Programmatic Assessment of RG-MOX Utilization Following Participation in the DOE Surplus Plutonium Disposition Program

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Abstract: EPRI is building a suite of tools for assessing nuclear fuel cycle options based on a platform of software, simplified relationships, and explicit decision-making and evaluation guidelines. This paper summarizes an example of an assessment from a utility perspective regarding continuing MOX utilization with commercial reactor-grade mixed-oxide fuel (RG-MOX) following successful utilization participation in the DOE Surplus Plutonium Disposition Program. This assessment reflects potential opportunities and problems based on topic familiarity and the perspective embedded in the scenario definition, as follows: (1) economic considerations will represent a primary driver for utilities operating in the U.S. commercial environment, and (2) back-end management issues must be flagged due to the number and magnitude of constraints in used-fuel management at U.S. nuclear plants for both wet and dry storage (and the important interface between them). While economic considerations are seen as the primary utility decision drivers with respect to RG-MOX use under the stylized conditions defined here, this assessment also showed that technical waste management issues could be showstoppers if not adequately resolved.

Keywords: PgRA, LWR, MOX Fuel, Advanced Nuclear Fuel Cycles.

1. INTRODUCTION

To address challenges and gaps in nuclear fuel cycle option assessment and to support research, develop and demonstration (RD&D) programs oriented toward commercial deployment, EPRI is seeking to develop and maintain an independent analysis and programmatic risk assessment (PgRA) capability by building a suite of assessment tools based on a platform of software, simplified relationships, and explicit decision-making and evaluation guidelines. The assessment tools support a decision analysis framework. The framework is intended to support and facilitate:

- Clear delineation of the issues associated with a fuel cycle option and the requisite activities needed to achieve a nuclear fuel objective.
- References to source material (e.g., reports, peer-reviewed manuscripts, and expert knowledge) to provide clear pedigree for inputs.
- Assignment of a readiness or “favorability” Figure of Merit (FOM) of an option and its uncertainty, reflecting the state of knowledge upon which the assessment is based.
- Ability to record the reasoning for each evaluation such that the overall basis for a decision path can be accessed and assembled in a summary report format.
- Identification of actions needed to address gaps in the state of knowledge, needed research, additional infrastructure, and regulatory and licensing requirements.

The framework provides a method for assembling and structuring available and relevant information for transparent, auditable assessments. It provides a structured, phased approach to evaluating or comparing nuclear fuel cycle options based on the level of detail desired and the amount of information available (Figure 1). The strategic assessment (Level 1) evaluates the alignment of the “what is being proposed and why” with strategic objectives whose satisfaction is of primary

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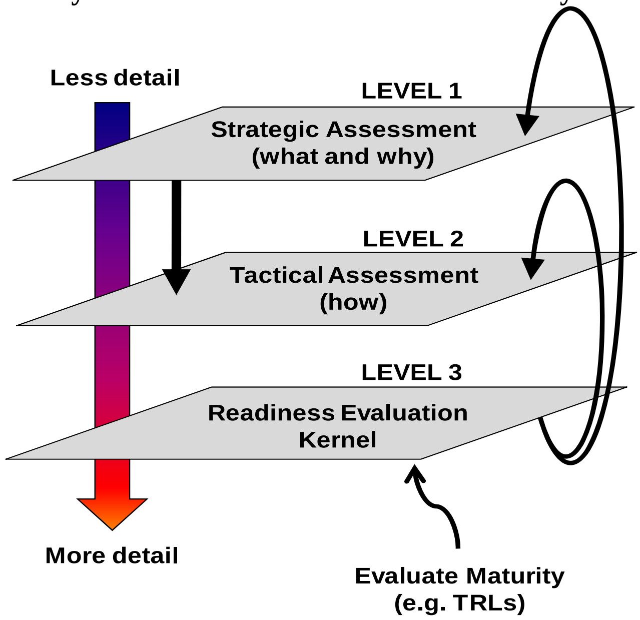
importance. For its nuclear fuel cycle options assessment work, EPRI has selected five criteria: Resource Utilization, Proliferation Resistance and Security, Waste Management, Fuel Cycle Safety, and Economic Competitiveness. EPRI Report 1025208 [1] defines and describes application of the decision framework in detail and provides a more complete listing of references in a preliminary evidence database format.

Figure 1: Basic Layered Structure of EPRI Decision Analysis Framework



At the initial stages of such an assessment, the metrics can be quite broad. For this type of assessment, qualitative figures of merit provide a reasonable categorization of assessment results (i.e., favorability) and uncertainty; i.e., confidence. A simple three-color scheme of red, yellow, or green is used to display the evaluation results in summary fashion. In general, the colors convey common interpretations of the suitability and/or difficulties of proceeding with the proposed program. In the context of this assessment, the specific meanings of the color scales are summarized in Table 1.

Table 1: Assessment Metrics and Guidelines for Their Use

Figure of Merit	Framework Element		
	Level 1	Level 2	All Levels
	Alignment with Strategic Objectives	**Favorability with Respect to Overcoming Barriers and Challenges**	**Confidence in Assessment**
ALERT	Option is either not aligned with strategic criteria or represents a critical condition, requiring resolution, clarification, or further evaluation.	Option difficult to implement. Actions required to address barriers.	Low level of confidence in basis for assessment. Actions required to increase confidence.
CAUTION	Option possibly not aligned with strategic criteria. Evaluations during Level 2 assessments should identify barriers and their significance.	Option challenging to implement. Actions should be considered to reduce barriers.	Some uncertainty in basis for assessment. Possible conflicting evidence. Actions should be considered to increase confidence.
SUITABLE	Option aligns with strategic criteria. No additional evaluation is needed.	Option can be implemented.	High level of confidence in basis for assessment. No additional evidence required.

This paper summarizes an example of an assessment from a utility perspective regarding continuing MOX utilization with commercial reactor-grade mixed-oxide fuel (RG-MOX) following successful utilization participation in the DOE Surplus Plutonium Disposition Program. It was selected because existing nuclear plants participating in this program will have gained the capability and experience for the utilization of MOX fuels. Therefore the programmatic issues involved in extending the use of MOX via the procurement of RG-MOX presented an opportunity to exercise and test the framework on a reasonable well defined question. The following sections summarize the assessment accomplished in EPRI Report 1025208 [1].

2. STRATEGIC ASSESSMENT

The first stage in applying the EPRI Decision Analysis Framework involves the assessment of alignment of the RG-MOX use scenario against the five strategic criteria (introduced above) that EPRI has adopted for its nuclear fuel cycle assessment work. Ratings may be based primary on documented evidence. The EPRI framework is supported by an evidence database, and documents and citations are linked to each evaluation. In addition, expert judgments and opinions incorporated into the assessment can and should be documented in the evidence database for transparency and future review. The strategic assessment not only evaluates the alignment of with strategic criteria, but also provides insight into which criteria could present significant barriers to implementation of the program.

The EPRI team judged that the successful utilization of WG-MOX over the duration of the DOE Surplus Plutonium Disposition Program provided adequate confidence that the strategic objectives of Resource Utilization, Proliferation Resistance and Security, and Fuel Cycle Safety can be met with RG-MOX. The option does not conflict with the sustainability criterion. At any time a utility has an option to return to use of UOX and there is clear evidence that there is an ample supply of natural uranium and manufacturing capacity for UOX fuel. Proliferation Resistance and Security and Safety are not impacted by implementation of the option at the utility and plant level. These issues are assumed to have been evaluated and found acceptable in preparation for and subsequent utility participation in the DOE SPD program, and any external, higher-level concerns, such as non-proliferation policy considerations, lie outside the scope of this assessment. No additional issues and requirements have been identified with the continued use of MOX. Accordingly, these three criteria were screened out from further evaluation. Two strategic issues,

However, Table 2 shows the strategic assessments of Economic Competitiveness and Waste Management revealed considerable uncertainty (red confidence findings) and significant concern regarding problems associated with the long term use of RG-MOX fuel (yellow and red alignment/favorability findings) to warrant a tactical assessment of technical and programmatic issues in these two areas.

The next section summarizes those results and discusses how the evidence evaluated by the EPRI team that conducted the assessment contributed to these results.

Table 2: Results from Level 1 Strategic Assessment Indicating Non-Alignment of Fuel Cycle Option with Criteria

Criterion	Assessment FOM	Confidence FOM	Basis	Result
Economic Competitiveness	ALERT	LOW	RG-MOX fuel cost relative to UOX expected to be the primary commercial decision driver. Substantial cost savings for plant modifications and upgrades will be realized from WG-MOX program participation. However, costs associated with continued MOX use and storage require evaluation. Discounted or incentivized RG-MOX fuel purchases could offset these other costs.	Level 2 assessment on costs for fuel procurement, waste management, O&M, etc.
Waste Management	CAUTION	MEDIUM	Greater decay heat and higher neutron dose rates for used RG-MOX (vs. UOX and WG-MOX) may have significant impacts for onsite wet and dry storage with continued MOX use beyond limited WG program unless arrangements for early offsite transport are provided.	Level 2 assessment on wet and dry storage challenges and barriers

3. TACTICAL AND PROGRAMMATIC ASSESSMENTS

The more detailed assessments of Economics and Waste Management issues are summarized in the following two subsections. Space limitations prevent the inclusion of all assessment here.. Findings indicating significant concerns regarding favorability (yellow or red) or low confidence (red) for technical Waste Management issues are summarized in Reference [2]. The scope and approach used to accomplish all assessments are documented fully in Reference [1].

3.1. Assessment of Economic Competitiveness

The economic competitiveness of continuing MOX utilization with RG-MOX fuel assemblies involves offsetting the potential increased cost of operating the plant with MOX fuel against the savings that can be achieved through a smaller cost of MOX fuel assemblies or incentives that produce savings in other areas. As these benefits are not yet known and purely speculative, the tactical assessment focuses on the increased costs that would accompany the continued utilization of RG-MOX fuel after a limited period of WG-MOX use under the DOE SPD program. At this preliminary stage it focuses on identifying and characterizing the additional requirements associated with MOX operations and identifies potential follow-on action items to pursue.

For this initial assessment example, the following simple breakdown of nuclear electricity generation, or total cost of electricity, is adopted. It consists of

1. Capital Costs
2. Fuel Procurement (i.e., front-end services)
3. Operation and Maintenance (O&M)
4. Cost of Waste Management (i.e., back-end services)

The first cost category area (i.e., capital expenditures for construction and major equipment upgrades) is excluded from this assessment. The capital expenditures necessary to accommodate WG-MOX fuel cycles are treated as sunk costs, and those modifications are assumed to be sufficient to permit the plant to continue operations with RG-MOX fuel. The other three cost categories, fuel procurement, O&M, and waste management, are examined further in the Level 2 tactical assessment.

3.1.1. Fuel Procurement

Fuel procurement addresses the potential differences in costs for fuel and associated services to support operation on partial (nominally 35%) RG-MOX cores versus the reference case of a return to 100% UOX. This includes the following considerations and activities:

- Fuel procurement cost of both RG-MOX and UOX fuel assemblies needed for the fuel cycles in which RG-MOX will influence the core load.
- Additional core design engineering and analysis needed to support partial MOX core loadings and operation.
- Changes to new fuel acceptance and inspection procedures to protect personnel from the increased radiation field emitted from assemblies containing recycled Pu.
- MOX parity with UOX in terms of fuel burnup and core design and management. Disparities between maximum burnups licensed for UOX fuel and MOX limits core design flexibility and fuel utilization, resulting in additional cost burdens in terms of fuel procurement and heterogeneous core management.

Table 3, reproducing Table 5-5 of [1] summarizes an initial assessment of the costs associated with the purchase and utilization of RG-MOX fuel, and Table A-3 of Appendix A of [1] contains citations contains the relevant citations cited in the table. In order to be cost competitive, a reduction in the cost of RG-MOX fuel procurement relative to UOX will likely be required to offset any additional costs that arise from all the requirements that must be implemented to operate the plant.

3.1.2. Operations and Maintenance

The operations and maintenance category accounts for the cost impact of additional requirements imposed on plant personnel to support plant operations with RG-MOX fuel. As used WG-MOX will already be present in the spent fuel pool (SFP) and onsite independent spent fuel storage installation (ISFSI), only the differential costs associated with the use of RG-MOX fuel are considered. The issues identified in this assessment include:

- O&M of systems required exclusively for the safe operation of the core containing RG-MOX.
- Changes to radiation protection programs in terms of additional personnel, equipment, training, and monitoring to meet radiation protection objectives for plant personnel.
- Additional procedures and activities to ensure regulatory compliance for plant operations with RG-MOX.
- Material degradation and aging management activities needed to monitor and mitigate potential impacts of RG-MOX use on the integrity and performance of systems, structures and components within the plant. These issues will need to be reflected in the aging management plan and may require mitigation.

Table 4, reproducing Table 5-6 of [1] summarizes an initial assessment of the additional costs associated with operations and maintenance with RG-MOX fuel, and Table A-5 of Appendix A of Reference [1] contains the relevant citations cited in the table. Use of RG-MOX is expected to incur costs associated with WG-MOX operations plus any additional costs, but the anticipated experience with WG-MOX provides high confidence that they can be controlled.

3.1.3. Costs Associated with Waste (Used Fuel) Management

Used Fuel Management addresses the additional costs of safely handling and storing the additional RG-MOX that will be discharged from the reactor. Issues selected for consideration include:

- Criticality control, which includes the costs of measures to ensure that criticality margins are maintained during all aspects of used fuel handling and storage.
- Heat load management, which addresses the costs associated with ensuring that used fuel remains within its thermal limits under all storage conditions.
- Radiation protection, which encompasses the cost of worker protection associated with the increased radiation from used MOX fuel assemblies.
- Dry storage, includes both the incremental cost of dry storage cask and canisters (DSC) capable of storing RG-MOX, loading and transport operations, in addition to ISFSI activities needed to meet the first three requirements.

Table 5, reproducing Table 5-7 of [1], summarizes the issues that could drive cost penalties associated with the management of used RG-MOX. Table A-4 of Appendix A of [1] contains the relevant citations cited in the table. Although there may be some increase in cost associated with reviews of criticality margins and radiation protection support, the economic issue flagged as being of greatest concern (red) relates to the additional costs incurred due to the impacts of greater cooling times for RG-MOX on the ability to offload fuel to dry storage in a manner compatible with the used fuel management requirements, such as maintaining full core reserve.

Table 3: Assessment of Fuel Cost Issues Associated with Use of RG-MOX Following Completion of the U.S. DOE SPD Program

Issue	Assessment FOM	Confidence FOM	Basis	References	Follow On Actions
Fuel Procurement Cost EC_FUEL01	ALERT	LOW	Fuel costs represent the primary economic (and likely overall) driver. Procurement of RG-MOX will need to be discounted relative to UOX or otherwise incentivized to offset other additional costs and "hassle". Future price of uranium and front-end services are highly uncertain, although natural U supplies remain adequate for next 50–100 years. Fuel costs are ultimately subject of proprietary commercial arrangements; external predictions of market characteristics are therefore speculative.	OECD-IAEA Redbook 2009 - 2	Monitor UOX cost projections.
Core Design Analysis EC_FUEL02	SUITABLE	HIGH	MOX fuel introduces heterogeneities that must be addressed in designing and controlling the reactor. Experience with WG-MOX will demonstrate that this can be done, but the effort and cost will likely be greater than that required for a full UOX core.	EPRI 1018896 - 31 ORNL TM-13421 - 1	None.
New Fuel Acceptance EC_FUEL03	SUITABLE	HIGH	Fresh RG-MOX assemblies exhibit higher dose rates relative to fresh UOX fuel, but these increases are relatively modest. Radiation protection measures will increase costs associated of the acceptance and inspection. However, once a suitable area and process is established to accomplish the required inspections, the impact should be minor and definable compared to other costs.	EPRI 1018896 - 34	Estimate cost of plant modifications (if any) and procedures needed to meet ALARA requirements.
MOX Parity EC_FUEL04	CAUTION	HIGH	Generally lower burnup limits for MOX do not align with industry trend toward higher fuel burnup. French plants operating on MOX were pursuing MOX/UOX equivalency, but the applicability to U.S. operations is doubtful. The Caution ranking reflects the challenge of achieving MOX parity, especially with respect to U.S. licensing.	EPRI 1018896 - 10 EPRI 1018896 - 49 IAEA TRS415-38 IAEA TRS415-39	Track progress with MOX utilization and it equivalency for fuel cycles expected to be used in the U.S.

Table 4: Assessment of Operations and Maintenance Costs Associated with Use of RG-MOX

Issue	Assessment FOM	Confidence FOM	Basis	References	Follow On Actions
O&M of systems needed only for MOX EC_OM01	CAUTION	HIGH	The principal additional O&M burden from MOX operation appears to be the use of enriched boric acid systems for reactor control and shutdown margin. Such systems incur additions costs due to required O&M resources, active monitoring, and routine replenishment of ^{10}B but may also produces benefits that could reduce O&M burdens.	EPRI 1003124 (multiple citations)	**Evaluate enriched boric acid systems further with appropriate readiness (Level 3) assessment** (See Table 5-8)
Radiation protection EC_OM02	SUITABLE	HIGH	Additional radiation protection actions may be required for the handling of fresh and used RG-MOX fuel assemblies. Accordingly, additional costs will be associated with radiation protection and fuel handling; however, these costs are definable and likely to be manageable.	ORNL TM-13421-3 EPRI 1018896-34 EPRI 1025206-2	Estimate costs of maintaining the occupational dose for RG-MOX operation.
Procedures and licensing EC_OM03	SUITABLE	HIGH	Except for the additional enhanced decay heat and radiation from used RG-MOX verses WG-MOX, it is anticipated any licensing requirements will bounded by licensing for WG-MOX use or their implementation will be relatively straight forward.	EPRI 1021048-6	Estimate costs of any additional analyses and reviews to support licensing and regulatory compliance.
Material degradation monitoring and aging management EC_OM04	CAUTION	HIGH	Increased embrittlement of reactor pressure vessel due to hardened neutron flux is a concern for economic life of plant but is considered to be manageable; e.g., via interior placement of MOX assemblies in core. Such considerations will have been taken into account for finite WG-MOX operation period, but continued operation on RG-MOX may warrant review.	ML993620025 – 3 (NRC, 1999)	Review core design and plant aging management plan and update if necessary to account for any changes for RG-MOX operation

Table 5: Assessment of Used Fuel Management Cost Issues Associated with Use of RG-MOX

Issue	Assessment FOM	Confidence FOM	Basis	References	Follow On Actions
SFP criticality control EC_WM01	SUITABLE	HIGH	Criticality calculations and precautions necessary to maintain sub-critical limits should not be significantly different from UOX. There may be additional restrictions and requirements for absorber materials, but these should be manageable using existing technologies and practices. Any differences should be bounded by the WG-MOX experience.	EPRI 1018896-38	None at this time.
SFP thermal management EC_WM02	CAUTION	HIGH	Continued use of MOX fuel will require the SFP cooling systems to support a greater heat removal capacity over a longer duration than if operations returned to exclusive UOX use. The ability to transfer used fuel to dry storage may be impacted by greater inventories of RG-MOX fuel that remains hotter longer relative to used UOX and WG-MOX.	EPRI 1018896-35 EPRI 1021048-14 EPRI 1025206-13 ORNL/TM-2011/290-4	Determine the maximum heat load the existing system can safely accommodate without additional capital expenditures.
Radiation protection for fuel receipt and back-end EC_WM03	SUITABLE	HIGH	Used RG-MOX yields higher neutron fields than UOX. This may require additional radiation protection measures and the costs associated with them. These costs, however, are well-understood and should be relatively minor.	EPRI 1018896-38 EPRI 1025206-15 to 18	None at this time.
Dry storage system procurement and management EC_WM04	ALERT	MEDIUM	Dry storage systems can be designed for higher heat loads from MOX, and existing systems can be adapted for use with MOX. These options will incur greater costs than for UOX due to design modifications for increased heat removal or reductions in loading capacities. While dry storage of MOX is a mature technology internationally, the potential disruption to a U.S. utility's used fuel management practices and changes in DSC designs and unit costs indicate the need for adequate review and preparation.	EPRI 1025206-12 EPRI 1021048-3	DSC and ISFSI design modifications should be considered as part of integrated back-end used fuel management approach.

3.2. Assessment of Technical and Programmatic Waste (Used Fuel) Management Issues

The Level 2 Waste Management assessment addresses the safety, O&M and licensing impact of introducing used RG-MOX fuel assemblies into the back-end infrastructure of an operating plant. Two distinct phases of waste management follow the progression of handling used fuel at the plant: wet and dry storage.

Wet storage addresses the period from discharge from the reactor vessel through the total time of storage in the spent fuel pool. Dry storage begins with closure and drying following transfer of fuel to a dry storage canister (or cask) and prior to transfer to an onsite ISFSI. These two phases define appropriate distinct stages for consideration and evaluation. Only on-site used fuel management is considered in the present example.

3.2.1. Tactical Assessment of Wet Storage

Key issues for wet storage consideration include:

- What are the implications for spent fuel pool management strategy and planning?
- What are the implications to on-going operation and maintenance activities, procedures, training and costs?
- Are any new criticality issues introduced?
- Are existing cooling mechanisms adequate (spent fuel pool cooling for wet storage/air cooling for dry storage)?
- Are additional shielding and radiation protection required?
- Are additional accident analyses required?
- What are the implications for licensing and regulatory compliance?

Table 5-3 of [1] summarizes the overall assessment of wet storage issues, and Table A-1 of Appendix A contains the relevant citations. Due to space limitations it will not be repeated in this paper. The primary concern for safety should be addressed under the regulatory and operation envelope for WG-MOX use, but needs to be reviewed and revised as necessary for application to RG-MOX as well. The ability of the SFP cooling system to accommodate the heat load of additional MOX fuel assemblies in the SFP will also be a concern. It may become necessary to transfer MOX fuel assemblies with higher heat loads to dry storage to maintain the ability to off-load fuel from the core in order to maintain plant operation. Failure to maintain adequate reserve capacity in the pool could lead to a costly, prolonged reactor shutdown

3.2.2. Tactical Assessment of Dry Storage

Key issues for dry storage consideration include:

- Impact of the heat dissipation capability of DSC systems on the storage capacity of MOX assemblies.
- Satisfaction of criticality limits must be demonstrated for all credible conditions, including during loading of canister and cask systems in the pool and under hypothetical transportation accident scenarios.
- Shielding and radiation protection limits within and at the boundary of the ISFSI.
- Ability of DSCs to meet criteria for transportation when off-site storage or disposal becomes available.

Table 5-4 of [1] summarizes the overall assessment of wet storage issues, and Table A-2 of Appendix A contains the relevant citations. Due to space limitations it will not be repeated in this paper. The primary concern is the availability of DSCs that are designed and licensed for the higher long term heat loads associated with used MOX fuel assemblies. As the used WG-MOX fuel should be the first used MOX fuel assemblies transferred to dry storage, it is anticipated that suitable DSCs will be qualified and licensed for both WG and RG-MOX when needed.

4. CONCLUSIONS

Application of the EPRI decision-support framework to a stylized, limited scenario illustrated the feasibility of the tool's use for broader, more ambitious assessments such as the transition to a closed fuel cycle employing fast spectrum reactor technology.

At one level, application of the decision framework provided the opportunity to synthesize existing static information sources (technical reports and peer-reviewed literature) and more ephemeral information sources (expert knowledge and industry experience) into a structured, concise, and reproducible format. The exercise itself illustrated the demands associated with conducting even a rudimentary assessment in a comprehensive, documented, evidence-based manner.

From EPRI's perspective, the most promising RD&D paths are those that leverage existing and proven technologies, infrastructures, and institutions to pursue as a core approach an evolutionary approach to revolutionary end states. One question that guides EPRI's development of assessment tools and expertise is how society might transition from the established LWR-based once-through nuclear fuel cycle to one reliant on unproven but promising fast neutron spectrum reactor technology (for increased natural resource utilization) while keeping the electricity generation safe, affordable, and reliable. EPRI envisions directing the application of the decision-support framework and other assessment tools to this larger technology implementation challenge in future reports. Development of the decision framework and associated assessment tools is ongoing. EPRI welcomes feedback in the form of comments, suggestions, and potential applications of interest.

References

[1] "*Program on Technology Innovation: EPRI Framework for Assessment of Nuclear Fuel Cycle Options – Framework Description and Example Application for Evaluating Use of Reactor-Grade Mixed Oxide Fuel in U.S. Light Water Reactors,"* EPRI, Palo Alto, CA, 1025208 (2013).

[2] A. Dykes, D. Johnson, A. Sowder, and A. Machiels, "*Evaluating Feasibility of Reactor Grade Mixed Oxide Fuel Use in U.S. Reactors: Application of EPRI's Decision Analysis Framework*," Proceedings of the 14th International High-Level Radioactive Waste Management Conference, Albuquerque, NM, April 28–May2, 2013, Manuscript No. 6927, American Nuclear Society, (2013).