding of SNF. Clad can be separated from fuel materials by mechanical, chemical, or combined methods. Chemical decladding of zircaloy-clad SNF has been done on a large industrial scale for defense SNF at the Hanford site in the U.S using the Zirflex process [5]. However, the higher waste volumes have made chemical decladding non-viable for commercial facilities that ship wastes to repositories. If volumes are not a constraint, chemical decladding of some fuels becomes a viable option with potential reductions in reprocessing plant capital costs and simpler operations.

Processing of high-temperature reactor fuel. In the early 1970s flowsheets were developed for reprocessing graphite-based SNFs where the first step was burning the

graphite—an efficient way to remove more than 90% of the mass of the SNF. However, the resultant carbon dioxide contained high levels of radioactive carbon-14. Experiments [6] demonstrated efficient and low-cost removal of the carbon dioxide from the off gas by scrubbing with calcium hydroxide but this created a high-volume waste stream. That waste stream could be easily solidified in cement and disposed of in an on-site repository. However, such an option is not viable if the waste have to be shipped offsite.

Conversion of oxides to metal fuels. Multiple processes have been partly developed for the conversion of fuel oxides from LWR SNF into metal fuels for fast reactors. The low-cost processes use metals such as magnesium, but the oxide wastes can not be recycled. The processes that can recycle the metal reducing agents have higher costs. The process choices and costs partly depend upon whether there are methods for on-site disposal of wastes.

Aqueous extractants. There are many highly selective extractants that could be used in separation processes but can not be recycled for one reason or another. Some of these use-once extractants could reduce the complexity of reprocessing and fabrication processes—if there are disposal methods for these wastes. In many cases there are such technologies but the waste volumes are increased.

Relaxing waste volume constraints can have major impacts on the size and complexity of waste treatment operations. Several examples can illuminate this point.

Failed equipment. The disposal of failed contaminated equipment is expensive because the equipment must be decontaminated, cut into pieces, packaged, and shipped to disposal sites. If on-site disposal is available, equipment can be placed in large packages (no disassembly), the packages are grouted with a cement-based materials to immobilize radionuclides (physically and reduce radionuclide solubility by chemistry control), and the packages are disposed of on site. Mine shafts and or truck access allow heavy waste packages to be emplaced underground

Volatile fission products. In the 1970s there were major programs in several countries to develop the technologies to capture and immobilize volatile fission products released during reprocessing of commercial spent nuclear fuel. These programs identified and tested many processes and waste forms for krypton, iodine, carbon-14, and tritium; but, most options were rejected because of their low waste loadings—the specific fission products only fitted into a few locations in the molecular structure of the waste form. Relaxing volume restrictions would increase waste form options and enables the use of many previously identified low-cost low-waste-loading waste forms with simplified waste processes. The low waste loadings has other benefits, it slows the diffusion rate of radionuclides from the waste form.

An example is krypton containing ^{85}Kr. This gas with a 10-year half-life can be stored in pressurized cylinders; however, there are significant safety advantages of storing krypton on a solid [7-8] because it avoids the possibility of rapid release if there is a leak in a gas cylinder. The solid absorber options with high waste loadings are expensive. If high waste volumes are acceptable, there are low cost absorbents.

Tritium control. Tritium control is a major issue in aqueous reprocessing plants. Much of the tritium can be removed as water in front-end processes such as voloxidation where it is removed from the off-gas stream as a concentrated waste. However some tritium enters dissolver. Water is recycled within the plant but recycling increases the concentrations of tritium in recycle streams and thus creates the potential for higher radiation doses to the work force and greater releases to the environment. With relaxed waste volume constraints, more tritiated water can be sent to waste. This reduces the equipment required for recycle, the buildup of tritium and other impurities in recycle streams, and plant tritium inventories.

Increasing waste volumes has the potential to improve repository performance by several mechanisms.

Isotopic dilution for solubility-limited radionuclides. The release rates of many radionuclides from a repository are limited by the solubility of the specific radionuclide in groundwater. If the specific radionuclide is diluted by a factor of a thousand with the non-radioactive isotopes of that element, its concentration in groundwater is reduced by a factor of a thousand which should lead to a commensurate reduction in radionuclide releases to the environment. Isotopic dilution is the most direct way to improve repository performance for solubility-limited radionuclides.

For example, radioactive carbon-14 can be removed from reprocessing off gas streams by scrubbing with calcium hydroxide to create calcium carbonate [6]. The calcium carbonate can be incorporated into cement with non-radioactive calcium carbonate. Because the actual mass of most radioactive isotopes in SNF is small, high isotopic dilution factors are possible ($>10^3$). The same can be done for other isotopes such as iodine by isotopic dilution with nonradioactive iodine and conversion into a barium iodate [9] in a cement matrix or other forms with low groundwater solubility.

Reduced waste-form radiation damage. Waste forms with high concentrations of radionuclides can be degraded by (1) long term radiation damage to the waste form and (2) change in the chemical composition of the wastes caused by the decay of radionuclides into different elements. Both effects are reduced by using waste forms with low waste loadings. Increasing volumes by a factor of ten reduces the cumulative radiation dose to the waste form per unit volume by a factor of ten. Low waste loadings can reduce or eliminate concerns about waste form radiation damage over time.

Termination of safeguards. If wastes contain significant quantities of plutonium and other fissile materials, there can be long-term safeguards concerns. However, dilution of wastes with small quantities of fissile materials can make such fissile materials "not practically recoverable" [10-11] and safeguards can be terminated before disposal. Required levels of dilution in cement and other waste matrixes have been defined [12-13] for termination of safeguards. For the type of facilities described herein, the fissile material concentrations would be diluted far below these limits.

Collocation and facility integration has potential safety benefits. Since the Bhopal chemical accident in India, there has been a revolution in chemical plant safety philosophy. The emphasis is on (1) minimizing in-process inventories of hazardous materials and (2) rapid conversion of hazardous materials to chemically stable (non-combustible), non-dispersible, insoluble forms. Potential accident consequences depend upon the inventory of potentially mobile radioactive materials. The proposed strategy herein may maximize implementation of this chemical engineering safety strategy to reduce risks and occupational radiation exposures.

IV. WASTE FORMS AND PROCESSING

The primary waste forms for an integrated reprocessing, fuel fabrication, and repository system are cement waste forms for cost and performance reasons. The last decade has seen the development of multiple low-cost, high-performance cements where inorganic additives control the internal bulk pH, control the redox potential, and absorb specific radionuclides [14-17]. The control of cement chemistry enables its wide use as (1) a waste form for many different types of waste and (2) the matrix material to create the appropriate geochemical environment to minimize the release of radionuclides from embedded waste forms. For many radionuclides (tritium, carbon-14, etc.) the cement is the waste form. For other wastes (krypton, iodine, etc.) the cement is the matrix that controls the local geochemical environment for the waste form to minimize radionuclide solubility, radionuclide diffusion, and minimize groundwater flow through the wastes. The processing of cement is as important as the chemistry. There are multiple processing options.

- *Grout in place.* In the 1960s and 1970s Oak Ridge National Laboratory disposed of its liquid radioactive wastes by cement hydrofracture [17, 18]. About 1.5 million curies were disposed of. Specially formulated cements were mixed with liquid waste and slurries. The mixture was pumped underground into a shale formation and solidified in place. The process was remarkably cheap—a few dollars per gallon of waste. The technology worked but there were operational failures. The technology would be simplified and most drawbacks eliminated by pumping the grout into engineered silos within the repository.

- *High viscosity mixers.* Cement processing technologies such as high viscosity mixers [16] enable the processing of wastes that could not previously be incorporated into cements and avoid additives (set retarders, viscosity reducers, etc.) that are often added to improve cement processability but that can degrade long-term waste performance. The waste form would be in containers for disposal

- *Steam curing and chemical processing.* Special cement formations have been developed to solidify transuranic and high-level wastes by use of special formulations and steam curing of the cement [19, 20]. Steam curing removes excess unbonded water from cement and accelerates chemical reactions to produce a highly stable waste form. Steam curing is commercially used to produce prefabricated cement beams and other highly engineered components. When applied to radioactive waste forms the elimination of unbonded water can effectively eliminate gas generation. It is not fully understood if this is a consequence of much lower radiolysis rate of bonded water in the cement structure or faster recombination rates. The higher processing temperatures can be used to destroy selected chemicals within the waste form. In effect, the waste solidification process can be used as a waste treatment process to change waste form chemistry.

The strategy herein is a reversal of the 40-year strategy for development of waste forms. Historically waste form goals have been (1) good performance and (2) high waste loadings. High waste loadings were required to minimize waste storage and transport costs. The goals

herein are high waste performance and minimization of the cost of the backend of the fuel cycle—but no requirement for high waste loadings. This implies changes in waste forms with a major emphasis on cement waste forms. Fortunately new developments in our understanding of cements may enable the qualification of such waste forms for disposal [21, 22].

V. REPOSITORY DESIGN FOR LOW-HEAT REPOSITORIES

While there is no operating geological repository for SNF or HLW, there are operating geological repositories for the disposal of transuranic and chemical wastes (Table 1). The first operating geologic repository in the world was the Herfa Neurode repository for chemical wastes in Germany [23]. Many of the chemical wastes are heavy metals that remain toxic forever. Since then, additional geological repositories have opened elsewhere in Europe for chemical wastes. The first repository for long-lived radioactive wastes was the Waste Isolation Pilot Plant (WIPP) in New Mexico [24]. WIPP is designed for low-heat transuranic wastes—primarily plutonium-contaminated wastes. The designs of WIPP and Herfa Neurode are similar. Both are located in salt. The WIPP facility is relatively small reflecting the small quantities of wastes to be disposed of. In contrast, Herfa Neurode has a disposal rate per year that approaches the lifetime capacity of WIPP.

TABLE 1
Operational Geological Repositories

Repository	Chemical	Radioactive
Facility	Herfa Neurode (Germany)	Waste Isolation Pilot Plant (U.S.)
Operational	1975	1999
Capacity	200,000 tons/y	175,570 m^3 (~ 350,000 tons)
Hazard Lifetime	Forever	>10,000 years

There are other operational high-volume underground facilities for the disposal of radioactive wastes. In 1988 Sweden opened the *Final Repository for Short-lived Radioactive Wastes* (SFR) facility [25] for low and intermediate level radioactive wastes. It is located under the Baltic seabed in granite about a kilometer off the Forsmark Nuclear Power Plant site with access by tunnel. Low activity wastes are disposed of in large mined caverns while higher activity wastes are disposed of in concrete silos with bentonite clay barriers between the silos and rock (Figure 1). Silo diameters are ~26 meters with heights of ~50 meters. Waste packages up to 100 tons in weight are placed in silos. A cement grout is used to create monolithic structures with low water permeability. The low surface to volume ratio minimizes the groundwater that can contact the silo and the wastes in the silo. The silos are high-performance packages for disposal of high-volume low-heat wastes.

Silo construction minimizes groundwater flow and thus radionuclide release into the groundwater. However, underground silos for reprocessing and fuel fabrication wastes must also be designed as geochemical waste packages. The composition of the cement and aggregate must be chosen to minimize radionuclide releases [14-16] by control of internal bulk pH, controlling the redox potential, and the absorption of specific radionuclides. This is not a new concept. The Waste Isolation Pilot Plant, a repository primarily for plutonium wastes, places magnesium oxide around the waste packages to reduce the solubility of plutonium and thus reduce the potential for release of plutonium from the repository [26]. The choice of additives depends upon the wastes and the local geology.

Other designs for underground radioactive waste monoliths have been investigated [27] including active cooling coils embedded within such monoliths to enable cooling up to several decades. The setting and curing of cement generates heat that can overheat the cement if very large monoliths of cement are poured. Since the construction of the Hoover Dam in the 1930s, civil engineers have incorporated cooling tubes in many large concrete dams to control temperatures during the cement curing process This eliminates any size limit for a cement pour. The more recent alternative is to modify the cement formulation to minimize heat from cement curing. This is a workable strategy but the use of cooling coils does allow a wider choice in cement compositions.

Cooling coils enable cooling of low-heat wastes for several decades if there is significant heat generation from short-lived radionuclides (tritium, krypton, etc.). The concentrations of such radionuclides in waste depend upon the time between discharge of SNF from the reactor and reprocessing the fuel. The capability to cool such monoliths assures no need to store such wastes before disposal. In this context, dilute wastes imply low heat generation rates per unit volume that, in turn, implies that any cooling system can have a failure and it will be months before there is a significant increase in local temperatures—time sufficient for any maintenance operations.

VI. INSTITUTIONAL STRUCTURES

The collocation and integration of reprocessing, fuel fabrication, and repository facilities change the

institutional structure of the backend of the fuel cycle. It would support the siting of geological repositories because a community accepting the repository would also receive other future backend facilities with large beneficial tax and long-term employment impacts. Many more people are associated with the operation of reprocessing and fuel fabrication plants than with a geological repository. However, for such an option to be credible to the local community and state government accepting a repository, there must be a credible case that collocation and integration does provide major economic and risk reduction benefits to facility owners. Thus, if the nation adopted a closed fuel cycle in the future the reprocessing and fabrication plants would be collocated and integrated with the repository.

Collocation and integration of closed fuel cycle facilities may have non-proliferation implications. One option to strengthen the non-proliferation regime would be for the major nuclear suppliers to take-back the SNF. In practice, if the major nuclear states took back SNF from the smaller counties, the impact on the large waste programs would only be about a 20% increase in SNF to manage by these programs [28]. That has not occurred because domestic opposition. The collocation strategy could help repository acceptance and enable adoption of a take-back policy by the major nuclear powers.

The direct and immediate disposal of wastes from reprocessing and fuel fabrication would (1) eliminate risks from long-term storage and transportation of wastes [excluding HLW that may require storage to reduce decay heat loads before disposal], (2) reduce plant risks by process simplification and reduction of in-plant waste inventories with just-in-time disposal, and (3) prevent the existence of legacy wastes as has occurred at many defense production sites in the United States, Great Britain, and Russia.

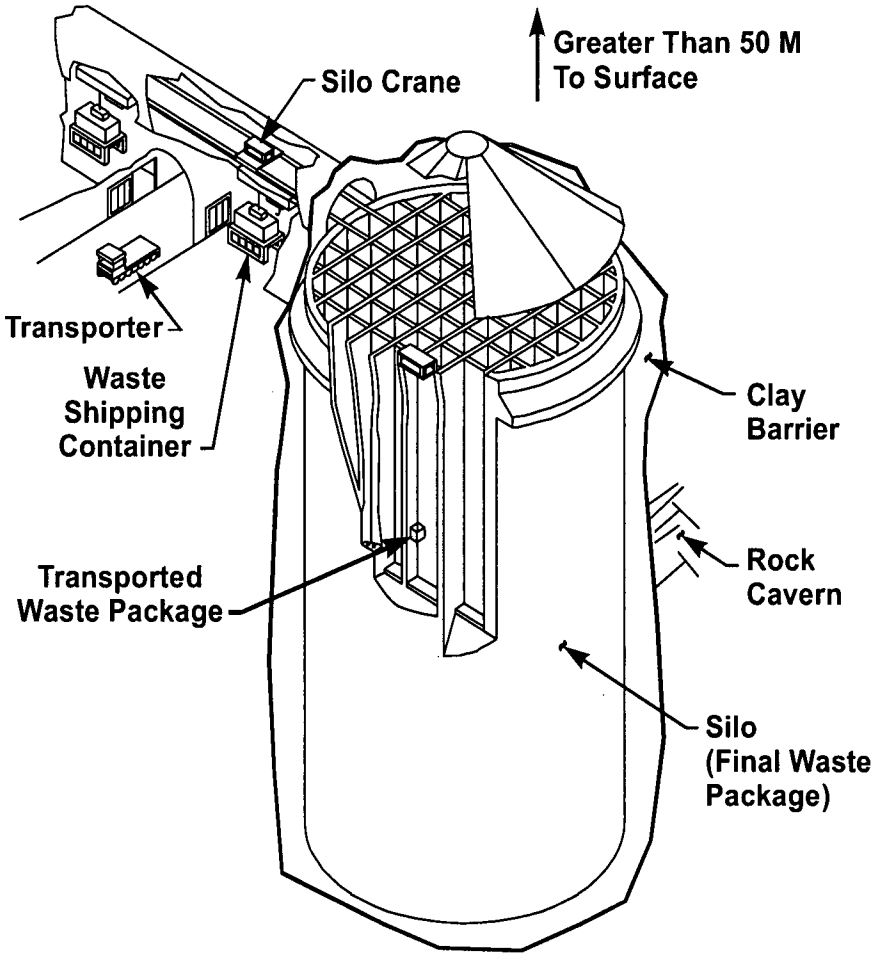

Fig. 1. SFR Silo Facility for Intermediate-Activity Wastes

VI. CONCLUSONS

Closed nuclear fuel cycles are uneconomic today in the United States. Major changes are required if costs are to be significantly reduced while reducing risks. One unexplored option is the collocation and integration of reprocessing, fabrication, and repository facilities. This option requires rethinking the technology, organization, and institutional structure of the back end of the fuel cycle. There are credible reasons to believe major cost savings and major reductions in risk are possible.

Collocation may reduce the challenges of siting a repository by creating large community and employment benefits from back-end facilities for communities and states accepting a repository. The potential gains and costs have not been quantified. The outlines of such a system have been identified and some of the key technologies have been identified. However much remains to be done to determine the viability of this option.

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Rulemaking Comments

From: Gallagher, Carol
Sent: Friday, July 08, 2011 8:17 AM
To: Rulemaking Comments
Subject: Comment letter on Potential Rulemaking
Attachments: NRC-2010-0267-DRAFT-0003.pdf

Van,

Attached for docketing is a comment letter from Charles Forsberg on a Potential Rulemaking on Spent Nuclear Fuel Reprocessing Facilities (76 FR 34007) that I received via the regulations.gov website on 7/7/11.

Thanks,
Carol