Supporting Document 1

Justification for Major Revision to 2017 Version of the *Advanced Fuel Cycle Cost Basis Report*: Addition of "Methodology Description" and "Revision History" to Every Fuel Cycle Module

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Since its inception on 2004 the *Advanced Fuel Cycle Cost Basis Report* has been a" living document" subject to the following:

- Addition or deletion of Modules
- Inclusion of new data forming the basis for the "What-it-Takes" unit cost tables and the associated probability distributions
- Inclusion of cost escalation
- Addition of new topical chapters at the beginning of the document
- Inclusion of an updated "Unit Cost Summary Table" at the front of the report
- In some years (e.g. 2016) the document has been produced as an *Update* rather than a "full" document including all Modules.

For every Module the "full" AFC-CBR version includes significant introductory and background material, including process descriptions, interfaces with other Modules, historical data, reference cost information, assessment of recent cost information, the "What-it-Takes" unit cost tables, and for later versions the suggested probability distributions to accompany the "WIT" data. This is all accompanied by a bibliography and/or a list of references. As a new version is developed, older historical information or reference cases are not deleted, but rather are augmented by the more recent information. For this reason, and the addition of new Reactor Modules in 2015, the "full version" document size has grown to well over 1000 pages. This large volume size makes the document difficult to review, and also difficult to edit, print, and distribute in a hard copy version. It also creates an electronic version which even in PDF format requires several dozen megabytes (MB) of file size, thus making it difficult to distribute electronically.

It should also be noted that in every year a "full" version was produced not all Modules were augmented with new material or even had the "WIT" table corrected for escalation. The FCRD program has not always had the funding resources to comprehensively revisit every Module during every year of issue. The modules selected for reanalysis are those that are judged to have the most effect on overall system fuel cycle costs and include the LWR (R1) and Fast Reactor (R2) Modules, the front-end Modules (A,B,C, and K1) for "once-through" fuel cycles, MOX fuel fabrication (D1-2), and the major Reprocessing Modules (F1 and F2/D2).

The new document production concept hereby introduced in 2017 is to create a large AFC-CBR "folder" where individual front-end chapters and individual Modules can be accessed from a centralized server via the Internet. (In FY2018 it is intended to submit the 2017 folder for formal classification review such that it can ultimately be made available on a Web-based public server.) It has been decided that every Module file in the overall document server folder needs brief explanatory material at the beginning that succinctly identifies its history (vintage) and the timing and nature of the most recent technical and cost escalation data upon which the WIT unit costs are based. It has also been determined that for consistency under a "level-playing field" approach all Module unit cost data should also include escalation to the year of document issue, even if new technical basis data is not included.

The following presents how the two new sections will appears in each Module (or each Sub-Module in the case of Modules A, C, D, E, F, G, K, L, O, and R). [For example, the Reactor Module contains 9 sub-Modules R1 through R9.] Possible entries for each of the generic "bullets" are shown.

X-MD. SHORT DESCRIPTION OF METHODOLOGY USED FOR ESTABLISHMENT OF MOST RECENT COST BASIS AND UNDERLYING RATIONALE

- **Constant $ base year for 2017 Update:** FY 2017 (the same for all Modules in this version)
- **Nature of this 2017 Module update from previous AFC-CBRs:** Two possibilities:
    - Escalation only from last time WIT values underwent technical assessment. Some edits may be included, however, that update the overall deployment status of the technology, such as known facility closures and new facility construction status that do not constitute a baseline cost data change that affects the existing WIT data.
    - Addition of new technical data and supporting new cost baselines and uncertainty bounds updating the WIT values and the probability distributions. Considerable explanatory data may be included.
- **Estimating Methodology for latest (2009 AFC-CBR) technical update from which this 2017 update was escalated:** Several possibilities exist here. Very specific technology information may be included.
    - Actual pricing data for the commodity or fuel cycle service
    - Known published service or unit product costs based on actual facility data
    - Unit costs calculated from a bottom-up life cycle cost estimate for a proposed new facility
    - Unit costs derived by scaling or analogy to a similar type facility for which costs are known or have been estimated
    - Data or opinions transmitted by personal communication and not necessarily vetted.

X-RH. Revision History

- **Version of AFC-CBR in which Module first appeared:**
    - Self explanatory. The AFC-CBR version in which a module was split into sub-modules or re-named is also mentioned.
- **Version of module in which new technical data was used to establish "what-it-takes" unit cost ranges:**
    - The AFC-CBR year in which new or revised technical data and an associated cost baseline resulted in new WIT table results and uncertainty ranges or distributions. Escalation from this "latest technical/cost reference" year to the present should be used for the 2017 updated WIT information.
- **New technical/cost data which has recently become available and will benefit next revision:**
    - List new reports that support or augment information in module. These reports can eventually be placed in a server-based electronic folder/file system similar to that for the actual modules.
    - Known technical and/or institutional developments in a particular fuel cycle area that are likely to have unit cost consequences, and that should warrant revisiting a particular Module in future AFC-CBR versions.

Supporting Document 2

Production Based Costing

Production Based Costing

1.1. Introduction

The purpose of this section is to outline a method of cost analysis whereby a significantly better representation of “should achieve” costs may be attained for NOAK systems. Based on economists’ notions of producer theory, and grounded in the cost analysts’ and project managers’ tool called the Work Breakdown Structure (WBS), this section describes best practices in cost estimation. It then illustrates how the Code of Accounts (COA) structure, developed by the Economic Modeling Working Group (EMWG) of the Generation IV International Forum in “Cost Estimating Guidelines for Generation IV Nuclear Energy Systems [EMWG 2007] (hereafter “Gen IV Guidelines Document”), can be used to differentiate “should achieve” versus “did experience” costs.

Economists use the theory of production, among other purposes, to analyze how technology specifies the combination and transition of inputs to process or system output. Think of output as a product, process, project, or service – anything that results from combining and/or processing inputs. The inputs into production are commonly grouped as land, labor, and capital where capital in this case refers to physical (as opposed to financial) resources such as machinery or equipment. Governed by the science and engineering of the technology being represented, the production function models how inputs combine to form output. Graphically technology is represented as the shape of the production function: P=f (input1, input2)

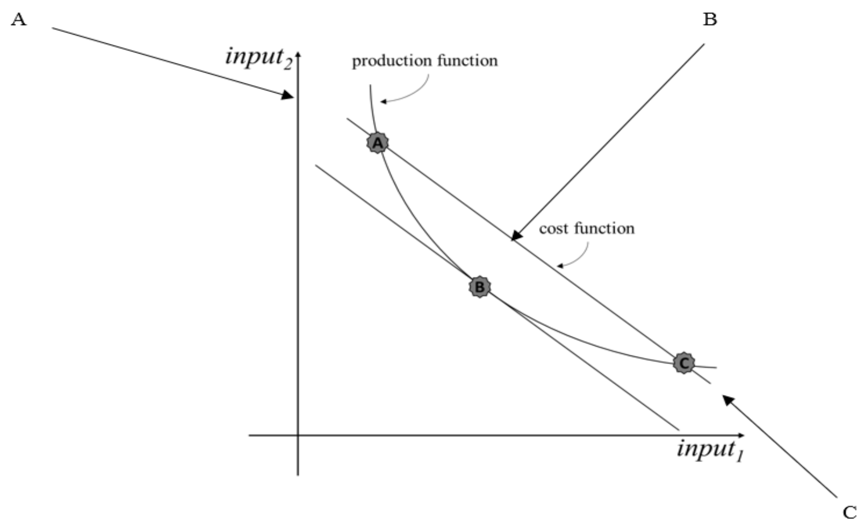


Figure 1. Stylized Representation of Producer Theory.

Figure 1 shows a simple, stylized model of a production function. In it, two inputs combine according to some level of technology result in product output. Three points (could be labeled as A, B, C top to bottom) show possible input combinations that will produce a fixed level of output, $P_{constant}$. In fact, any combination of inputs along the production function illustrates alternative ways of using inputs to produce the same level of output. Not illustrated, increasing levels of production correspond to the production function moving to the upper right of the figure. So, input combination ‘A’ results in the same level of output as ‘C’ although ‘A’ favors input 2 while ‘C’ favors input 1. As an example, one can think of this simplistic model representing a surveillance facility. Surveillance is the output and inputs 1 and 2 might be people and cameras, respectively. The level of people and cameras can be adjusted in many combinations, each combination producing the same level of surveillance.

The production function can be thought of as a three dimensional “response surface” (Fig 2) which is a function of input1 and input2 (the figure below is a generic example). On a map, altitude would be a function of x and y coordinates, and a "contour" [line of constant altitude] would be a curve similar to our production function above where P (input 1, input2) = $P_{constant}$.

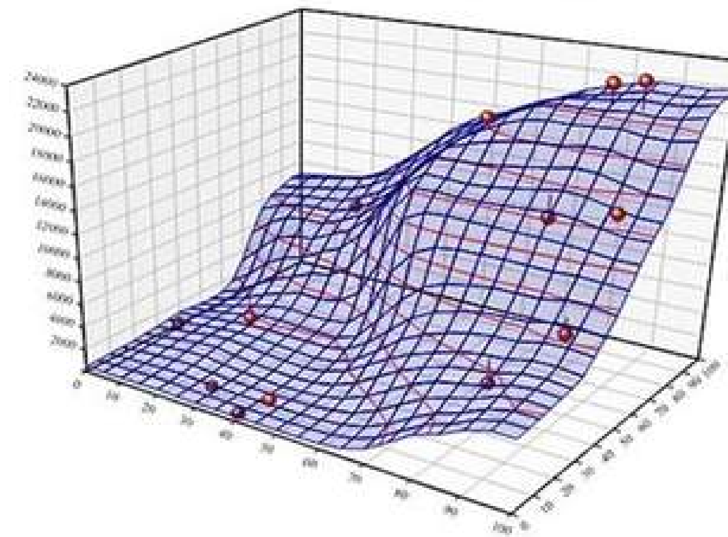


Figure 2. Production Function as Three Dimensional Response Surface

Composed of input prices and budgetary expenditure, Figure 1 also illustrates two cost functions that are separated by expenditure level. Like the production function, increasing costs are represented with cost functions increasing to the upper right of the figure. The intersection of the cost function with the production function represents the expenditure necessary to pay for the corresponding input combination. Points 'A' and 'C' are on the same cost function, indicating that to produce output with either level of input combination results in the same level of expenditure. But point 'B' is on a different cost function. It indicates that the same level of output (technical performance) can be attained with the input combination given by 'B'. That is, 'B' indicates the combination choice that attains the least cost of producing the stylized level of output, i.e. performance. Essentially the performance is "cost optimized" with respect to the two variable inputs.

Input combination 'B' indicates what producing the represented level of output should cost. Points 'A' and 'C' can both produce the same level of output, but 'B' is clearly a better way to combine resources and minimize cost. The WBS is the analytic tool that cost analysts use to organize input requirements for some type of output – be it a process, product, service, or project – so that cost can be assigned to all necessary inputs. For analysis of nuclear projects, the code-of-accounts (COA) is the tool for keeping track of input costs in a systematic manner. Together these facilitate identifying the least cost alternative, such as point 'B' in the simple model.

1.2. Organizing Structures

Organizing the elements of a system into some type of structure is critical for accurately estimating cost. The organizing structure should be one that specifies all that is required in order to produce output [Stewart 1991]. Such a structure provides a clear assessment of what is included in the project, product, or service. A well-defined organizing structure articulates partitioned information, becoming a communication tool about the project to various implementation perspectives, such as system engineering and program management [GAO, 2009]. The organizing structure is needed to accurately estimate cost, schedule, and budget; however it, is also valuable in identifying where risks may exist in the project or where crucial information may be missing. Analogous to the simple model in Figure 3 the organizing structure should represent at least two perspectives: the set of inputs required to produce output, and the cost of those inputs. A WBS and the corresponding COA are two analytic tools that can be used in conjunction to reflect the two important perspectives (inputs and costs) in an organizing structure.

1.2.1. Work Breakdown Structure (WBS)

A seminal text on in the field of cost analysis indicates that the first step in cost estimating is to produce a WBS for the system to be analyzed [Stewart 1991]. Similarly, guidance on cost analysis for US government projects indicates that the "WBS is the cornerstone of every program because it defines in detail the work necessary to accomplish a program's objective" [GAO 2009, p. 65]. The WBS arranges inputs into a hierarchy where inputs accumulate to the output under analysis. Figure 3 is a simple representation of a WBS from the US Government Accountability Office GAO).

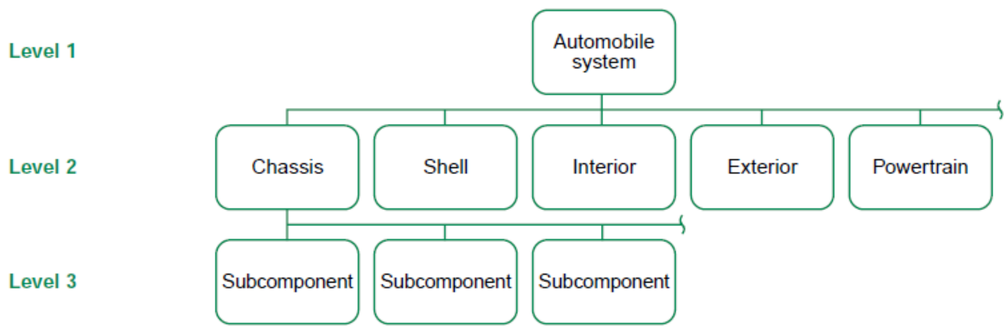


Figure 3. Product-Oriented Work Breakdown Structure (GAO, 2009, p. 66).

Figure 3 shows a simple example of a WBS for an automobile system. In it the automobile system (indicated as Level 1 of the hierarchy) is the output under analysis. Level 2 divides the output into components necessary in order for the system to work. Level 3 disaggregates each component into subcomponents. Level 3 may or may not be the level where inputs are assigned. The hierarchy continues until components can no longer be disaggregated so the levels of the hierarchy adjust with the level of specificity and complexity of the components in the activity. As Stewart describes, the WBS is the framework for collecting, accumulating, and organizing work activity by the outputs under consideration [Stewart 1991]. Its essential function is to divide output into the major activities and elements (or components) necessary to accomplish the work [Stewart 1991]; [GAO, 2009].

A WBS communicates information. It informs those using it of the inputs that have been accounted for in the structure. This reduces duplicity because inputs in the WBS must follow the principle of being mutually exclusive and being collectively exhaustive, i.e. without serious data omissions. If inputs can be used in more than a single element of the WBS, then input allocation can be handled in at least two ways. The input can be assigned to the element where it will have the majority of use, or it can be split up into more than one element where it will be used. (This is discussed in more detail later in the cross-walking discussion). Finally, the WBS is accompanied by a "WBS dictionary" that defines what the analyst has included in each element of the structure. For example, an accompanying dictionary would answer questions about what the analyst meant by "Chassis" when it was listed in the WBS in Figure 3.

1.2.2. Code of Accounts (COA)

Originally set up as the Energy Economic Data Base (EEDB) by the Atomic Energy Commission-Energy Research and Development Administration, then later adjusted to fit the purposes of the International Atomic Energy Agency (IAEA), the Economics Modeling Working Group (EMWG) of the Generation IV International Forum most recently developed the Code of Accounts (COA) [EMWG, 2007]. Itself an organizing structure, the COA details how to account for various components of nuclear systems [EMWG 2007]. In the spirit of this section, the COA is a hierarchical organizing structure. The discussion on COA herein will sound very similar to the WBS above. They are, in fact, very similar. But like the simple model in Figure 3 illustrates, each represent different perspectives of the same system.

The COA organizes costs; it is an accounting structure that can be applied to various types of nuclear, and even non-nuclear, systems. Similar to the WBS, the COA is organized in a hierarchical fashion and for this application enumerated with a 2-digit level coding system. The original EEDB COA structured a 5-digit system, essentially drilling down to the level of small pumps and transformers, but that level of detail for a nuclear power plant would result in over 100 plus pages of densely-written text. As the COA can be used to estimate total lifecycle cost of a system, six categories of the COA are to account for costs in building a facility while three account for the use and disposal of the system. Table 1 shows the COA structure used to compute investment cost and Table 2 shows the COA structure for estimating operations and maintenance. Accompanying the COA, and again similar to the WBS, is a dictionary of what belongs in each account. This dictionary is located in Appendix F of the Gen IV Guidelines Document.

Table 1. Generation IV International Forum Nuclear Energy Plant Code of Accounts [EMWG 2007, p. 30].

Account Number	Account Title
1	Capitalized Pre-Construction Costs
11	Land and Land Rights
12	Site Permits
13	Plant Licensing
14	Plant Permits
15	Plant Studies
16	Plant Reports
17	Other Pre-Construction Costs
19	Contingency on Pre-Construction Costs
2	Capitalized Direct Costs
21	Structures and Improvements
22	Reactor Equipment
23	Turbine Generator Equipment
24	Electrical Equipment
25	Heat Rejection System
26	Miscellaneous Equipment
27	Special Materials
28	Simulator
29	Contingency on Direct Costs
Direct Cost	
3	Capitalized Indirect Services Costs
31	Field Indirect Costs
32	Construction Supervision
33	Commissioning and Start-Up Costs
34	Demonstration Test Run
Total Field Cost	
35	Design Services Offsite
36	PM/CM Services Offsite
37	Design Services Onsite
38	PM/CM Services Onsite
39	Contingency on Indirect Services
Base Construction Cost	

Account Number	Account Title
4	Capitalized Owner's Costs
41	Staff Recruitment and Training
42	Staff Housing
43	Staff Salary-Related Costs
44	Other Owner's Capitalized Costs
49	Contingency on Owner's Costs
5	Capitalized Supplementary Costs
51	Shipping and Transportation Costs
52	Spare Parts
53	Taxes
54	Insurance
55	Initial Fuel Core Load
58	Decommissioning Costs
59	Contingency on Supplementary Costs
Overnight Construction Cost	
6	Capitalized Financial Costs
61	Escalation
62	Fees
63	Interest During Construction
69	Contingency on Financial Costs
Total Capital Investment Cost	

Table 2. Structure of the Generation IV International Forum Operations and Maintenance Code of Accounts [EMWG 2007, p. 33].

Account Number	Account Title
7	Annualized O&M Costs
71	O&M Staff
72	Management Staff
73	Salary-Related Costs
74	Operations Chemicals and Lubricants
75	Spare Parts
76	Utilities, Supplies, and Consumables
77	Capital Plant Upgrades
78	Taxes and Insurance
79	Contingency on Annualized O&M Costs
8	Annualized Fuel Cost
81	Refueling Operations
84	Nuclear Fuel
86	Fuel reprocessing Charges
87	Special Nuclear Materials
89	Contingency on Annualized Fuel Costs
9	Annualized Financial Costs
91	Escalation
92	Fees
93	Cost of Money
99	Contingency on Annualized Financial Costs

The two-digit coding shown in the tables above can be disaggregated to reveal a greater level of specificity, and for earlier nuclear power cost-experience studies sponsored by DOE-NE and its predecessors in the 1975-1988 timeframe NPPs were broken down to the five digit level under the EEDB program. The guidelines document [EMWG 2007] articulates how the accounts coding should be adjusted based on facility type and purpose. For example a numerical code in the structure indicates if the system under analysis applies to units, plants, systems or facilities, or commodities. Further, facility type designates a code depending on the facility function, i.e. power plant, fuel fabrication, fuel reprocessing, desalination, hydrogen generation, other processes, or waste repository [EMWG 2007, Appendix F].

The COA in the Gen IV Guidelines Document evolved from a previous structure developed by the IAEA. IAEA developed a structure, basically based on the US EEDB mentioned above, to aid developing countries in analyzing the quality of bids for nuclear power plant projects. The IAEA built the structure with the thought that it would be completed as a useful tool with the help of vendors, architect-engineers, and constructors from industrialized countries. The EMWG re-organized how the structure was originally developed because the IAEA bid evaluation type structure led to inherently high-level estimates. EMWG re-tooled it to allow for greater specificity, primarily changing the labor accounting.

1.2.3. Cross-walking WBS and COA

The WBS and the COA provide two perspectives of the same information, but together can fit into an organizing structure to enable a better understanding on “should” costs and “did” costs. The WBS is an organizing structure that supports identifying all inputs (materials, labor, equipment, etc.) needed to produce output (a functional facility). The COA is an accounting structure that applied to WBS provides information on input cost. For example, COA 21 is for civil structures and improvements. In a WBS applied to a nuclear system, COA 21 would likely be applied over several WBS elements. The COA structure, detailed in the Gen IV Guidelines Document, has a coding system whereby specificity greater than two digits i.e. the ability to drill deeper into an estimate beyond the basic subsystem (civil, nuclear island, electrical, heat removal et al) level can be attained. Using the COA in tandem with a detailed WBS for nuclear systems will support the analyst’s ability to identify the “should cost” (target achievable cost) of a system.

1.3. References

EMWG 2007 – *Cost Estimating Guidelines for Generation IV Nuclear Energy Systems*. Gen IV International Forum: OECD Nuclear Energy Agency, 2007.

GAO 2009 – *GAO Cost Estimating and Assessment Guide: Best Practices for Developing and Managing Capital Program Costs*. United States Government Accountability Office, 2009.

Stewart 1991 – Stewart, R.D., *Cost Estimating, 2nd Edition*, John Wiley & Sons, 1991.

Supporting Document 3

Cost Correlations

COST CORRELATIONS

1.1 Introduction

Cost correlations quantify the degree to which two summary costs are built up from the same underlying costs. A simple example is the cost of two buildings, which both include the cost of concrete foundations. The concrete material costs would be correlated, even if the rest of the two buildings were entirely different.

Cost correlations are important in the CBR and its application for two reasons. First, cost uncertainty distributions include uncertainty on unit costs of labor, equipment and materials. When comparing the costs of two different systems using a Monte Carlo sampling or similar approach on their cost distributions, the correlated unit costs need to be considered to move together while the uncorrelated costs need to move independently. If the correlated cost components are sampled independently, the calculated delta cost distribution will be much wider than it should be, making it harder to determine if one system costs more than the other.

Second, correlations can be applied at a higher level, such as the main functions of the system, to develop a more accurate estimate of costs for a facility using advanced technology that has never been built by extrapolating from a similar facility using current technologies and better known costs. This is a form of cost estimating by analogy, as discussed above in the Main 2017 AFC Report. For example, some major systems and structures of an advanced reactor such as the steam turbine or the containment dome may be identical or nearly identical to an existing reactor, even though the reactor cores are very different. By breaking the reactors down into their major cost components and determining the degree to which these components are the same or different, partial cost correlations can be developed and used to improve the cost estimation of the advanced technology.

The EWG has been developing cost correlation methods and tools for several years. This has included collection of information on correlation theory and methods, development and internal testing of expert elicitation of partial correlation coefficients [Schneider 2014], inclusion of partial correlation calculations into the Monte Carlo capabilities of NE-COST [Ganda 2014], and recently the trial application externally of expert elicitation of partial correlation coefficients for different reactor types [EPRI 2016].

This chapter provides an overview of the drivers for developing correlation coefficients, status on efforts to develop partial correlation coefficients, and recommended next steps. Mathematical methods for developing and using correlation coefficients were previously documented by the FCO EWG in Chapters 6 and 7 of [Ganda 2014].

1.2 Cost Correlation Mechanics

Nuclear energy system cost analysis can provide vital inputs to R&D decision-makers. To be effective, this decision support tool must overcome significant challenges. Most crucially, costs are highly uncertain. Total project costs can vary widely for identical reactors at different sites or constructed at different times. Technological uncertainties compound the issue for less mature concepts. While reactors represent most of the cost of nuclear energy systems, each fuel cycle function also has significant cost uncertainty. The prices for yellowcake, conversion, SWUs, and enrichment vary from year to year and by location. Many back-end costs are not well defined, especially for SNF/HLW disposal and reprocessing

Time is also an important factor in cost analyses. Transitions to new reactors and fuel cycles can take a century or more. Cost uncertainties increase the further into the future the cost projection is carried. These include the cost of capital, labor, and materials and the impact of changes in regulations, tax rates, etc. Regulatory changes are unpredictable, but usually increase costs.

The CBR presents estimates of the unit overnight cost, in $/kWe of installed capacity, for several nuclear reactor technologies. These unit costs are used to calculate the Levelized Cost at Equilibrium

(LCAE) for a fuel cycle. The LCAE is a specific application of the more common Levelized Cost Of Electricity (LCOE) using an equilibrium fuel cycle mass balance.

It is recognized that reactor and fuel cycle costs are uncertain, so the CBR includes uncertainty as well as pointwise cost estimates. These take the form of uniform or triangular probability distributions defined by their lower and upper bounds and most likely (mode) values; see Figure 1 for an example.

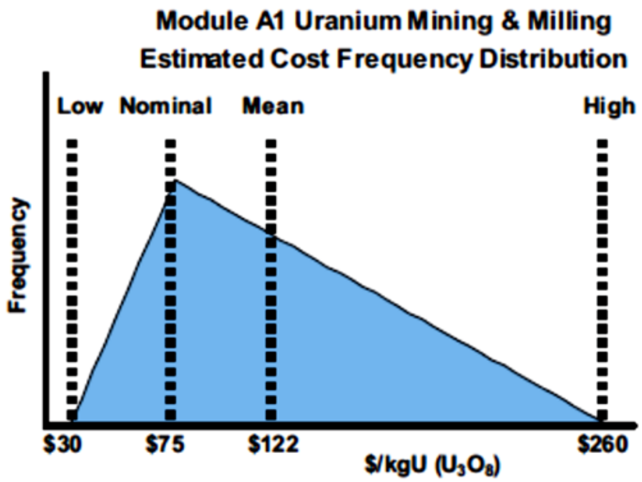


Figure 1. Example of cost distribution from the Advanced Fuel Cycle Cost Basis report: Uranium mining and milling.

Monte Carlo methods are used to calculate probability distributions of the LCAE for a strategy by summing the distributions from the CBR describing unit costs of relevant fuel cycle steps as well as operation and construction of one or multiple reactor types that may be present.

In most prior applications of this calculation, each unit cost distribution has been treated as uncorrelated with the others but perfectly correlated with itself. This means that construction costs for different reactor technologies, for instance, are treated as completely independent, even though the technologies would almost certainly have many cost inputs in common (e.g. labor, raw material and equipment costs).

However, omitting the correlations between concepts artificially increases the uncertainty in the LCAE difference between two strategies. It also narrows the LCAE uncertainty distribution for a given strategy. These effects stem from cancellation of errors: the cost of reactor type 1 being sampled as high, for instance, implies that labor, equipment and/or material costs have proven to be high. Therefore, reactor type 2 should probably also be high cost – but instead, if independent distributions are assumed, it is equally likely to have a low cost. When the correlation between uncertain input costs is correctly accounted for, the corrected probability density function of the LCAE difference will become narrower.

The results obtained when adding or subtracting distributions such as those in the CBR are strongly affected by the correlation between them. Figure 2 shows the effects when two cost distributions, one uniform between $1500 and $3000 and the other uniform between $1000 and $2000, are subtracted. The figure illustrates the extent to which the uncertainty in the difference between the distributions is reduced as the strength of correlation between them increases.

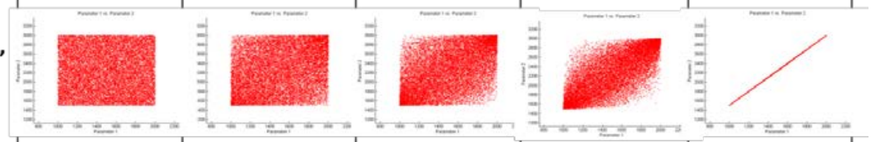
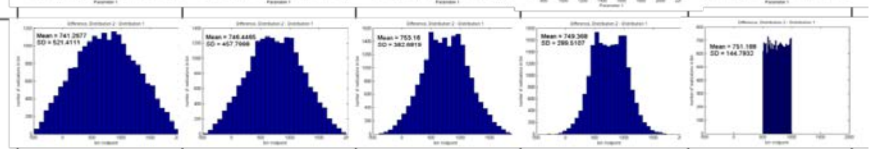
Correlation Coeff., ρ	0.0	0.25	0.5	0.75	1.0
Scatter Plot, Cost 1 vs. Cost 2					
Cost Difference Histogram					
Standard Deviation of Cost Difference	$521	$458	$382	$290	$145

Figure 2. Subtraction of correlated distributions.

Two issues must be overcome to improve the treatment of cost correlations and their impact on the accuracy of cost comparisons. First, while the construction costs for various reactors and fuel cycle technologies are certainly correlated and likely very strongly so, limited data is available concerning the extent of the correlation. Bottom-up cost estimates would provide this data through the comparison of material, labor and equipment requirements, but these estimates are generally proprietary. Second, many of the technologies of interest to FCO are at a relatively low technology readiness level (TRL) so the available reactor design information is largely conceptual in nature. This precludes a bottom-up approach. Instead, expert judgment must be relied on to understand the similarities and differences in costs between systems with different or low TRLs.

Figure 3 shows an example of probability distributions which convey cost uncertainties, in this instance for two fuel cycles. The reference UO_2 and O-T/3.2 cycles whose costs are illustrated in the figure both feature the once-through strategy but with different enrichments and burnups. The average LCAE for reference UO_2 is 48.13 mills/kWh, and its standard deviation is 6.84 mills/kWh. The average LCAE for O-T/3.2 is 46.11 mills/kWh with a standard deviation of 6.88 mills/kWh. The difference between the average LCAE of the two strategies is 2.02 mills/kWh.

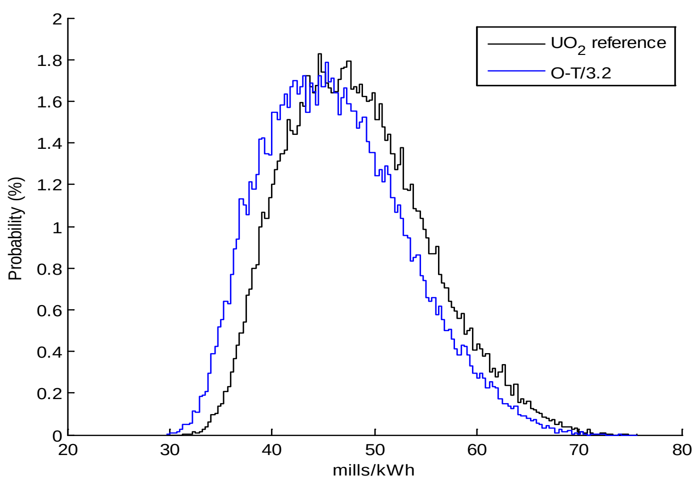


Figure 3. LCAE probability density functions (PDFs), reference once-through UO_2 cycle and O-T/3.2 cycle.

Subtracting the uncertainty distributions can give rise to valuable decision-relevant information: for instance, the difference between the distributions conveys the likelihood that one strategy will be cheaper as well as the probable extent of the cost difference. While reduction of total uncertainty is not practical, reduction of this 'delta uncertainty' in a pair-wise comparison is possible. We know that many of the factors determining the costs of two future facilities correlate when comparing systems at the same location and same point in time, with the same inflation and labor rate, same cost of uranium, and so forth. In a pair-wise comparison, correlated costs should cancel out, leaving only the costs associated with differences between the systems.

As a naïve example of what happens if correlations are ignored, consider the difference between the two distributions shown in Figure 3 if all reactor and fuel cycle costs are assumed to be uncorrelated. Figure 4 shows that the resulting distribution describing the difference in LCAE is very broad, with a standard deviation of 9.68 mills/kWh. This result implies that there is a reasonable probability that the costs of the strategies would differ by more than 1 cent/kWh in either direction – a difference that is largely driven by the (thus far uncorrelated) uncertainties in the reactor capital costs.

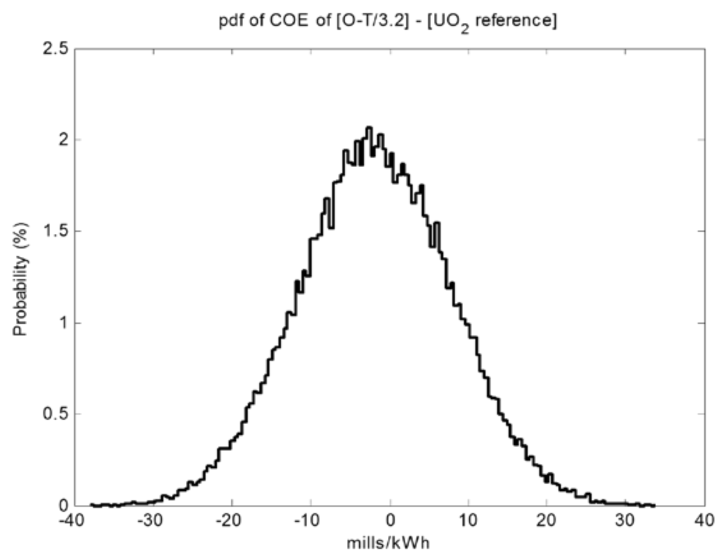


Figure 3. PDF of COE difference, O-T/3.2 minus UO_2 reference, no correlations.

The previous results are misleading, if not outright incorrect. Many of the random variables in the two systems are not independent, but correlated. Examples of variables which should have a perfect correlation (correlation coefficient of 1) between the two systems include:

- Specific overnight capital cost of reactor;
- Discount rate;
- Years for construction;
- Interest rate during construction;
- Cost of uranium;
- Cost of SWU;
- Depleted U de-conversion;
- Cost of fuel fabrication;
- Cost of conversion;
- Cost of SNF conditioning before shipment to the repository;
- Cost of geologic disposal.

Accounting for these correlations does not change the difference between averages of the LCAE: it is still around 2 mills/kWh. But taking the correlations into account does have a dramatic effect on the difference between the two cost probability distributions – see Figure 5. The standard deviation of the difference in the LCAE has fallen to 0.47 mills/kWh, and because the probability distribution is now entirely in the negative portion of the graph, it becomes clear that O-T/3.2 is virtually certain to be a marginally less expensive cycle than reference UO_2.

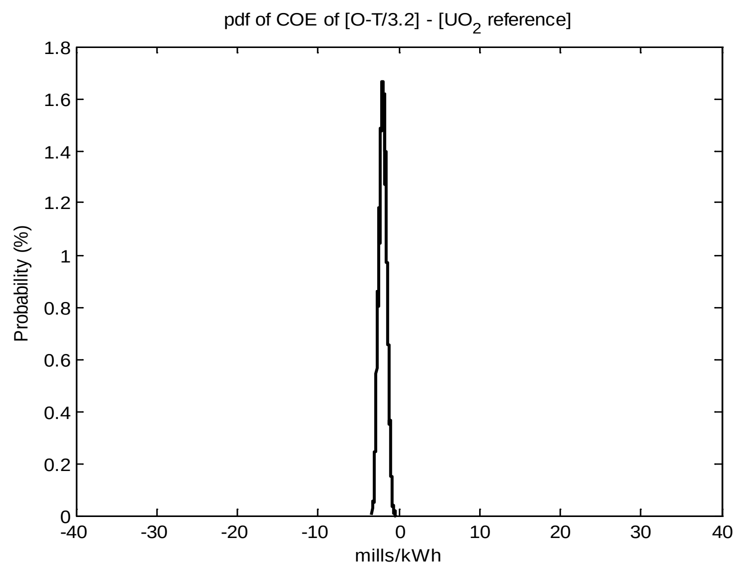


Figure 4. PDF of COE difference, O-T/3.2 minus UO_2 reference, correlations accounted for.

The recently completed Fuel Cycle Evaluation and Screening used a Basis of Comparison for pair-wise assessment of systems. The uncertainty of differences in LCAE for systems similar to the Basis of Comparison (cycle EG01) were substantially reduced, as shown in Figure 6. Uncertainties of differences with less similar systems (i.e., those that did not include the same reactor type present in EG01) were very large.

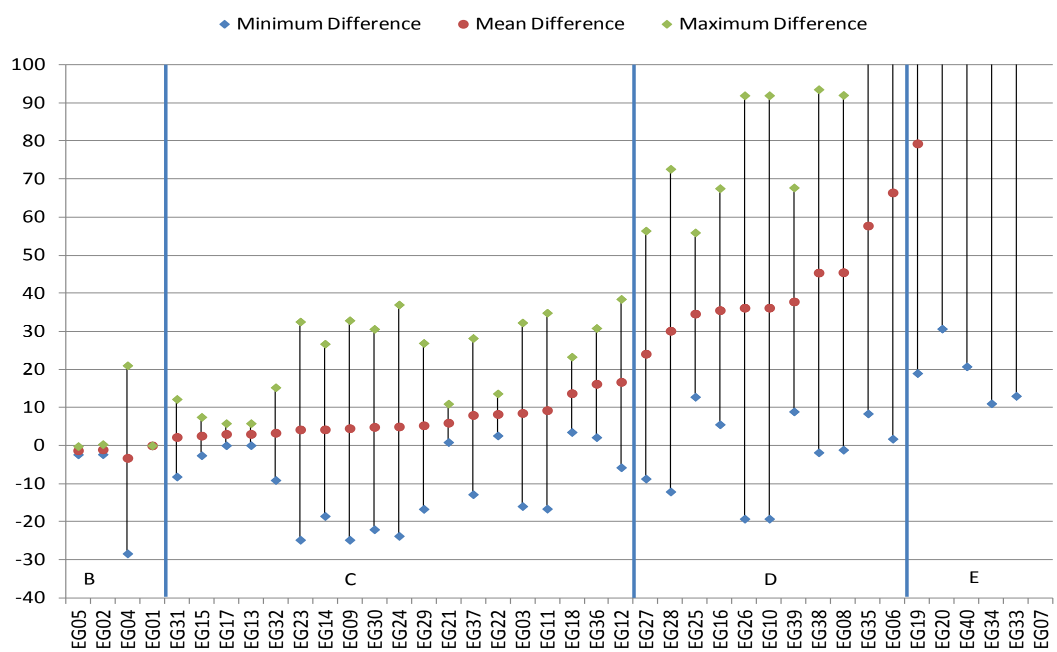


Figure 5. Fuel cycle evaluation and screening cases and their LCAE uncertainties.

The primary factor driving these large uncertainties was reactor type. Reactors make up the majority of the LCAE of a nuclear energy system. Since the analysis example for the Basis of Comparison was an LWR-based system, uncertainty in delta costs compared to other LWR-based systems were much smaller than for systems primarily using other reactor types.

1.3 Partial Correlation Coefficient Elicitation Status

Cost Correlation Coefficients indicate the degree to which two cost parameters move in concert. A correlation of 1.0 indicates that an increase in one parameter is always accompanied by an increase in the other, such as when a material cost (e.g. concrete) is common to both of two construction projects. A correlation of 0.0 indicates total independence, where changes in one parameter have no effect on the value of the other (e.g. cost of concrete versus cost of carpenter labor). A correlation of -1.0 indicates an inverse correlation, where an increase in one parameter always coincides with a decrease in the other parameter. It is noted that this definition is based on rank correlations, such as the Spearman and Kendall correlation coefficients. Conversely, the degree of linear association between random variables, normally measured with the Pearson's product-moment correlation coefficient, is less relevant here, since random costs may have non-linear associations that would be nevertheless important to capture when evaluating cost uncertainties.

A partial correlation coefficient quantifies an imperfect relationship between two parameters. In CBR applications, this will typically but assumed with rolled up or top-down costs, where the details of correlations are not available. For example, generally an increase in the cost of a PWR would coincide with an increase in the cost of an SFR, but of a different magnitude because both have materials/equipment/labor costs in common but also have major differences; while a change in the cost of concrete would impact both, the portion of the total cost that is concrete costs differs between the two reactor types.

Since detailed bottom-up information is not available for advanced reactors and fuel cycle facilities with lower TRLs, expert elicitation is used to develop cost correlation coefficients for advanced facilities as compared to mature technologies (e.g. LWRs).

The FCO EWG developed a method for elicitation of correlation coefficients and tested it internally [Schneider 2014], then updated the approach and tested it externally with a group of people attending a nuclear fuel cycle assessment workshop [EPRI 2016]. The primary purpose of the external solicitation was to test methods and learn from the experience in preparation for eliciting from reactor costing experts.

Two trial applications of the partial correlation elicitation have been performed, both involving development of coefficients between eight different transmutation systems (reactors and externally driven systems).

The internal trial used FCO EWG members as experts. Each EWG member was asked to fill out a chart of coefficients along with their confidence in the values provided. The resulting coefficients were combined using the confidence factors to weight the contributions with the weighted arithmetic mean of the answers establishing the consensus value for each correlation coefficient. The resulting coefficients are shown in Figure 7.

Experience from the pilot study was used to develop briefing material and an Excel-based elicitation tool for use in the next trial.

	R1: Light Water Reactor	R2: Fast Spectrum Reactor	R3: Gas Cooled Reactor	R5: Press. Heavy Water Reactor	R6: Accel-erator Driven System	R7: Liquid Fueled Salt Cooled	R8: Solid Fueled Salt Cooled	R9: Fission Fusion Hybrid
R1: Light Water Reactor	**1.00**	0.77	0.75	0.91	0.45	0.60	0.74	0.44
R2: Fast Spect. Reactor		**1.00**	0.74	0.76	0.51	0.58	0.64	0.49
R3: Gas Cooled Reactor			**1.00**	0.79	0.42	0.58	0.71	0.42
R5: Press. Hvy Water Reactor				**1.00**	0.45	0.55	0.73	0.44
R6: Accelerator Driven System					**1.00**	0.49	0.50	0.56
R7: Liquid fuel Salt Cooled						**1.00**	0.83	0.50
R8: Solid fueled Salt Cooled							**1.00**	0.50
R9: Fission Fusion Hybrid								**1.00**

Figure 6. Weighted average correlation coefficients from 2013 FCO pilot study.

The external trial used EPRI workshop participants as experts. Participants were supplied with three read-ahead documents: a summary of the reactor technologies, condensed from the CBR, a description of the implementation of correlations in the NE-COST tool used by FCO to calculate LCAE, and a briefing on the elicitation process. Three additional background readings were provided: an article describing the FCO cost analysis methodology [Ganda 2014a], a description of the impact of including correlations on FCO option analysis economic results [Ganda 2015] and a summary of the methods and results of a small-scale pilot elicitation carried out in 2013 [Schneider 2014]. The process during the workshop included presentations on the background and objectives of the study, an overview of the reactor technologies, and information on how the cost correlations would be used.

Three different types of elicitations were conducted over the course of the day. In the first, participants compared the same eight system concepts as in the original internal trial. They were also asked to specify their degree of confidence in each coefficient. The Excel-based tool aided the process by limiting responses to allowed ranges. After the participants provided their responses, the results were checked for consistency and combined to determine the confidence-weighted arithmetic mean. Figure 8 shows the results, in which the coefficient values were generally lower than those from the internal trail.

Figure 9 and Figure 10 provide the standard deviation of the participants' responses and the average confidence level the participants indicated, respectively. The standard deviations are generally lowest (darkest) when at least one mature, commercialized technology is present in the pair. High standard deviations are present for technologies that are far from being mature such as the FFH and ADS. The participants' confidence levels are notably higher (lighter shading) when the technology pairs share a clear common feature. Otherwise, the experts' confidence levels are fairly uniform and in the moderate-to-low range.

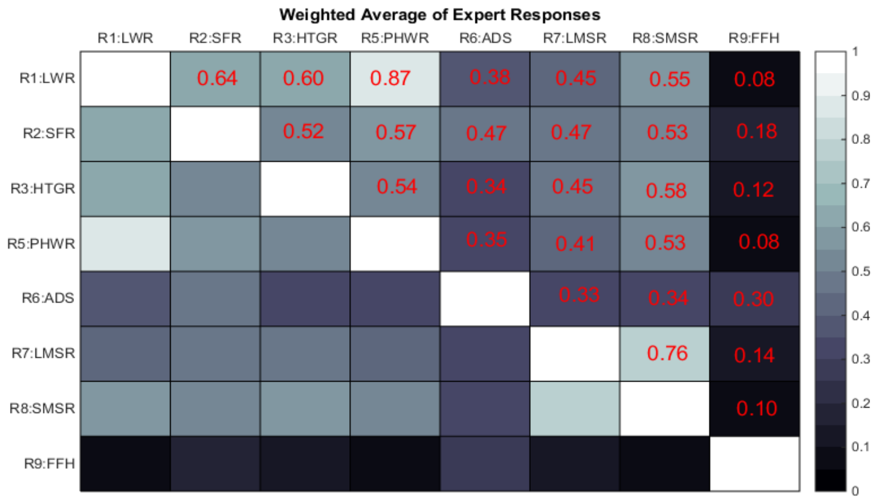


Figure 7. Elicited values of correlation coefficients.

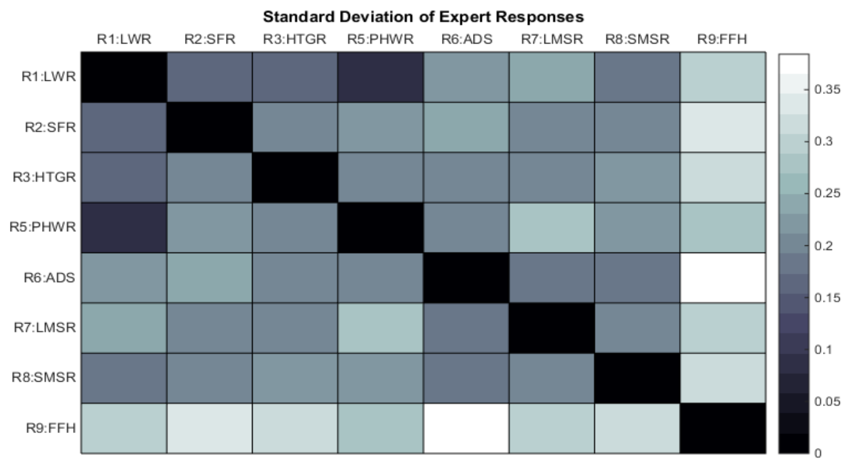


Figure 8. Standard deviation of participant responses.

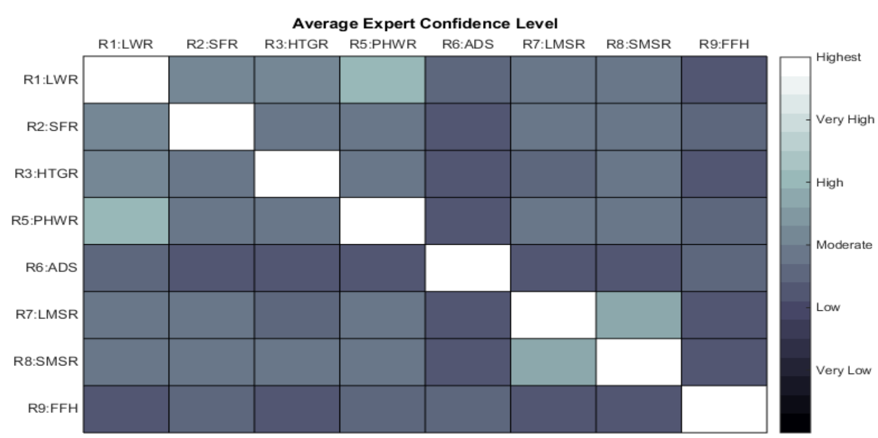


Figure 9. Average participant confidence level.

In the second elicitation, participants were asked to provide their best estimate of an overnight capital cost for each concept. The results are shown in Table 1.

Table 1. Elicited values of overnight capital costs.

mean	Overnight Capital Cost [$/kWe]	% difference relative to LWR	Standard Deviation [$/kWe]
R1: Light Water Reactor	4314	0%	1102
R2: Fast Spect. Reactor	5552	29%	2437
R3: Gas Cooled Reactor	6402	48%	3149
R5: Press. Hvy Water Reactor	4628	7%	956
R6: Accelerator Driven System	9048	110%	5646
R7: Liquid fuel Salt Cooled	4962	15%	1632
R8: Solid fueled Salt Cooled	5300	23%	1316
R9: Fission Fusion Hybrid	24740	473%	33597

Finally, the participants were asked to compare only a PWR to an SFR, but to do so using the first level of the code of accounts structure. The results are shown in Table 2. Note that the approximate correlation when using the code of accounts detail was higher than when the participants were asked to compare the systems at the top level in the first elicitation (0.7 versus 0.64), indicating the participants felt there were more similarities between the systems when they were asked to evaluate the correlations for different system parts. The weight in this case was based on the relative contributions of each part to the total estimated system cost.

Table 2. Elicited values of correlations between code of account items for PWR and SFR.

mean	Correlation Coefficient	Weight	Aggregation
Structures and Improvements	0.80	11%	0.09
Reactor and Boiler Equipment	0.47	17%	0.08
Turbine, Generator Equipment	0.76	13%	0.10
Electrical Equipment	0.87	5%	0.04
Cooling and Miscellaneous Equipment	0.66	5%	0.03
Design, project management, commissioning	0.69	31%	0.22
Staff recruitment, training, salaries, owners' costs	0.86	9%	0.08
Contingency	0.72	9%	0.06
Approximate Correlation			**0.70**

1.4 Next Steps

This section summarizes important questions and feedback received from the workshop participants. It also describes the next steps for the capital cost correlation effort.

The elicitation exercise at the EPRI workshop represented a step in the process of assembling the correlations. Hence, given the nontechnical background of many of the participants, there was not an expectation of accuracy and definitive correlation results, but rather a need to learn and to understand what matters when conducting a successful elicitation of this data. The outcome was thus process information rather than definitive data. A recommendation for future elicitations is to invest more time in explaining what correlation means, using examples of facility costs. An option to allow experts to learn from the process would be to pursue a Delphic style elicitation. In a two–round Delphic style elicitation, there would be briefings on bottom up cost components as well as on findings from literature of how humans tend to think about (and underestimate) correlations. Crucially, after being briefed (and possibly viewing interim results for the group) experts are allowed to go back and revise their results.

There was a consensus that when another round of elicitation is carried out it would be desirable to provide a more specific description of a single “generic” system that represents each reactor type. An alternative to this, which was suggested by multiple participants, would be to ask experts to consider an average across the range of systems that fit within each reactor module/type. Since there can be several major technology options within each module, it could be cumbersome to present sufficient data to the experts for each option. Alternately, a future elicitation could be limited to fewer reactor types but ask for evaluation of each major option, or the briefing materials could only focus on areas where the options are substantially different.

Ensuring that the expert group is provided the right background information for the task, tailored to the experts’ expertise areas, will thus be essential. One morning worth of briefings is arguably not sufficient for a specialized, technically-focused elicitation. When working with a group of reactor construction experts, it will be important to give more information on how costs break down for each option: for instance, the costs associated with labor versus standard materials versus specialized equipment, financing costs, and so forth. This may only be possible for the more mature, well-characterized technologies, but nonetheless it will provide experts with a numerical basis for their estimates.

It will be important to identify the purpose of future elicitation sessions – education or information gathering. If working with experts to get information, it will be best to provide all available information at the start and then do the elicitation, possibly at a lower level of detail so as not to provide them with preconceptions regarding the outcome. Experts may also need an additional briefing on how the information will be used in fuel cycle economics calculations so they have an understanding of which items are important to consider and which are not.

One path forward would be to work with a group of LWR experts and ask them to develop correlations between types of LWRs. With people who are already expert, there will be an expectation of deeper background information, so it will be best to start out with a bottom up way of thinking. For example, starting with the detailed account code for a reference LWR design, one could first consider correlations between LWR options, e.g., BWR vs. PWR, where details are available. Subsequently, when they have completed this task and understood the mechanics of the correlations, they can proceed to compare LWRs to other reactor types. Also, since the existence of several options within a reactor group caused consternation, it is desirable to be more specific by choosing one example technology for each type.

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Supporting Document 4

Considerations on Scaling

CONSIDERATIONS ON SCALING

Scaling considerations involve the calculation of "new" facilities' construction and O&M costs starting from available information (from actual facilities and/or studies) on cost of similar facilities of different sizes.

Generally, because of economies of scale, the construction cost C1 of a facility of size S1 is calculated from the known cost C_0 of a facility of known size S_0 with the following equation:

$$C_1=C_0\cdot(S_1/S_0)^{\alpha}$$

Where α is called the "scaling factor", and assumes a value typically between 0 and 1. Values close to 1 indicate the existence of little economies of scale, so that the cost increase/decrease is close to linear, while values close to zero indicate the presence of large economies of scale, for which an increase in size produces little effect on costs. A typical value of scaling factors for chemical facilities and equipment that is often cited in the literature, e.g. (Peters & Timmerhaus) is 0.6.

The methods for increasing capacity should be considered when developing scaling factors. In some facilities, the individual pieces of equipment may simply be increased in size, while in others, parallel trains of equipment of a constant size may be employed. As equipment is enlarged and/or equipment trains added, buildings will increase in size, either by square footage of floor space or cubic footage of building volume or additional buildings will be added. Scaling also applies to operational costs, where the number of operators may be driven by the number of equipment trains while other labor categories such as security may change little with size.

Construction methods should also be considered as the size of the facility changes. At smaller sizes, it may be possible to fabricate more of the facility in a factory environment, holding down both construction costs and rework. Two types of fabrication should be considered, "equipment" and "modules", where equipment includes pumps, steam generators, and smaller reactor pressure vessels, while "modules" are construction building blocks that include structures, walls, piping, electrical, etc. A modular construction approach may apply at multiple scales, while equipment can only scale to the limit of lifting and transport equipment and at some point must instead be reduced to sub-components that are assembled on site. Referring to the described concept in supplementary document SD2: "Production Based Costing," factory fabrication of nuclear grade equipment such as the reactor vessel may involve a different, more efficient production function (point B in the figure) versus on-site fabrication (points A or C). The scaling equation above assumes a constant production function, so such changes may result in discontinuities (steps) in the otherwise continuous scaling function.

The issue of cost scaling with size has been studied for reactors, especially in light of the recent interest in small modular reactors (SMRs). Results of past studies on this issue produce results that are not fully consistent, and therefore one cannot draw definitive conclusions. For example, the results of the econometric analysis of construction costs between 1971 and 1978 performed in [Komanoff 1981], show that the "*unit size*" variable had virtually no effect on costs (+0.5%), indicating that the beneficial effects of economies of scale were completely counterweighted by other factors that increased the unit costs of larger units. Later econometric analyses with more comprehensive data sets found that larger sizes actually *increased* the cost per MW installed [Zimmerman 1982], [Krautmann 1988], [Cantor 1988] and [McCabe 1996]. Similar results were also found as a result of a statistical analysis conducted by DOE/EIA in 1986, the conclusions of which are quoted here [DOE 1986]:

> *"The analysis indicates that the indirect effect of size on real cost, through the influence of lead-time, outweighs the direct reduction in costs per kWe of capacity that would result from the construction of large power plants if the lead-time and size were not related."*

In particular, the study found that a 25% increase in the power level of the plant would lead to a reduction in cost per kWe of capacity of 12%, *if* the larger power level would not induce an increase in lead time. However, a 25% increase in power level was found to be associated with a 18% increase in lead time, which was in turn found to be associated with an increase of 22% in the real cost of construction. It is cautioned here that “lead-time”, being quantitative and readily and precisely available, was used in [DOE, 1986] as a proxy variable for a number of un-quantifiable variables such as design changes, safety and environmental retrofits required by regulatory change, and labor productivity, which were directly responsible for the cost increases.

On the other hand, a more recent econometric analysis performed in [Ganda 2016a], indicated that given a 10% increase in reactor power, costs per kWe of capacity (i.e. the actual cost outcome after construction was completed, normalized for the reactor power) decreased by 17.8% (implying an escalation factor of -1.05) and budget per kWe of capacity (i.e. the pre-construction cost estimate, normalized for the reactor power) decreased by 6.9% (implying a scaling factor of 0.25). Both estimates were found to be significant at the 99% level, and were found when controlling for a number of variables, including size, location, reactor type, time built, etc. When all these variables were not controlled for, the elasticity becomes 0.32, i.e. a 10% increase in reactor power would result in cost per kWe of capacity increase of 3.2%, implying instead diseconomies of scale.

It is noted that most past analyses (one exception is [Ganda 2016a]) simply used “did cost”, and did not attempt to include “should cost”. By using only “did cost” the combined trends toward larger reactors over time and to more regulation over time may have impacted scaling results. Another factor is the use of data primarily or exclusively from Western countries, which all saw an increase in construction time in the 1970s-80s and not including data from Asian countries that did not experience the same increases. Figure 1shows the historic construction duration trends (from first nuclear concrete to first grid connection) for the three largest Western and three largest Asian reactor fleets. These figures imply that factors other than scaling were driving the historic cost increases. A separate supplementary document (2017-CBR-SD5) to the 2017 AFC-CBR discusses learning.

In summary, it is recommended to use caution when applying cost savings due to economies of scale for reactor facilities, since a definitive consensus on this topic has not been reached yet.

For other fuel cycle facilities, and in particular for reprocessing facilities, the issue of estimating proper escalation factors is especially important, since few cost data points exist, and some of those plants have very different annual throughput. For a meaningful comparison of those costs, it is necessary to have a well-developed approach for escalation that includes understanding how capacity increases would be physically achieved.

Few studies have been performed on the cost of reprocessing, including [Haire 2003] and more recently [Bunn 2016]. An extensive discussion of aqueous reprocessing plant scaling considerations is provided in Module F1 of this 2017 AFC-CBR.

Haire [Haire 2003] points out the following:

> *“In the familiar rule-of-thumb scaling law, capital costs are proportional to the nth powers of capacity; however, n is not a constant. The value of n approaches 0.1 for very small-capacity plants and 0.9 for very large plants. Thus, there is an upper limit to the axiom that states that the larger the plant size, the smaller the unit cost. For example, doubling the throughput rate of a large-capacity plant nearly doubles capital costs”.*

The considerations in [Bunn 2016] are based on cost data derived from the construction experience of a 50 MT/y pilot plant at the Jiuquan nuclear complex, and are applied to the derivation of the cost of a hypothetical industrial-size 800 MT/y facility. Chinese experts’ estimates mentioned in [Bunn 2016] use a scaling factor of 1.0 for facilities that are between half and double the size of the reference facility, and a scaling factor of 0.6 for facilities larger than twice but smaller than 50 times as large. For this reason, a scaling factor of 0.85 was considered the most realistic for a scaling of a 50 MT/y plant to an 800 MT/y plant in [Bunn 2016]. However, it is also mentioned in (Bunn 2016) that a study of aluminum refineries (which are also expanded primarily by adding production line, rather than by scaling equipment, similarly to reprocessing facilities), found a scaling factor of 0.93 to be appropriate.

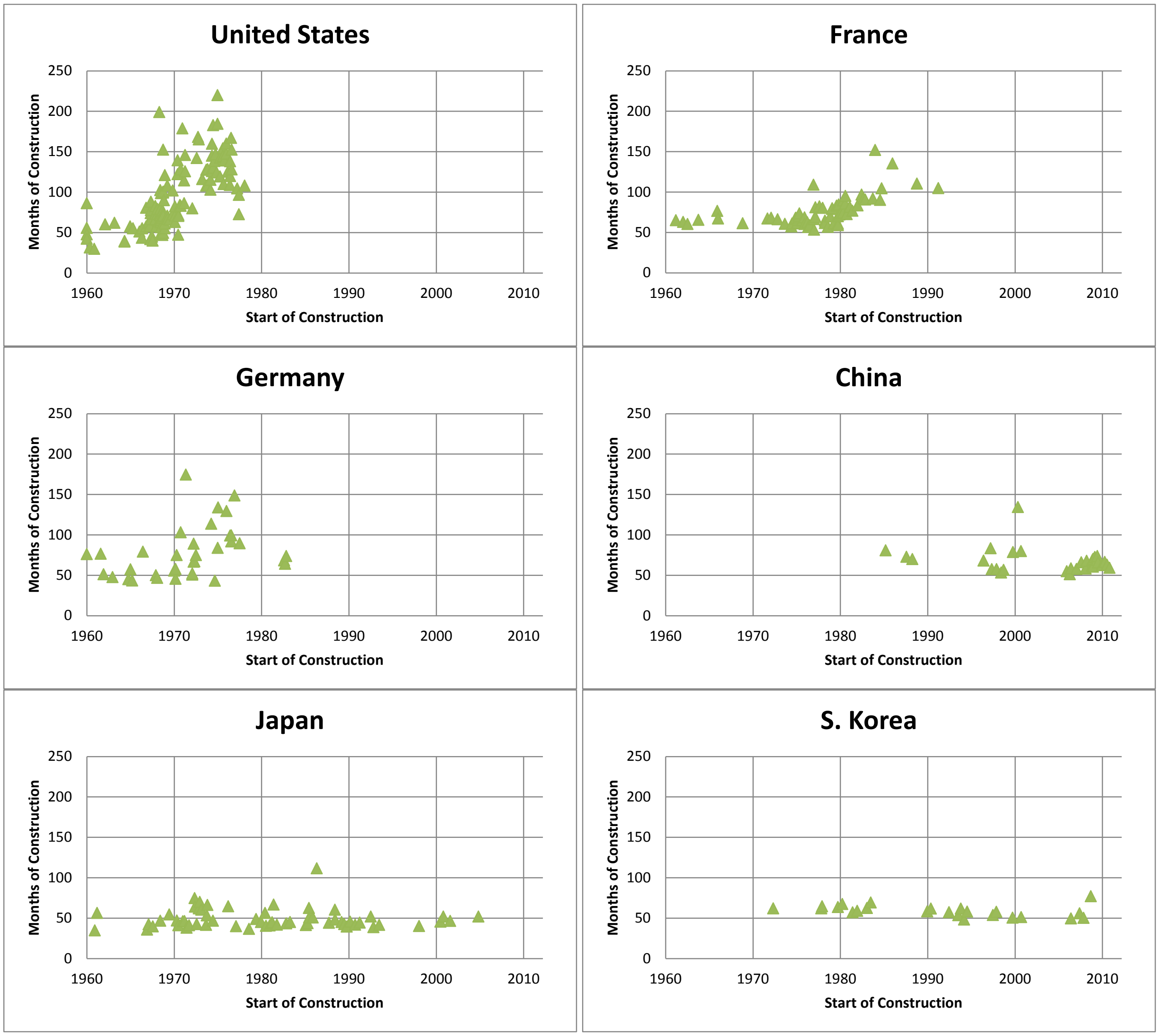

Figure 1. Reactor construction start year versus duration in three Western and three Asian countries.

In a separate study, [Carter 2010] Westinghouse Savannah River Company (WSRC) identified that an electrochemical reprocessing facility that was originally designed for a throughput of 21.3 MT/y, could be modified to a 70 MT/y throughput facility with minimal additional capital spending, because of the suboptimal optimization of equipment that needs a certain minimum size for its required functionality. This consideration is in agreement with that provided by Haire with regards to “very small capacity plants” having a scaling factor close to zero.

In summary, the approach to cost scaling needs to be done differently for different modules, and the exact quantitative approach needs to be carefully addressed separately for individual modules. Where data is available, a discussion on this topic is provided in the CBR to inform the reader on this topic, for example in the F1 Section on aqueous reprocessing. In general, more defensible, high quality data needs to be generated on this important topic.

1.1 References

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Supporting Document 5

Considerations on Learning

CONSIDERATIONS ON LEARNING

Learning refers here to the increased experience associated to each new build of a given type of fuel cycle facility, which results generally in design improvements, increased construction and operational efficiencies and reduced mistakes, and therefore in reduced costs. These are important considerations, for example, when modeling transitions from first-of-a-kind (FOAK) to nth-of-a-kind (NOAK) nuclear facilities and deciding the magnitude of the cost reduction (if any) to be applied to each successive build. Different assumptions on learning can significantly affect the results of the economic analyses during transitions. Other competing electricity-generation technologies, such as wind and solar power for example, have demonstrated substantial cost reductions through learning during the last few decades.

1.1 Learning in Design and Construction

There is no clear evidence of the existence of learning effects in the construction of nuclear facilities, based on the US and French historical construction experience: the early analysis by Komanoff [Komanoff 1981], for example, found a small reduction in cost (13%) due to learning at the Architect-Engineer level for the period 1971-1978. Later analyses (e.g. [DOE 1986] and [McCabe 1996]), however, found that learning was significant only when the utility directly managed the construction, while no learning was found when construction was managed by an external contractor:

> "*when an outside contractor managed the construction of a power plant, there was no correlation between the real costs of the plant and the constructor's experience. If outside contractors did benefit from increased experience, such learning effects did not result in lower costs. There is evidence, however, that the real costs of power plants built by utilities that acted as their own construction manager fell as they gained experience, in relation to the costs of power plants built by utilities that employed outside contractors*." [DOE 1986].

This is a cost reduction that was explained in [McCabe 1996] with the fact that experienced construction firms had substantial market power, which allowed them to charge relatively high prices. Therefore the savings due to experience were retained as profits by the firms supervising the construction instead of being passed on to the utilities and their customers. Therefore, in the case of external architect-engineers, it would not be possible to see cost reductions due to learning.

A more recent econometric analysis [Ganda 2016a], confirmed the trends found in [DOE 1986] and [McCabe 1996]. After controlling for a number of relevant variables, it was found that for each additional reactor the architect-engineering firm previously built, both the costs/kw (i.e. the actual cost outcome after construction was completed, normalized for the reactor power) and budget/kw (i.e. the pre-construction cost estimate, normalized for the reactor power) increased by 10%. A separate quantification was performed for the effect of the architect-engineer being the same as the constructor, based on data from the Nuclear Regulatory Commission. It was found that when the two firms were the same for a certain project, cost/kw were 15% less and budget/kw 22% were less than when the two firms were distinct. This effect was determined to be statistically significant.

The regulatory filings of Georgia Power with the Georgia PSC also briefly mentioned the issue of FOAK construction of Vogtle 3 and 4 [Georgia Power 2014] in the U.S.:

> "*Technical and quality issues have occurred as nuclear components are fabricated for the first time in three decades for domestic nuclear units; however, to date these issues have been adequately resolved by the Contractor to support the current construction schedule*".

The language of the filings indicates that Georgia Power considers the effect of FOAK for procurement as manageable, and having a small or negligible impact on costs. This is consistent with the findings presented in this Section.

A similar analysis performed on the construction costs in France led to similar results [Grubler, 2010]:

> *"The uncertainties in anticipated learning effects of new technologies might be much larger than often assumed, including also cases of "negative learning" in which specific costs increase rather than decrease with accumulated experience".*

Also in [Rangel, 2012] with regards to the French nuclear construction program, it was found that, somewhat surprisingly, *"neither the scale-up neither the cumulative experience, induced cost reductions"*, even though a small learning effect was found within the same reactor type and within the same *palier*.

Unlike the previous studies, [Lovering 2016] looked not only at Western experience but also included additional international evidence on the effect of learning and associated cost reduction, utilizing the cost of 349 reactors in the US, France, Canada, West Germany, Japan, India, and South Korea, encompassing 58% of all reactors built globally. It was found that trends in costs have varied significantly in magnitude and in structure by era, country, and experience. In contrast to the rapid cost escalation that characterized nuclear construction in the United States, evidence was found of milder cost escalation in many countries, including absolute cost declines in some countries (especially South Korea and Japan) and specific eras, which would support the possibility of actual cost reduction associated with learning.

Another area of construction learning is in construction practices. Construction efficiency is generally highest when performed in controlled environments with ready access to tools and materials, as for example in factory fabrication. Efficiency declines when fabrication moves to "laydown" or preassembly areas in the field, and declines even further when activities must be performed in the weather and above or below grade on partially completed structures where personnel may be in awkward positions and tools and materials must be hauled to the construction location. The need for nuclear quality certified construction aggregates this trend, for example requiring moving weld x-ray equipment to the weld location. For these reasons, nuclear construction has been evolving toward modular fabrication under factor-controlled conditions followed by assembly of modules in the field. Small modular reactors promise to extend this trend to even include most assembly in the factory. To date, the total volume of construction has been too small to definitively measure the impact of this trend with any accuracy.

In summary, the reader is advised to use caution when applying construction cost reductions associated with learning for nuclear construction, since different studies on this topic had mixed outcomes.

1.2 Regulatory Learning and Regulatory Stringency

There is evidence that other factors may be playing a role in the cost trends over the nuclear construction time periods in different countries and in different decades. One such factor is the effect of regulatory learning, as distinct from constructor learning discussed above. Regulatory learning played a key role in the cost overruns experienced in the US in the 1970s and 1980s [Ganda 2014], especially when plants were required to make changes during construction because of changing regulatory standards. In general, regulatory learning is likely to lead to increased costs across an industry, since stricter safety standards may be required. Additionally, when regulatory learning impacts retroactively existing plants, or plants under construction, it generally results in loss of revenue and extra refurbishment costs for existing plants, and large inefficiencies and wastes in the construction process for plants under construction, leading to both cost and schedule overruns.

In addition, and separate from, regulatory learning is regulatory stringency, which added cost to nuclear plants constructed in the U.S. in the 1970s and 1980s by mandating the addition of safety features and more stringent construction standards, in order to reduce the total probability of accidents of the entire nuclear sector, in light of the rapidly increasing number of nuclear plants ordered in the early

1970s. For example, the Advisory Committee on Reactor Safeguards (ACRS) – an influential body of senior nuclear experts that advised the AEC and later the NRC – in a letter to the AEC in 1965, wrote:

> *"The orderly growth of the industry, with concomitant increase in the number, size, power level and proximity of nuclear reactors to large population centers will, in the future, make desirable, even prudent, incorporating stricter safety standards in many reactors" [ACRS 1965].*

The increased regulatory stringency for US nuclear plants manifested itself in:

1. The application of more stringent and explicit safety standards, which caused a direct increase in the amount of labor, material and equipment required to build nuclear plants;
2. The expansion of the regulatory effort, requiring greater documentation and standardization of regulatory requirements: this mostly caused a substantial increase in labor costs.

Learning is also a relevant consideration in the estimation of operation and maintenance (O&M) costs for nuclear facilities. In this case, the historical US experience has shown substantial learning in the efficient operations of nuclear plants, which can be quantified with the increase in availability and capacity factors for existing nuclear plants, as shown in Figure 6-1.

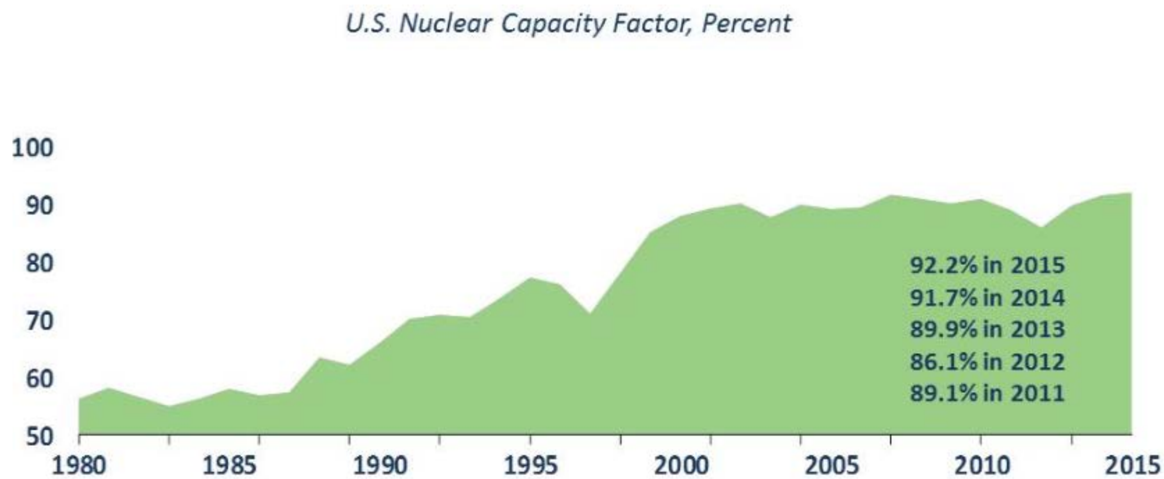

Figure 6-1. Average US nuclear capacity factor [NEI].

1.3 Conclusions

Learning is the increased experience associated to each new built or each additional operating year of a given type of fuel cycle facility. Learning is important to model in a cost analysis when transitioning to a new technology or fuel cycle that may involve first-of-a-kind facilities transitioning to nth-of-a-kind.

Several different types of leaning have been identified, with some acting on individual designs and others applying to the whole industry. The types of learning that have been identified for nuclear facilities include design, construction, operational, and regulatory. The first three theoretically result in cost reductions because experience enables identification of construction and operational efficiencies and fewer mistakes. In practice, there is clear evidence of operational learning while construction learning results are inconclusive. Regulatory learning results in a better understanding of how integrated systems perform and where additional safety measures may be warranted. These typically increase costs, with the cost impact reduced if existing facilities or facilities already under construction are "grandfathered" from new regulations. Regulatory stringency is separate from regulatory learning, though the impacts are similar. Regulatory stringency may increase faster that generating capacity if a trend toward deploying large numbers of facilities (e.g. SMRs) develops.

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Supporting Document 6

A Proposed Methodology for Transformation of Reactor Cost Data to the 'What-It-Takes' Table

A PROPOSED METHODOLOGY FOR TRANSFORMATION OF REACTOR COST DATA TO THE 'WHAT-IT-TAKES' TABLE

Note: This document represents work undertaken to refine the CBR approach for arriving at recommended cost values for the reactor sub-modules. This information is provided to indicate the possible direction of evolution in future CBR updates and encourage comments from CBR users.

Since this document was developed concurrent with many of the R-modules, the methodology was applied only in the analysis of the fast reactor (2009 Module R2) data. In future revisions an attempt will be made to use this methodology uniformly.

1. Basic Information

There are many sources of data that will be available of varying levels of quality and fidelity. These data need to be transformed from the year of dollars for the estimate and the technology, scale, learning, and other conditions to the appropriate year dollars and for the final full scale (FS) Nth-of-a-kind (NOAK) commercial power plant. This requires a number of adjustments that are inherently quite uncertain, but well known as significant factors to be corrected for. This summarizes the corrections that need to be made and the basis for making those corrections to the available data.

For illustration purposes, the data are taken from the 2009 Advanced Fuel Cycle Cost Basis (AFC-CBR) report for fast reactors (Module R2) and used to provide a method that would retain traceability back to the original raw unadjusted data taken from the various references, to the What-it-Takes (WIT) table in current year dollars. This should allow users to apply their own assumptions and judgment to adjust the WIT table as they see fit. By doing this it suggests that the original WIT table in the 2009 AFC-CBR report had a value for the Upside (lowest cost) for the specific overnight capital cost (SOCC) that was too high based on the data included in the tables including historical and projected capital costs.

2. Cost Adjustment Factors

The data that are available will range from historical data for small scale demonstration projects to cost targets for the final full scale NOAK commercial power plant. The historical demonstration plants are likely to be one-of-a-kind facilities that will undergo significant design optimization and technology changes relative to the final commercially deployed technology because of differences in their purpose and/or knowledge gained from successful or failed demonstration. The cost targets for the final FS NOAK may be grounded as much in wishful thinking as they are in solid engineering. There is an entire spectrum of historic cost data and cost estimates for reactors that fall in this wide range between these two. The SOCC for the worst demonstration project will be well beyond the downside cost of the FS NOAK commercial power plant because of the small scale, learning, and other factors. The SOCC of the lowest cost targets are likely well below the upside costs of the FS NOAK since as the design progresses through more thorough safety analysis and licensing there are likely significant cost additions without any cost reductions.

The following subsections describe the adjustment factors to be applied to a given cost estimate taken from a reference to adjust it to the FS NOAK commercial power plant estimate. This is only when no data exist to perform more accurate estimates of these adjustments. These adjustment factors are highly simplified to try and bound the range of the likely adjustment that would occur in practice. That should be considered when using the information for the WIT table estimates. The next section will discuss the logic of how to use that adjusted data for the WIT table estimates.

2.1. Adjustment to Overnight Capital Cost

The value of interest is the overnight capital cost in a specific year dollars. Many estimates will include financing costs or year of expenditure dollars. Therefore, they require adjustments to get to the actual value of interest, which is the overnight capital cost exclusive of financing and inflation. The appropriate adjustments should be documented, and the factor is the ratio of the value reported to the overnight capital cost in the specific year of dollars.

2.2. Inflation Adjustment

All costs need to be adjusted to the same year and in the future adjusted to the current year dollars. The appropriate factor is difficult since the total cost is the sum of different fractions of things whose relative value will vary over time. It is the aggregate average that is correct, but only vendors generally have the kind of information needed to attempt to do this accurately. For this exercise, the value to get from the 2009 AFCCBR report to 2012 was 1.019/0.936 taken from the updated addendum on the subject.

2.3. Demonstration Adjustment

Demonstration projects amongst other adjustments must account for differences in scope or learning that comes from demonstration that leads to a more optimum design. If it is a commercial demonstration, then all the regulatory requirements have been incorporated and it is going to lead to improved designs and technology. The value of this adjustment is going to be highly subjective, but generally should lower the SOCC because it should generally lead to a more cost effective design than the demonstration power plant or cost savings related to additional capabilities included in the demonstration project. Demonstration reactors will range from primarily research facilities up to a reduced-scale first-of-a-kind (FOAK) commercial power plant. There should be no adjustment for the reduced scale FOAK making the adjustment factor 1.0, but if there is design optimization or scope reduction before the FOAK FS commercial power plant, then it should be less and possibly significantly less than 1.0. The basis should be discussed and documented.

2.4. Unit Size Scale Adjustment

If the design is for less than FS, the SOCC must be adjusted for the difference in scale. If the final FS NOAK commercial power plant is a large monolithic type of power plant, then the economics typically relies on significant economy of scale which should significantly reduce the SOCC relative to smaller scale demonstration projects.

From the EMWG Generation IV cost estimating guidelines, the exponential method to adjust for plant size, capacity, or rating is described by the following.

$$C = A + Bp^n$$

where

A = a fixed component,

B = the variable component, with

p = being the power ratio to the reference plant, and

n = being the exponent that reflects the size benefit.

Since the lack of data will exist to fit all 3 parameters, the assumption that most aspects of the unit will be variable costs is probably not a bad assumption. The EMWG has separate exponents for the nuclear Island (0.33) and balance of plant (0.66). Given differences in technology and other factors, these probably are bounding since it is the sum of these two components. The assumption is that this scales on the thermal power (not electrical) of the individual reactor core. Corrections for multiple reactors on a single site and improved thermal efficiency are adjusted separately.

The following is the approximation for specific capital cost.

$$c_i = \frac{C_i}{P_i} = \frac{A + Bp^n}{P_i} \approx \frac{Bp^n}{P_i} = \frac{BP_i^{n-1}}{P_{ref}{}^n}$$

The unit scaling adjustment factor is the ratio of the unit cost at FS commercial to the scale of the cost estimate being adjusted.

$$f_{unit} = \frac{c_{FS}}{c_{demo}} = \frac{BP_{FS}{}^{n-1}}{P_{demo}{}^n} \frac{P_{dem}{}^n}{BP_{demo}{}^{n-1}} = \left(\frac{P_{FS}}{P_{demo}} \right)^{n-1}$$

2.5. Multi-Unit Adjustment

Siting multiple units on a single site has a significant cost benefit. Scaling for this is difficult, but it can be assumed to follow the same exponential behavior. However, the exponent will be much lower than that for the unit scaling. Some fast reactor concepts involve multiple reactor cores supplying thermal energy to a single turbine generator. With sufficient detail, these would all need to be scaled separately, but the assumption is these data do not exist. A low value of n from 0.1 to 0.2 is assumed for this factor.

$$f_{multi} \approx \left(\frac{\left(N_{\text{Rx per SG}} N_{\text{SG per Plant}}\right)_{FS}}{\left(N_{\text{Rx per SG}} N_{\text{SG per Plant}}\right)_{demo}} \right)^{n-1}$$

2.6. Learning Adjustment

Learning theory predicts that for each doubling of production, the unit cost will be reduced by a certain fraction. Obviously, there is a limit to this, but it is a good approximation to get from a FOAK estimate to an NOAK assuming a reasonable learning rate and a reasonable number of multiples of production of the FOAK. In the Gen IV EMWG guidelines learning rates are in the 90% to 94% range for equipment and labor. They also assume an 8 GWe overall nuclear deployment capacity for spreading of the deployment costs (non-repetitive costs) that need to be recovered in the initial deployment phase prior to reaching NOAK where all costs are repetitive costs and do not include the initial licensing and R&D costs. If this information is available better estimates can be made. For this approximation, bounding the learning adjustment will assume learning at a 90% rate for 16 GWe (highest learning) and learning at 94% for 8 GWe (lowest learning). This is based on the power level of a single complete unit and not the power plant, so for multiple units on a single site, there is learning from unit to unit.

$$f_{learn} \approx \left(\frac{P_{learn}}{P_{FSFOAK}} \right)^{\frac{\ln(r_{learn})}{\ln(2)}}$$

2.7. Thermal Efficiency Adjustment

Many of the initial demonstration designs are at lower outlet temperatures and lower thermal efficiencies. How to account for this is not clear without detailed estimates. The range is (1) from no correction, and (2) assuming that is accounted for in the learning or other adjustments to the limit of the ratio of the demo thermal efficiency to the final thermal efficiency.

3. Estimated Full Scale Nth-of-a-Kind Commercial Power Plant

Using the existing data from the 2009 AFCCB report produces the following results. Table 3-1 provides the original raw data taken directly from the reference and converts it to specific overnight capital cost in constant year dollars. The first 6 columns should never change from revision to revision. Adjustment factors may be revised, but the raw data unless transcribed in error should never change providing continued traceability to the specific reference that it was taken from. There could be multiple lines for the same power plant if there is conflicting or revised data.

Table 3-2 provides the information needed to make the described adjustment.

Table 3-3 shows the calculated or assumed adjustment factors both for the upside (leads to lowest cost estimate) and downside (leads to highest cost estimate) and the multiplication of those factors with the SOCC of that reactor to give an estimate of the range of the ultimate SOCC.

The next challenge is how to interpret these data without simply reflecting the biases of the estimator.

Figure 3-1 shows a plot of all of this data including the old and proposed sodium-cooled fast reactor (SFR) and current LWR upside and downside.

How to choose the upside and downside from this data is obviously very speculative. The values chosen were simply 25% premium on the average of the JSFR and S-PRISM. Is it appropriate to add a premium (thereby rejecting their work as implausible) onto the estimate from a corporation that is a commercial reactor vendor? The downside was a 50% premium on the most recent BN-800 revision. Both were rounded to 2 significant figures. This put it somewhat above the unadjusted cost. Exactly how much conservatism to add on designs at early stages of development or how to translate the cost of reactors built

Table 3-1. Raw Data Converted to Specific Overnight Capital Cost in 2012 year dollars.

	Information Taken From Reference						Calculations		
	Total Capital Cost ($B)	Specific Capital Cost ($/kWe)	Year	Estimate Type	Net Electrical Generation (MWe)	References	Adjustment factor to Constant Year Overnight Cost	Adjustment factor to 2012 dollars	Specific Overnight Capital Cost in 2012$ ($/kWe)
MONJU	6	N/A	2006	Overnight	280	2009 AFCCB	1	1.089	23,329
SuperPhenix	9B Euros = $11B	N/A	2006	Overnight	1240	2009 AFCCB	1	1.089	9,658
JSFR	2.3		2006	All-in	1500	2009 AFCCB	0.90	1.089	1,509
BN-800	2		2006	Overnight	800	2009 AFCCB	1	1.089	2,722
BN-800 Revised		6000	2006	Overnight	800	2009 AFCCB	1	1.089	6,532
Future French Prototype	2		2007	Overnight	800	2009 AFCCB	1	1.056	2,640
Kalpakkam Prototype FBR	0.717		2003	Overnight	500	2009 AFCCB	1	1.355	1,943
CRBR	3.6		1984	Overnight	350	2009 AFCCB	1	1.905	19,596
ALMR - 1994	2		2006	Overnight	800	2009 AFCCB	1	1.089	2,722
S-PRISM	0.717		2003	Overnight	500	2009 AFCCB	1	1.355	1,943

Table 3-2. Information for Adjustment to Full Scale Nth-of-a-kind Commercial Power Plants.

	Cost Data Power Plant						Full Scale Commercial Power Plant				
	Description (Demo/FOAK, NOAK, etc.)	Reactor Size (MWt)	Reactors per Turbine	Turbine Size (MWe)	Turbines per Site	Ref.	Reactor Size (MWt)	Reactors per Turbine	Turbine Size (MWe)	Turbines per Site	Ref.
MONJU	Demo	714	1	280	1		3530	1	1500	2	
SuperPhenix	FOAK Commercial	3100	1	1240	1		3100	1	1240	2	
JSFR	NOAK Design Concept	3530	1	1500	2		3530	1	1500	2	
BN-800	Outdated Estimate	2300	1	800	1		2300	1	920	4	
BN-800 Revised	FOAK Commercial	2300	1	800	1		2300	1	920	4	
Future French Prototype	Demo	2300	1	800	1		2300	1	920	4	
Kalpakkam Prototype FBR	Demo	1400	1	500	1		4200	1	1680	2	
CRBR	Detailed Demo Design – Abandoned	1000	1	350	1		3750	1	1500	2	
ALMR - 1994	NOAK Design Concept	840	2	622	3		840	2	622	3	
S-PRISM	NOAK Design Concept	1000	2	760	3		1000	2	760	3	

Table 3-3. Adjustment Factors and Estimated Specific Overnight Capital Cost of the Full Scale Nth-of-a-Kind Commercial Power Plant.

	Demonstration		Unit Size Scaling Adjustment		Multi-Unit Adjustment		Learning Adjustment		Thermal Efficiency Adjustment		SOCC FS NOAK Commercial Power Plant ($/kWe)	
	Upside	Downside	Upside	Downside	Upside	Downside	Upside	Downside	Upside	Downside	Upside	Downside
MONJU	0.900	1.000	0.343	0.581	0.871	0.933	0.698	0.861	0.923	1.000	4,034	10,887
SuperPhenix	1.000	1.000	1.000	1.000	0.871	0.933	0.678	0.847	1.000	1.000	5,699	7,629
JSFR	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1,509	1,509
BN-800	1.000	1.000	1.000	1.000	0.758	0.871	0.648	0.824	0.870	1.000	1,162	1,953
BN-800 Revised	1.000	1.000	1.000	1.000	0.758	0.871	0.648	0.824	0.870	1.000	2,789	4,688
Future French Prototype	0.900	1.000	1.000	1.000	0.758	0.871	0.648	0.824	0.870	1.000	1,014	1,895
Kalpakkam Prototype FBR	0.900	1.000	0.479	0.688	0.871	0.933	0.710	0.870	0.893	1.000	462	1,086
CRBR	0.900	1.000	0.412	0.638	0.871	0.933	0.698	0.861	0.875	1.000	3,751	9,744
ALMR - 1994	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1,524	1,524
S-PRISM	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1,948	1,948

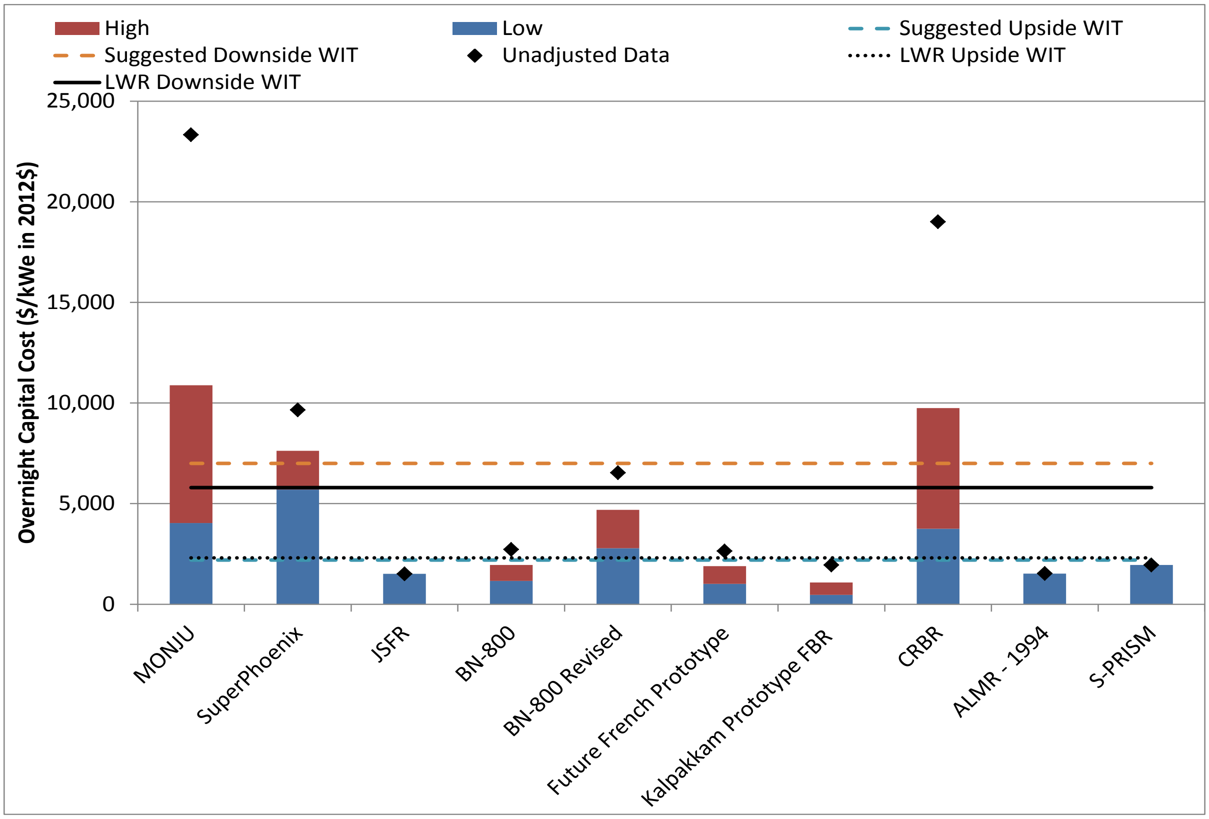

Figure 3-1. Specific Overnight Capital Cost Information.

or being developed in other countries with very different labor rates, productivity, practices, and regulatory environments is not clear. The same is true for the very large uncertainties in scaling small demo designs from concepts that have since been abandoned and are not being carried forward because of their failures. Clearly, they should not set the upper bound of the cost, but how much improvement is realistic is certainly highly speculative. As far as a choice of nominal values, clearly the cost data is clustered at or below the upside value choses so a value of 3800 (1/3rd – 2/3rd split between upside and downside) was chosen to reflect this skewing of the data. This is however lower than the nominal for LWRs, something that many SFR designers believe is achievable because of the low pressure, higher thermal efficiency, and low corrosion, but must overcome the challenges of working with sodium and the cost of an intermediate heat exchanger.

Table 3-4 shows the values of the lines plotted in Figure 3-1. This methodology suggest that the upside was way too high at more than double that of the JSFR estimate and nearly 70% higher than the S-PRISM estimate. The downside value is probably a little too high, but it’s not clear how to put a number on this. At a slightly more than 30% premium on the most expensive LWR, the slightly reduced 20% seems more in line with the old thinking that there is a 20% premium above LWRs. The new value for the downside on the SFR is a 6% savings on the best LWR, which is consistent with the current thinking of design development and optimization that has taken place since CRBR and other demonstration reactors. The exact values are obviously not so precise and probably should be rounded off to $2,200 and $7,000 per kWe in 2012 dollars.

Figure 3-2 shows the cumulative distribution of the adjusted data in Table 3-3 compared to the What-it-Takes (WIT) distribution from Table 3-4. The results show that relative to the data the WIT distribution is shifted to significantly higher values than even the high values for those estimated at the lowest cost. This is because most of this data is not for completed reactors, recent design concepts, or U.S. reactors. A number of additional factors have been proposed for incorporation that relate too much of the implicit adjustment in the very low end of the data. These additional factors included:

- paper reactor to practical reactor
  - o done implicitly, but should have been made explicit
- foreign country to U.S. adjustment
  - o costs of the SFR being built in India would need significant adjustment to determine the equivalent cost of building that reactor in the U.S. beyond currency conversion
- current regulatory standards adjustment
  - o even building an LWR in 2012 would involve more cost than building that same reactor a couple decades ago
- non-recurring costs in demonstration projects
  - o were any of these costs included in the overnight cost, which is likely and should be removed from the starting overnight cost before trying to project to the FS-NOAK-CPP.

Table 3-4 What-it-Takes Table Information ($ per KWe).

	Upside	Mean	Nominal	Downside
Old FR	3,266	5,029	4,200	7,621
SFR	2,200	4,600	4,600	7,000
New LWR	2,300	4,033	4,000	5,800

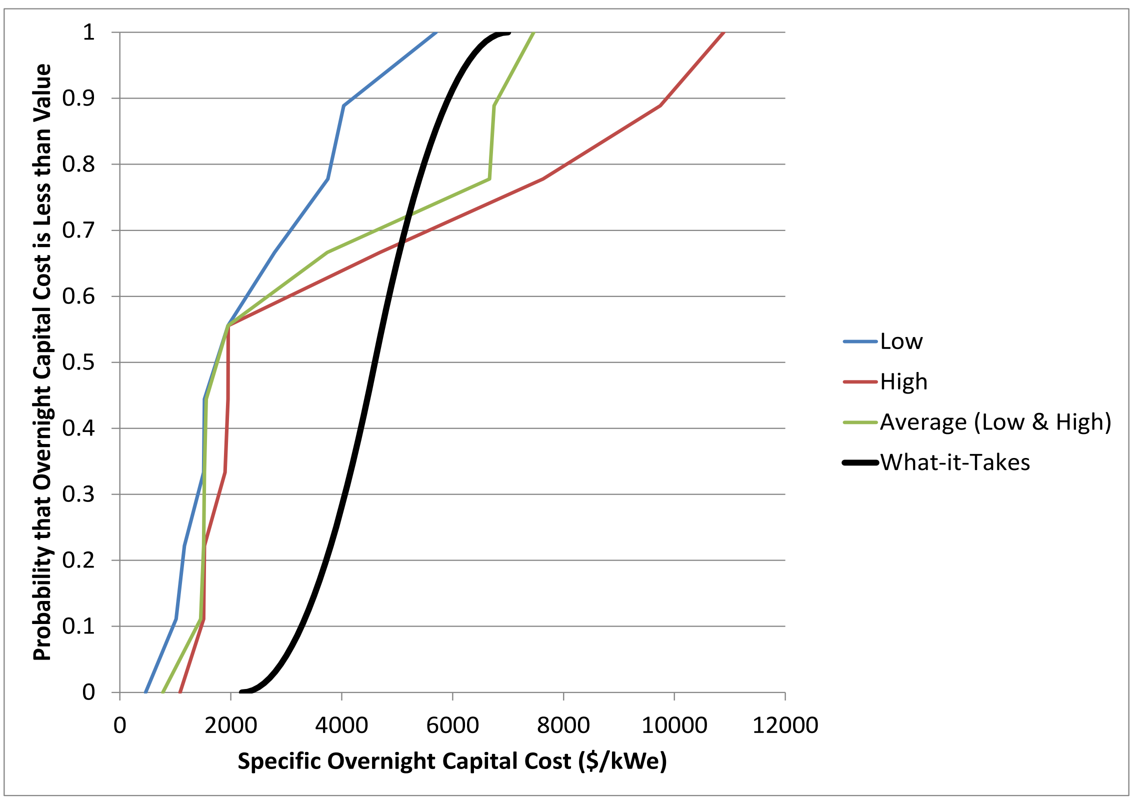

Figure 3-2. Cumulative Distribution Function for Low, High, Average of Low and High, and What-it-Takes Values.

Supporting Document 7

Presentation: Du and RU Disposal Costs


DU and RU Disposal Costs

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April 2015

Present Situation

- Worldwide DU and RU in various chemical forms are some of the largest legacy products of the nuclear industry (defense & power) in both mass and volume
  - DU: > 10E+6 MTU (from large scale enrichment)
  - RU: > 10E+5 MTU (from large scale reprocessing)
- Chemical forms include U metal or alloy, UF6, UO2, UO3, U3O8, and UF4
- Most of this material is now in above ground storage
- Due to chemical stability and low water solubility oxides are the preferred form for safe storage and ultimate disposal

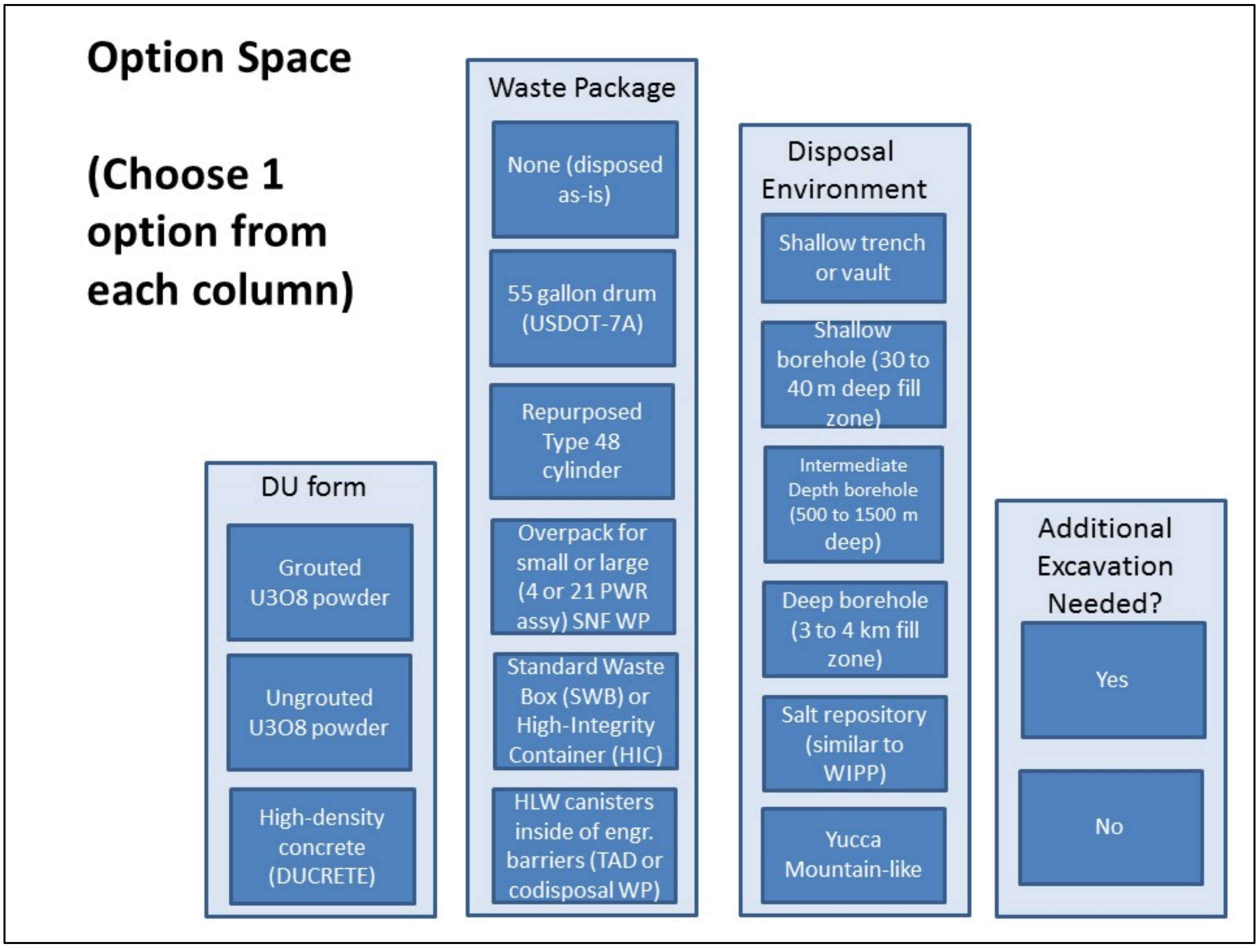
Long term U disposal in large amounts presents more of a potential radioactivity problem than its conversion and temporary storage

- Now a near term problem with freshly-mined uranium ore, radon emanation will eventually be a long-term problem for both DU and RU dispositioned in large quantities at a specific location
  - Separated* Uranium's specific activity increases with time (mining/milling, enrichment, and reprocessing remove non-U daughters, hence time=0 starts after these ops)
  - Millions of years, however, to reach secular equilibrium
  - Any shallow burial essentially results in a "uranium mine" with U concentration in the inherent dense solid medium of over 60%
  - Planned disposal of DU and RU forms in shallow LLW disposal sites meeting some institutional resistance.
  - Large quantities may require expansion of LLW disposal land area at some sites

  ***U-ore processing/milling, uranium enrichment, and spent fuel reprocessing physically or chemically separate uranium from non-uranium decay daughters and other non-U elements**.

We will first consider DU

- Two sources of DU
  - Enrichment process "tails" (< 0.711% U-235) collected as DUF6 in large steel cylinders
    - Some facilities convert this to more stable U3O8
    - "Tails" has been produced since 1945
    - Most tails is "virgin", i.e. it arises from unirradiated U fed to uranium enrichment plants and is free of trace fission products or transuranics
    - Tails with significant FPs or TRUs therein would be treated like RU.
  - Irradiation of LEU driver fuel or Natural or depleted U blankets/targets can result in U-235 assays less than 0.711% U-235 in recovered reprocessing U product, depending on burnup
    - This separated low-assay product is sometimes re-enriched
    - This material is really reprocessed U (RU) and will be considered in second part of this presentation



Cases considered in this study

ID	DU Form	Waste Package	Disposal Environment	Additional Excavation?	AFC CBR module designator
1	Ungrouted	Drum, cylinder, or SWB	Shallow Trench or Vault	Yes	K1, J, L2 alts. 4 and 5
2	DUCRETE	Overpack for small or large WP	Yucca Mountain-like	No	--
3a	Unrgouted	55 gallon drum or Type 48 cylinder	Yucca Mountain-like	No	K2
3b	Unrgouted	55 gallon drum or Type 48 cylinder	Yucca Mountain-like	Yes	--
3c	Ungrouted or grouted	HLW canisters in co-disposal WP	Yucca Mountain-like	Yes	L1
4a	Ungrouted	Drum, cylinder	Shallow borehole	Yes	L2 alternative 3
4b	Ungrouted	None or equivalent of drum/cylinder	Intermediate depth borehole	Yes	--
4c	Ungrouted	None or equivalent of drum/cylinder	Deep borehole	Yes	L1 alternative 7
5	Ungrouted	Drum, cylinder, or SWB	Salt repository	Yes	L1 alt. 2, L2 alt. 2

Four DU Waste Forms

Form	Nominal Density [kg/m3]	Uranium Density [kg/m3]	Comment
U3O8 Powder	2800 (max packing)	2370 (max packing)	WAC limit at NTS for shallow DU disposal is 2600 kg DU/m3
Grouted U3O8	~3000	1190	
UF4	3000	2270	May be compatible with certain environments, not considered further here
DUCRETE	5500	3550	Make high-density 'DUAGG' ceramic by sintering U3O8 with silica, alumina

Most cost studies to date have dealt with DU/RU conversion, DU/RU storage and possible DU/RU shallow disposal

- Conversion is the process of producing a safer, "above-ground" storable chemical form from the enrichment plant or reprocessing plant outputs (UF6 or uranyl nitrate hexahydrate respectively);
  - "Tails cylinder" stored UF6 to U3O8 for DU: conversion now underway in US and France
  - Uranyl Nitrate Hexahydrate solution to UO3 or U3O8 (after LWR-SNF aqueous reprocessing)
  - Uranium metal is likely form from pyroprocessing of metallic fast reactor fuels
- Few studies have considered "deeper" disposal of packaged oxide or metal DU or RU forms
- Advanced Fuel Cost Basis Reports began to do this in 2009 and 2012
- We are revisiting these uranium disposal fuel cycle steps again and looking at some new options!

Current unit cost values in *Advanced Fuel Cycle Cost Basis Report (2012 Update)*

- Geologic Disposal* of Packaged DU3O8:
  - Low — 2 $/kgDU — Most favorable estimate found in literature
  - Most Likely — 4 $/kgDU — High end of private LLW site estimates
  - High — 22 $/kgDU — Avg of DOD ThO2 & anti-nuke "deep disposition" estimate

*Deconversion/packaging costs not included

Packaging: 55 gallon drums, standard waste boxes (SWBs), high-integrity containers HICs

- Cheapest disposal packaging options would be none at all (e.g. pour powder directly into a borehole) or reuse of DUF6 cylinders
- A 55-gal carbon steel drum (~$100) would contain 540 kg U3O8 (Hightower 2000).
  - Unit cost : **$0.2/kg DU**
- DU may be disposed in containers typically used for other LLW or GTCC waste rather than 55-gallon drums or surplus Type 48 cylinders
  - LLW at the NNSS is typically disposed in Type B-25 SWBs
- A high-integrity container is designed to meet the structural stability requirements of 10 CFR §61.56
  - 10 CFR §61.56 says that the stability of waste be provided by the waste form itself, by processing the waste into a stable form, or by placing the waste into a container that provides stability after disposal
  - HICs are required to withstand 30 foot drop onto an unyielding surface and designed to contain waste for 300 years
- Commercially-approved HICs include
  - NUKEM Nuclear Technologies NUHIC-55
  - SEG Enduro Pak HDPE HIC
  - SEG SQ113 Concrete HIC

High Integrity Container of Class A LLRW being placed in a cylindrical disposal vault.

Reference: Hightower, J.R. and Trabalka, J.R., "Depleted Uranium Storage and Disposal Trade Study," ORNL/TM-2000/10, 2000.

Use of Standard Waste Boxes (SWBs) or High-Integrity Containers (HICs)

DU form	Waste Package	Disposal Environment	Additional Excavation?
Ungrouted or grouted U3O8 powder	Standard Waste Box (SWB) or High-Integrity Container (HIC)	Any	Any

- The Container Products Corporation B-25 will be considered as a reference SWB
  - Cost: \$2,500
  - Internal volume: 2.55 m^3
  - Maximum load: 2700 kg
- Given the density of DU3O8, the maximum load is limiting, so 2700 kg DU3O8 (2290 kg DU) can be loaded per B-25
- Therefore using this SWB for disposal would add \$2,500/2,290 = **\$1.1/kg DU**
- The Enviralloy EA-50C will be considered as a reference HIC
  - Cost: \$50,000
  - Internal volume: 1.19m^3
  - Maximum load: 1900 kg
- Given the density of DU3O8, the maximum load is limiting, so 1900 kg DU3O8 (1610 kg DU) can be loaded per HIC
- Therefore using this HIC for disposal would add \$50,000/1610 = **\$31/kg DU**

Sources for B-25 costs and dimensions/payload: http://c-p-c.net/b-25-waste-containers.asp and Arkansas Nuclear One Decommissioning Cost Analysis, Document E11-1605-002.

1. 'Shallow' Disposal at LLW Facility

DU form	Waste Package	Disposal Environment	Additional Excavation?
Ungrouted U3O8 powder	Type 48 cylinder, 55 gallon drum or SWB	Shallow trench or vault	Yes

- Was considered in Modules K1 (and indirectly J and L2)
- Module K1 presented 3 cost estimates for trench/vault disposal which ranged from \$1.5-\$4/kg DU
- One of these estimates was developed for the Waste Control Specialists (WCS) facility in Texas
  - WCS is now authorized to dispose large quantities of depleted uranium in concentrations greater than 10 nCi/gram
  - DU will be encased in concrete at a depth ca. 100 feet
  - More on the WCS facility later in the presentation
  - No new cost data specifically applicable to WCS was found

Shallow Disposal of DU at LLW Facility – cost from Module J of 2009 CBR

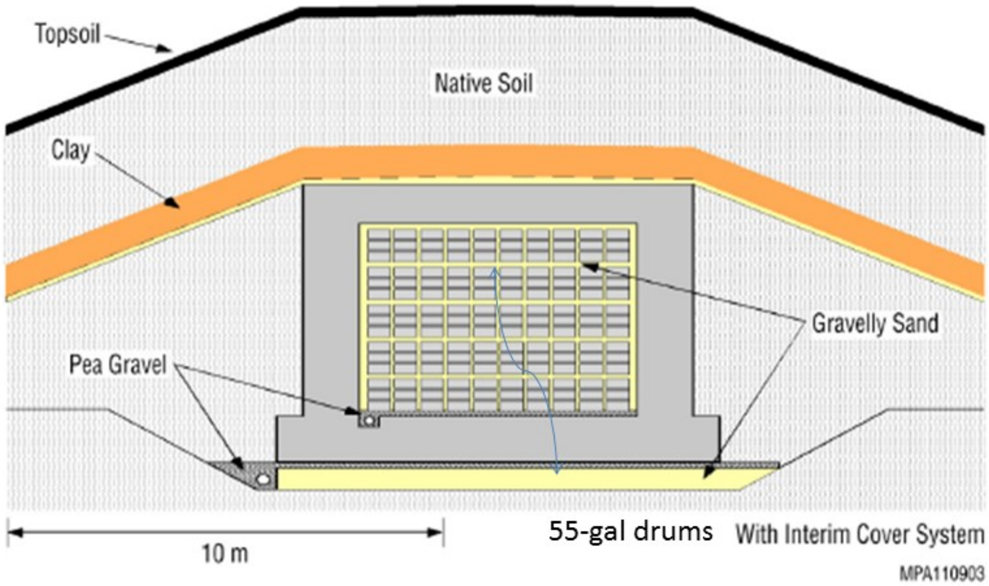
- Module J of the 2009 CBR featured a bottom-up assessment of LLW disposal at a NNSS-like facility
  - it was developed with non-DU LLW in mind, but aside from packaging costs (discussed earlier) it is applicable to DU co-disposal and provides another unit disposal cost estimate

Shallow Disposal of DU at LLW Facility – cost from Module J of 2009 CBR and comparison to Module K1 of 2012 CBR

- From Module J:
  - Unit disposal cost per volume of waste: \$1,250/m^3 (nominal)
  - Volume of B-25 SWB: 2.55 m^3
  - Mass of DU loaded per SWB: 2,290 kg DU
  - Unit disposal cost: 1,250*2.55/2,290 = \$1.4/kg DU (\$1.5/kg DU in 2011 dollars)
  - high end Module J unit disposal cost of \$2,500/m^3 corresponds to \$3/kg DU in 2011 dollars
  - Adding packaging costs of \$1.1/kg DU brings the total for shallow DU disposal at an NNSS-like facility to **\$2.6-\$4.1/kg DU**, much the same as the **\$1.5-\$4/kg DU** from the three estimates used to develop the low and nominal cost estimates in Module K1

Shallow Burial in Vaults from Module L2 option 5:

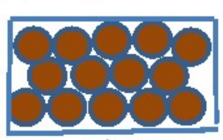
Specially-constructed vaults have been considered for DOE-EM GTCC waste and could be adapted to DU3O8



Consider this vault option for DU3O8-filled Type-48 steel cylinders

- Module L-2 of AFC-CBD Update (Geologic Disposal: GTCC) gives a unit cost of \$4333/m3 of vault space (for cylindrical stacked drums)
- Stacked 48-G cylinders could provide effective vault volume utilization of 80%, i.e. 80% of vault volume is dispositioned bulk U3O8 powder

Assume that instead of 55-gallon drums stacked vertically 4 high, that Type 48 U3O8-filled "tails" cylinders could be laid horizontally side to side and stacked vertically up to 3 high in the vault.



- Adjusted Unit cost would then be ~\$5420/m3 of powder
- Unit cost depends on bulk density (1.8 to 2.6 MT/m3):

Density	\$/kg DU3O8	**\$/kg DU**
2.6	2.08	**2.46**
2.3	2.35	**2.78**
1.8	3.01	**3.55**

- This falls in mid-range of better-known "shallow" burial unit costs and agrees with the results derived from Modules K1 and J and shown above
  - But the more complex vault volumetric cost estimate might be low.

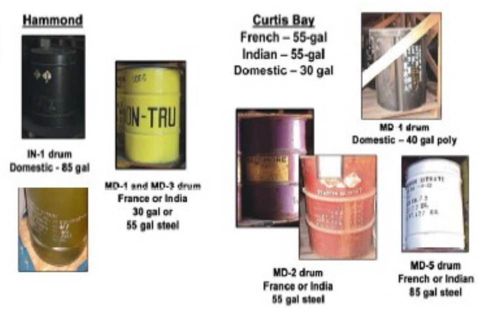
Shallow disposal at LLW facility: experience disposing thorium nitrate at NNSS

- 1,290 tonnes of $Th(NO_3)_4*5H_2O$ (not an oxidizer) were disposed at the NNSS in the early 2000s
  - Th was inside 55 gallon drums in cargo containers similar to the B-25
- Cost of this effort was \$15M, translating to **\$14.5/kg Th** in 2012 dollars

Figures and data from: Hermes, W., "Removing the Source Term – Thorium Nitrate Disposal at the Nevada Test Site," 2007 HPS Midyear Topical Meeting.

Shallow disposal at LLW facility: experience disposing thorium nitrate at NNSS

- Why is this cost nearly an order of magnitude higher than the estimated cost of shallow burial of DU?
  - Cost includes transportation and packaging: some 12% of drums were found to be pressurized, needing venting w/ filtration



  - Project was around two orders of magnitude smaller in scale than DU disposal effort
  - Bulk density (1.9 g/cm^3) and Th mass fraction of material lower than density and U mass fraction in DU3O8
  - Disposition took place in a trench at Area 5: total depth of cover needed to meet 1000-yr ^{222}Rn (from ^{230}Th decay) limits was some 6 meters, so a custom trench had to be dug at Area 5

Figures and data from: Hermes, W., "Removing the Source Term – Thorium Nitrate Disposal at the Nevada Test Site," 2007 HPS Midyear Topical Meeting.

Waste Control Specialists

- WCS operates the only commercial facility in the U.S. licensed (in the past 30 years) to dispose of Class A, B and C LLW and Mixed LLW
  - It is the site for the Texas Low-Level Radioactive Waste Disposal Compact facility for commercial LLRW and the Federal Waste Facility for waste from DOE
  - WCS has contracts in place with most of the nuclear power plants in the U.S. and a nationwide contract with DOE that can be used by DOE or its contractors.
- The WCS facility sits atop a formation of 600 feet of impermeable red-bed clay

Source: WCS press release, February 2015

WCS facilities

NRC and TCEQ Regulations

- Texas is an Agreement State, so licensing of the WCS facility is delegated by NRC to the TCEQ (Texas Commission on Environmental Quality)
- As of August 2014, WCS is authorized to dispose of DU
  - WCS is actively seeking to expand its TCEQ license to dispose GTCC wastes
  - WCS also plans to submit license application for ISFSI to NRC by April 2016 (evidently this must go through the NRC)
- TCEQ regulations for GTCC and GTCC-like LLW stipulate that dose to a member of the public remain below 25 mrem/yr and to an inadvertent intruder below 500 mrem/yr for 1,000 years or until peak dose is reached, whichever is longer
- GTCC waste would be disposed and grouted inside a so-called 'Modular Concrete Canister'

** http://pbadupws.nrc.gov/docs/ML1503/ML15034A195.pdf

Modular Concrete Canister

A MCC is approximately 3 meters high and 2 feet in diameter. It weighs approx. 4.5 tonnes when filled with grouted irradiated hardware (or other GTCC). Dose rates are to be < 150 mrem/hr at 30 cm from the MCC surface.

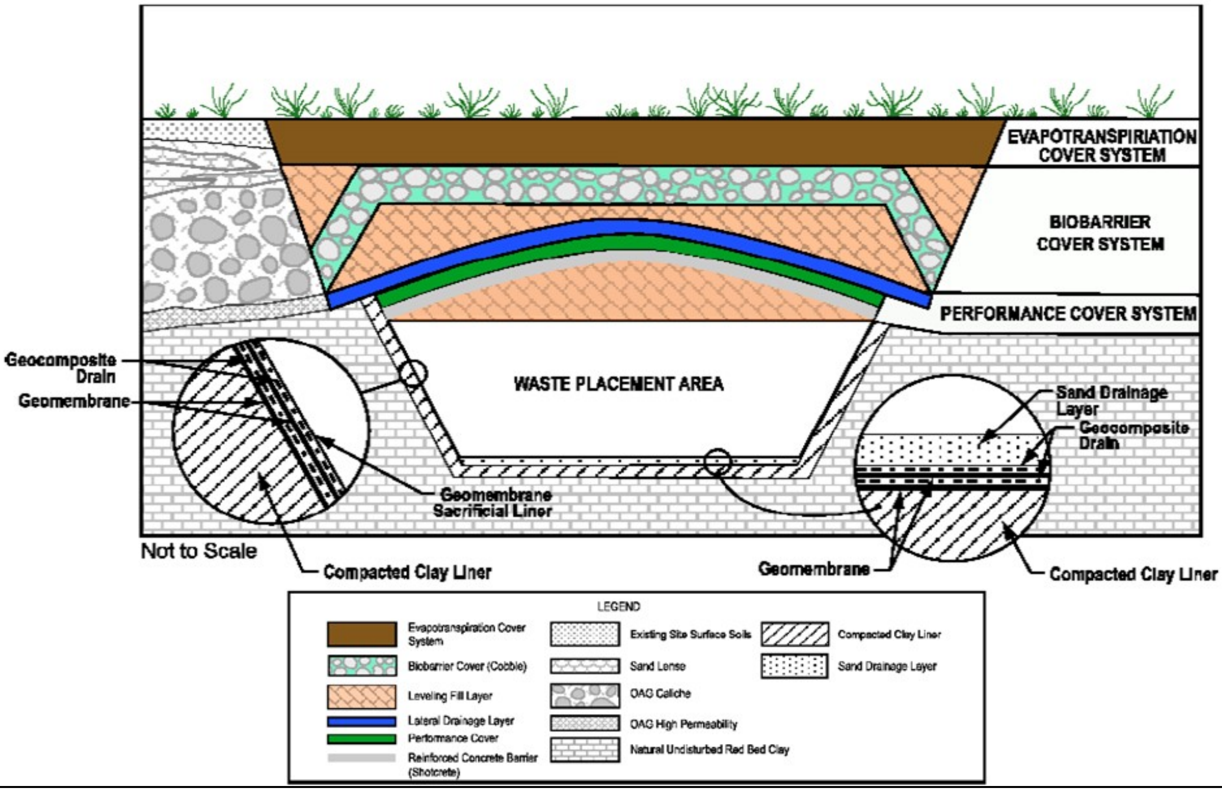
WCS has two facilities

- Compact Waste Disposal Facility (CWF) and Federal Waste Disposal Facility (FWRF)
  - The CWF accepts commercial LLRW (containerized Class A, B, and C)
  - The FWF accepts LLRW and Low Level Mixed Waste (LLMW) that is the responsibility of the Federal government under the LLRW Policy Act, e.g., (Department of Energy (DOE) waste, U.S. Navy vessel decommissioning waste, government atomic weapons Research and Development (R&D), testing or production waste, excluding Greater than Class C).

WCS Federal Waste Facility

Disposition operations will take place 40 meters below grade

WCS post-emplacement cover plan



WCS license provisions from Texas Commission on Environmental Quality (TCEQ)

- Permitted above ground possession of:
  - Any source material not to exceed 30,000 kg
  - SNM not to exceed 350 grams of U-235 (or 200 grams of Pu or U-233)
- Total volume of disposal facilities* increased to 35 million ft^3
  - volume of CWF (where civilian DU would likely be emplaced) increased from 2.93 to 9 million ft^3 (255,000 m^3)
  - total decay corrected radioactivity not to exceed 9.49 MCi (of which 3.89 MCi in the CWF)
  - Disposal of DU is authorized under the TCEQ license as of August 2014
- GTCC waste is still excluded but WCS is actively seeking to amend their license to allow GTCC disposal**

* Compact Waste Disposal Facility plus Federal Waste Disposal Facility.

** http://pbadupws.nrc.gov/docs/ML1503/ML15034A195.pdf

DU disposition by WCS

- DU is classified as Class A but increases in radioactivity over time
  - WCS will disposition DU encased in concrete at a depth of more than 100 feet with a cover system that is 30 feet thick
- To obtain the license from TCEQ, WCS had to update its performance assessment to consider disposal of large quantities of DU:
  - "WCS demonstrated that the geological characteristics of WCS' LLRW disposal facilities are extraordinarily protective and isolate long-lived radionuclides, such as DU, from the biosphere for a period of at least one million years, which was the maximum measurement term of the performance assessment."*

*http://www.wcstexas.com/2014/license-amendment-enhances-disposal-options/

DU disposition by WCS

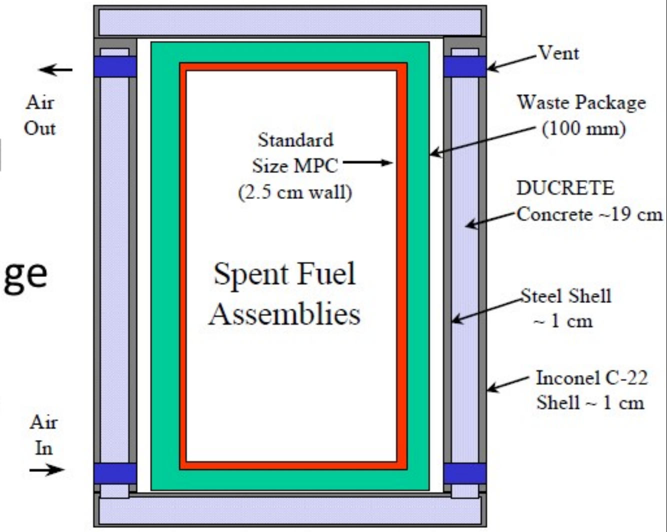
- If converted to oxide with a nominal density of 2800 kg/m^3, the 550,000 tDU currently held in the US would occupy a volume of 230,000 m^3
  - This represents around 90% of the 255,000 m^3 of volume currently authorized by TCEQ
- Checking against activity:
  - The specific activity of 'fresh' DU is ca. 15 MBq/kg
  - The peak specific activity of initially pure DU, occurring at around 1 million years, is 170 MBq/kg
  - The activity of the 550,000 tDU at 1 million years would be around 2.5 MCi
    - This represents around 65% of the 3.89 MCi regulatory limit for the CWF
- Therefore as of August 2014 the WCS facility has been licensed to dispose hundreds of thousands of tonnes of DU

*http://www.wise-uranium.org/rup.html

2. Disposal of DU as DUCRETE (Waste Package Overpack)

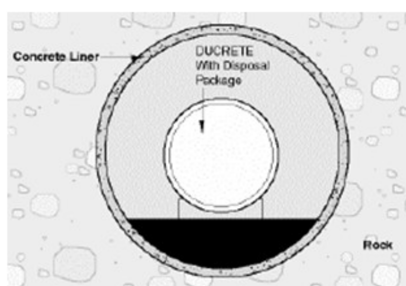
DU form	Waste Package	Disposal Environment	Additional Excavation?
High-density concrete (DUCRETE)	Overpack for small or large (4 or 21 PWR assm) WP	Yucca Mountain-like	No

- Considered for YM in the 1990s to early 2000s
- DUCRETE overpack would take the place of conventional waste package overpack
- Emplacement, operations costs were shown to be largely unaffected



DUCRETE fabrication and overpack

- DU must first be deconverted to U3O8 or UO2 (this cost not included here).
- 'DUAGG' ceramic produced by liquid phase sintering UO2 with silica and alumina
- DUCRETE is then made by combining DUAGG with Portland cement to produce a very dense (5-6 g/cc) concrete
- DUCRETE overpacks then take the place of conventional overpack



References:

Powell, F.P., "Comparative Economics for DUCRETE Spent Fuel Storage Cask Handling, Transportation and Capital Requirements", INEL-95/0166, 1995.

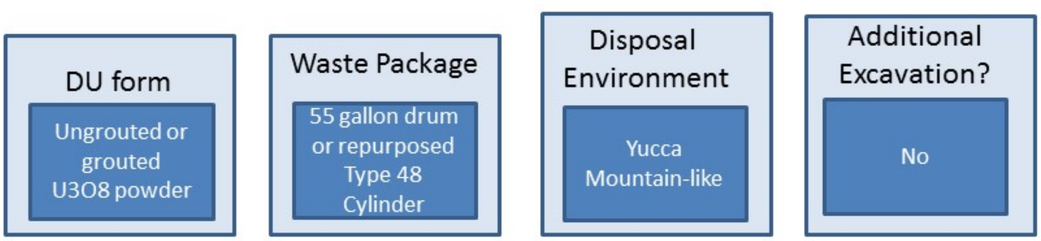
Quapp, W.J. et al., "DUCRETE: a cost-effective Radiation Shielding Material," Spectrum 2000, Sept 24-28, 2000, Chattanooga, TN.

Quapp, W.J., "DUCRETE Shielding Applications in the Yucca Mountain Repository," WM99, February 28-March 4, 1999.

Disposal of DU as DUCRETE overpack: Costs

- There are two cost components:
  - Fabrication of the DUAGG and DUCRETE, estimated cost (inflated to 2011$): $3.0/kg DU (Quapp 2000)
  - Fabrication of the overpacks (inflated to 2011$): $1.5/kg DU (Powell 1995)
  - Emplacement cost difference was evaluated in (Powell 1995) to be very small
  - Bottom line: **$4.5/kg DU** for emplacement of DU in Yucca Mountain like repository (no additional excavation)

3a. Return of DU3O8 to 48Y Cylinders or 55 Gallon Drums, Emplacement in YM-like Repository



- Likely the simplest DGR option. First step is to deconvert to U3O8
  - The U3O8 powder can be grouted (mixed with cement to form concrete) at minimal cost
  - Grouting can decrease risk of airborne particulate transport
  - (Hightower 2000) showed that grouting increases volume (a negative since underground space is valuable) but is not an effective long-term barrier to radionuclide transport
  - Grouting not considered further

Reference: Hightower, J.R. and Trabalka, J.R., "Depleted Uranium Storage and Disposal Trade Study," ORNL/TM-2000/10, 2000.

Return of DU3O8 to 48Y Cylinders or 55 Gallon Drums, Emplacement in YM-like Repository

- Cylinders assumed available at no cost but might not be in reusable condition
  - each cylinder has an interior volume of 3.85 m3 and can hold 10,700 kg U3O8
- Each 55-gal carbon steel drum would contain 540 kg U3O8
- A YM-like repository would have ample space without additional excavation
  - Total excavated volume of YM is 4.4E6 m3
  - Type 48 cylinders filled with DU from 109,300 tIHM of SNF would occupy 3.9E5 m3 of volume (drums about the same)
    - 109,300 tIHM of SNF was the basis for the 2007 YM TSLCC estimate
  - Therefore, the DU would occupy around 9% of the excavated volume – can envision emplacing it in available space

Costs of emplacement

- First order estimate: from the 2008 YM TSLCC analysis, emplacement operations contribute $8,050M to the total cost of $82,500M
  - Strategy envisions emplacing ca. 72,300 Type 48 cylinders which would contain all DU, 660,000 tonnes, produced from fabrication of 109,300 tIHM of SNF
    - Mass of a Type 48 cylinder is 2,000 kg (http://web.ead.anl.gov/uranium/guide/prodhand/sld035.cfm)
    - Total mass to be emplaced = 72,300*2+660,000 = 805,000 tonnes
  - The YM PA called for emplacement of some 17,500 SNF and HLW waste packages with an average mass of ~50 tonnes (DOE 2008, Rechard 2014)
    - Total mass to be emplaced = 17,500*50 = 875,000 tonnes

DOE, "Analysis of the Total System Life Cycle Cost of the Civilian Radioactive Waste Management Program, Fiscal Year 2007," DOE/RW-0591, 2008.
Rechard, R. P. and M. Voegele, "Evolution of repository and waste package designs for Yucca Mountain disposal system for spent nuclear fuel and high-level radioactive waste", Reliability Engineering and System Safety, 122, 2014.

Costs of emplacement, cont'd.

- **Very conservatively** assuming that emplacement costs are proportional to mass, DU cylinder emplacement would add \$8,050*(805,000/875,000)=\$7,400M to the TSLCC.
  - Likely to be significantly less costly because of lower radiation field associated with DU containers
- Unit cost of emplacement would be \$7,400M/660,000 tonnes DU = \$11.2/kg DU (year 2007\$) or **\$12.2/kg DU.**
  - Aside from deconversion, other costs associated with this strategy are negligible

3b. What if additional excavation is needed?

- Conclusion from the above is that emplacement and disposal of DU in a DGR will be cheap if
  - a DGR for SNF and/or HLW already exists, and
  - no additional excavation is required to make space for the DU.
- Consider that engineering, procurement and construction/excavation costs at YM were \$18,130M for the existing 875,000 tonnes of material to be emplaced
  - Conservatively hypothesize that the additional 805,000 tonnes of material would directly add to these costs

Costs of Additional Excavation

DU form	Waste Package	Disposal Environment	Additional Excavation?
Ungrouted U3O8 powder	55 gallon drum or repurposed Type 48 Cylinder	Yucca Mountain-like	Yes

- Excavation would then add $18,130*(805,000/875,000)=$16,700M to the TSLCC.
  - This assumes that the additional excavation also complicates licensing, design and surface infrastructure in proportion to the additional mass disposed
- On a per-unit mass basis, this is $16,700M/660,000 tDU = $25.3 (year 2007$) or **$27.6/kg DU (year 2011$).**
- Adding this to the emplacement cost calculated previously, the unit DU disposal cost would be **$39.8/kg DU.**
  - This is close to the highest estimates for deep geologic disposal of U3O8 ($50/kg U) reviewed in AFC CB module K1

3c. What if the DU must be disposed behind SNF-like engineered barriers?

- In the worst case, assume that the DU must be placed behind the same set of engineered barriers as SNF and HLW
- Assume that ungrouted DU is placed inside HLW canisters, and 5 HLW canisters are contained within one co-disposal cask
  - Interior volume of a HLW canister is $\pi/4*0.61^2*5=1.46\ m^3$.
  - The volume of ungrouted DU3O8 powder from 660,000 tDU is 278,000 m^3.
  - A total of 190,000 HLW canisters inside of 38,100 co-disposal waste package would be required

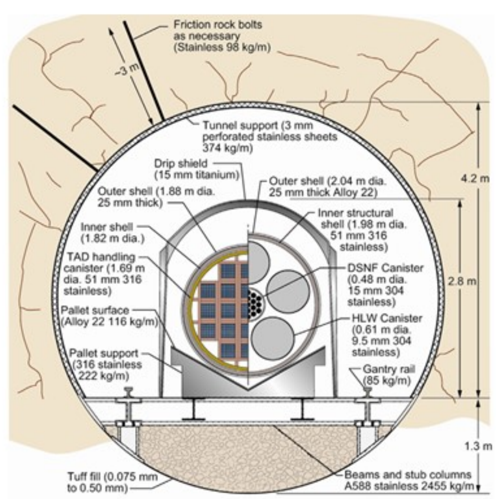
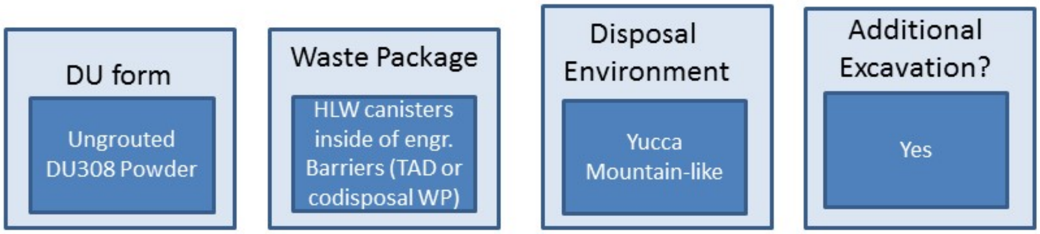


Figure and dimensions from [Rechard 2014].

Worst case: dispose of DU in HLW canisters inside co-disposal WPs



- Cost of waste package and drip shield fabrication for the 17,500 WPs in the 2007 TSLCC assessment was $12,820M (WPs) plus $7,630M (drip shields). Performance confirmation and regulatory, infrastructure, management support add $6,050M; adding these components gives $26,500M.
  - Conservatively assuming they are proportional to the number of packages, adding 38,100 more packages would increase the cost by $26,500*(38,100/17,500)=$57,700M.
  - Additional excavation would be needed too since the DU has a larger footprint if emplaced this way rather than in cylinders or drums.
  - Assuming the excavated volume increases in proportion to the number of waste packages, additional excavation cost would be $18130M*(38,100/17,500)=$39,500M.

Worst case: dispose of DU in HLW canisters inside co-disposal WPs

- Similarly, emplacement costs would increase with the number of packages: $8,050M*(38,100/17,500)=$17,500M.
- The total additional cost would then be $57,700M + $39,500M + $17,500M = $114,800M.
- On a per-unit mass basis, this is $114,800M/660,000 tDU = $174 (year 2007$) or **$189/kg DU (year 2011$).**
- Unsurprisingly, this is close to the figure Kent produced for repository disposal of DU by directly scaling the repository disposal module unit costs.
  - At this level, the DU is being disposed under the same engineered barrier system as SNF and HLW. It occupies a large footprint, and additional WP and excavation requirements are enormous
  - This remains somewhat lower than the SNF disposal cost ($650/kg IHM) because the DU can be packed more densely inside the WPs than the SNF
  - Since there are ca. 6 kg of DU per kg of SNF, though, under this scenario **the DU disposal cost per unit electricity produced would be higher than the SNF disposal cost**

4. Boreholes

DU form	Waste Package	Disposal Environment	Additional Excavation?
Ungrouted U3O8 powder	None or appropriately-sized drum	Shallow, intermediate or deep borehole	Yes

- "Depth" and "diameter" of BH will determine cost.
- Module L-2 of 2012 AFC-CBD [GTCC] considers "not-so-deep" 40m deep BHs for GTCC at unit cost of $2750/m3
  - Shallow Boreholes must be above water table
  - Diameters considered ranged from 1 ft to 12 ft dia.
- This presentation is first look at deeper boreholes for DU3O8 disposition

Borehole (BH) Options

- Borehole drilling technology has benefitted from oil and gas drilling industry, especially deep underwater drilling
- DOE's Sandia National Laboratory has considerable analysis and research on this concept
- BH has been considered for following wastes or materials
  - Plutonium (1996 studies) and (2013 studies)
  - Hanford cesium capsules
  - Spent nuclear fuel (SNF)
  - High Level Waste (HLW)
  - Greater-than-Class C waste (GTCC)

Borehole Options (cont'd)

- For purposes of our discussions boreholes come in three "sizes"
  - Shallow BH: 30 to 300 m depth (possible for GTCC and lower specific activity and lower "proliferation attractiveness" level materials)
    - Holes are above water table
  - Intermediate depth BH: 300 to 2000 m depth
    - Probably below water table and adaptable to higher specific activity wastes
  - Deep boreholes: 2000 to 5000 m depth (possible for higher activity and high proliferation "attractiveness level" materials)
    - Would be difficult to "re-mine"
    - Emplacement zone of BH well below water table

General comments on BH sizing and costs

- Higher diameters possible for shallow boreholes (1 to 12 ft or 0.3 to 3.7 meters)
- Intermediate and deep boreholes will likely need to be less then 0.5 m (20 inches) in diameter
- Drilling cost per unit depth ($/m) increases with depth
  - Different unit drilling costs will be assumed for each of the three cases considered for DU
- Sandia estimates deep borehole costs at $25 M to $40M per BH.
- Deep borehole R&D program has been estimated at $75M, including "pilot" borehole

4a. Shallow Borehole

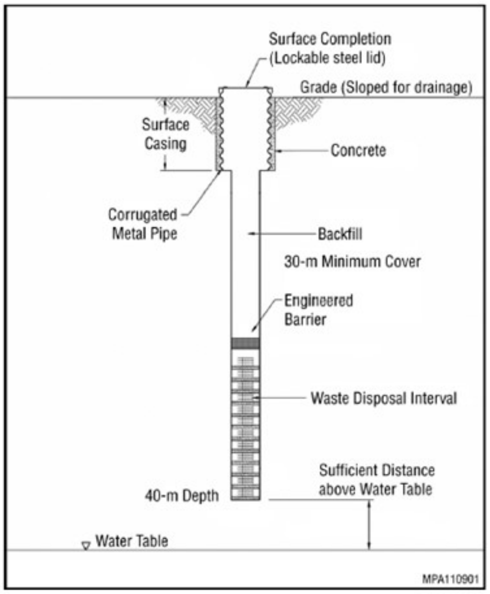
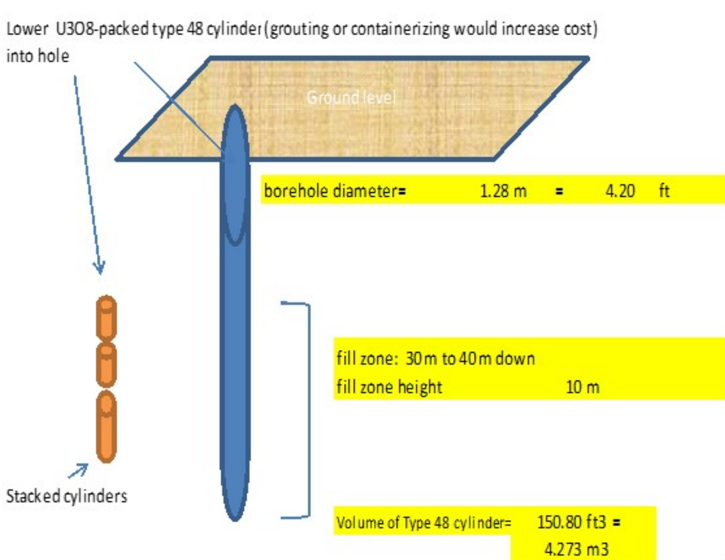


Diagram from 2012 Update to AFC-CBR

- Concept considered by DOE-EM for GTCC disposal (called "intermediate-sized" in DOE-EM EIS Report)
- Described in Module L-2 of 2012 Update to Advanced Fuel Cycle Cost Basis Report
- Capped to prevent re-drilling
- EM-proposal had normalized disposal cost of $2750/m3 of disposal space (fill zone or waste disposal interval)

Assume DU3O8-Packed Type 48 Cylinders Could be Vertically Stacked End-to-End in Multiple Shallow Boreholes

40-meter deep Borehole



- Hole diameter just over 48" would allow direct emplacement of DOE-legacy DU3O8-filled cylinders from B&W deconversion facilities at Paducah and Portsmouth
- For 10m high "fill zone" 3 cylinders could be stacked "end to end"
- At bulk density of 2.6 MT/m3 each cylinder holds 10 MT U3O8
- ~185,000 boreholes req'd to disposition U3O8 from 700,000MT DUF6
- 7.4 km2 field for boreholes if centerlines are 20 m apart.

Shallow boreholes cont'd

- Unit disposal cost inversely proportional to packed bulk density of U3O8 powder in cylinder
- At 2750 $/m3 of borehole "fill zone", 90% occupancy of fill zone by cylinders, and bulk DU3O8 density of 2.6 MT/m3, unit costs of 1.18 $/kg DU3O8 or 1.39 $/kg DU are calculated
- For lower bulk DU3O8 powder densities:

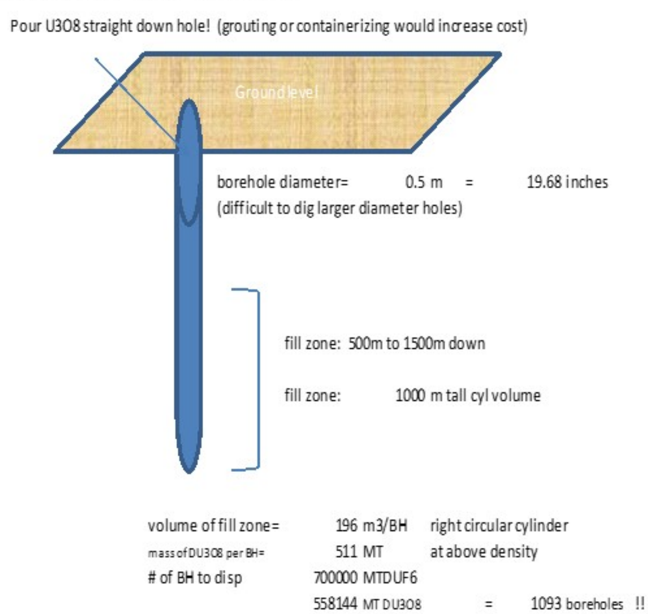
Density	$/kgDU3O8	$/kgDU
2.3	**1.35**	**1.57**
1.8	**1.70**	**2.00**

- Number of boreholes and land area increase inversely proportional to U3O8 bulk density
- Borehole drilling cost just below $1000/m of borehole (top to bottom)
- Drilling technique probably large auger rather than conventional drill bit

4b. Intermediate Depth Boreholes

Assume DU3O8-Powder could be poured directly down multiple Intermediate Depth Boreholes (or packaged in narrow steel cans for vertical in-hole stacking)

1500-meter deep Borehole



- 0.5 m hole diameter would allow reasonable drilling cost and higher depth would allow direct emplacement of DOE-legacy DU3O8 powder from B&W deconversion facilities at Paducah and Portsmouth or newer commercial facilities.
- Fill zone is one kilometer tall
- At bulk density of 2.6 MT/m3 each 196m3 fill zone holds 500 MT DU3O8
- ~1100 boreholes req'd to disposition U3O8 from 700,000MT DUF6
- 0.4 km2 field for boreholes if centerlines are 20 m apart.

Intermediate depth boreholes cont'd

- Unit disposal cost inversely proportional to packed bulk density of U3O8 powder in fill zone
- At 3000 $/m drilling cost for 1500 m deep holes, a cost of $4.5M/borehole results
- Each borehole has ~200m3 of useable space (fill zone). At a bulk DU3O8 density of **2.6 MT/m3** each hole can hold ~500 MT DU3O8. Distributing the $4.5M cost of each borehole over this mass results in unit costs of **9 $/kg DU3O8 or 10.6 $/kg DU** are calculated
- About 1100 BHs req'd to disposition the DU3O8 deconverted from 700,000 MT DUF6. Land space of 0.4 km2 required if BH centerline to centerline spacing is 20m
- For lower bulk DU3O8 powder densities more BH needed, hence higher cost:

Density	$/kgDU3O8	$/kgDU
2.3	**10.2**	**12.0**
1.8	**13.0**	**15.3**

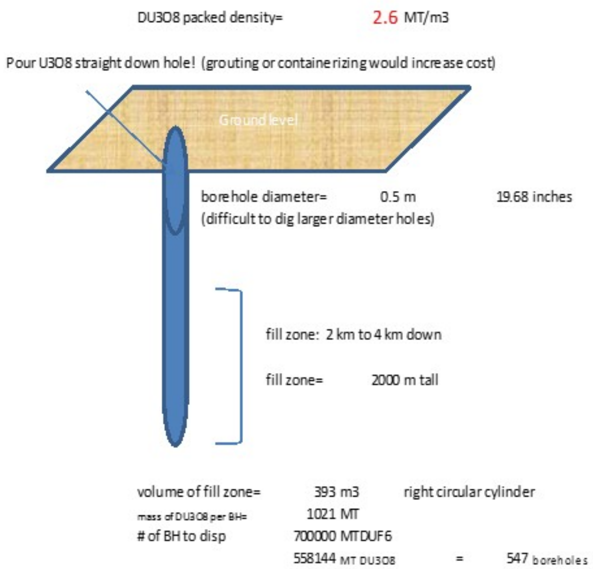
- Number of boreholes and land area also increase inversely proportional to U3O8 bulk density
- Intermediate unit depth ($/m) drilling cost was selected as average of better known values for shallow and deep boreholes
- If U3O8 powder requires "canning" before emplacement, add about $1/kgDU to above unit costs. (This might required to achieve higher packed density)

4c. Deep Boreholes

- Deep boreholes could provide non-retrievable disposal of powder or containers at depths of 3 to 5 km
- Deep boreholes should be thousands of meters below the water table
- Sandia gives cost of Nth-of-a-kind deep BH at ~$25 million (17 inch dia and 5 km deep)
- Normalized cost is $5000/m of depth (compared to $1000/m for shallow depth BH)
- At this depth it might be possible to simply pour U3O8 powder down to form 2000m tall layer between 3 and 4 km depth
- Many BHs required to disposition U3O8 resulting from deconversion of 700000 MT DUF6 (depends on packing density in BH)
- Over 500 BHs required for density of 2.6MT/m3 bulk density

Deep Borehole Concept

4000 m deep borehole



- 0.5 m hole diameter would allow reasonable drilling cost and higher depth would allow direct emplacement of DOE-legacy DU3O8 powder from B&W deconversion facilities at Paducah and Portsmouth or newer commercial facilities.
- Fill zone is 2 kilometers tall
- At bulk density of 2.6 MT/m3 each 393m3 fill zone holds ~1000 MT DU3O8
- ~547 boreholes req'd to disposition U3O8 from 700,000MT DUF6
- 0.22 km2 field for boreholes if centerlines are 20 m apart.

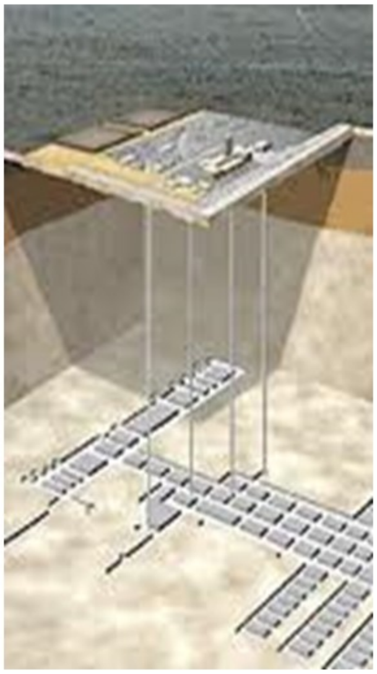
Deep borehole disposal unit costs

- 4 km borehole costs $20M
- ~547 required for 558144 MT DU3O8 at bulk density of 2.6 MT/m3. 0.22 km2 land area req'd at 20m center to center spacing
- Program cost: $11B !! For 700,000MT DUF6
- Cost per kg >>

Cost per kg >>	DU3O8	DU
– Density of 2.6	19.6	23.1
– Density of 2.3	22.2	26.1
– Density of 1.8	28.3	33.4

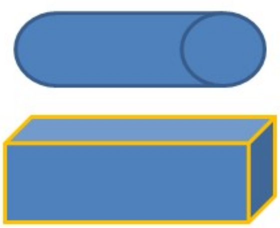
- If "canning" of DU3O8 required before emplacement, add $1/kgU to above

5. Emplacement in Deep-mined Salt Repository



- Waste Isolation Pilot Plant (WIPP) is America's only DGR
  - Located near Carlsbad NM
  - Licensed to accept carefully packaged transuranic (TRU) wastes from DOE sites
  - Most emplaced material is defense waste from Pu production (most in 55-gal drums)
  - Capital cost: $3B (2012$)
  - O&M cost $200M/yr for 25 yr (2012$)
  - Emplacement capacity: 175600 cubic meters per Land Withdrawal Act
  - Presently just over 50% full
  - Remaining space all reserved
  - Salt will slowly "flow" into mined galleries and engulf waste packages, hence waste considered non-retrievable
  - Similar concept has been studied for SNF and HLW
  - Concept now being studied for surplus weapons-grade Pu and HEU

Deep-mined Salt Repository, cont'd



3.85m3 U3O8 Volume in Type 48 cylinder

5.44m3 of WIPP-like Gallery space req'd for one cylinder

If 558,144 MT DU3O8 dispositioned
At 2.6 MT/m3 powder density, ~55760 U3O8-filled cylinders would need emplacement in WIPP-like facility. Space req'd would be around 303,300 m3, nearly twice The entire capacity of WIPP!

- Assume new WIPP-like DGR constructed for emplacement of U3O8-filled cylinders from 700,000 MTDUF6
  - Dividing WIPP Life cycle cost ($8B) by its volumetric capacity gives $45558/m3
  - DU3O8 occupies 70% of available space
  - At **bulk powder density of 2.6 MT/m3**, effective emplacement density is 1.84 MT/m3 (@10,010 kg U3O8 per cylinder)
  - Dividing unit capacity cost by emplacement density gives **~$24,700/MT DU3O8**
- Salt beds in SW USA could easily accommodate new DGRs
  - Permitting would be major issue

Costs for Salt DGR disposal

DU form	Waste Package	Disposal Environment	Additional Excavation?
Ungrouted U3O8 powder	55 gallon drum or repurposed Type 48 Cylinder	Salt repository (similar to WIPP)	Yes

- Life cycle cost of over $14B to disposition DU3O8 arising from 700,000 MT DUF6
  - Life Cycle Cost and Unit Cost Higher if bulk DU3O8 density less than 2.6 MT/m3:

Density (MT/m3)	$/kg DU3O8	$/kg DU
2.6	24.7	29.1
2.3	27.9	32.9
1.8	35.7	42.1

Summary of Results

ID	Description	Cost [$/kg DU]
1	drums, cylinders, or SWBs disposed in shallow trench or vault	1.5 – 4.1
2	DUCRETE waste package overpack disposed in Yucca Mountain-like repository	4.5
3a	Drums or cylinders emplaced in YM-like repository, no additional excavation	12.2
3b	Drums or cylinders emplaced in YM-like repository, additional excavation required	39.8
3c	DU emplaced in HLW canisters inside co-disposal waste packages, emplaced in YM-like repository w/ add'l excavation	189
4a	DU powder or drums emplaced inside shallow (30-40 m) boreholes	1.2 – 3.0
4b	DU powder or drums emplaced inside intermediate-depth (500-1500 m) boreholes	10.6 – 16.3
4c	DU powder or drums emplaced inside deep (3000-4000 m) boreholes	23.1 – 34.4
5	Drums or cylinders emplaced in WIPP-like salt repository, additional excavation required	29.1 – 42.1

Disposal of Reprocessed U (RU)

- Not a lot of cost data in literature
- Countries who have RU are storing it
- Most complete existing cost analyses appear in *2009 Advanced Fuel Cycle Cost Basis Report*
- Numbers in AFC-CBD are re-examined here in light of new cost data for DU disposal above
  - RU can present challenges vis-à-vis DU, however nature of geologic medium may minimize these

Reprocessed U (RU) presents special issues

- U-232 formed during irradiation has very potent daughters, such as Thallium-208, with very penetrating gamma rays.
  - Activity increases rapidly in a few months and peaks at 70 yrs.
- Reprocessing does not completely remove all fission products (FPs) and transuranics (TRUS) from RU product stream
  - Ruthenium and technicium FPs often present in trace amounts
  - Neptunium and plutonium TRUs may also be present in trace amounts
- Amounts present depend on separation technology used for reprocessing
  - Aqueous separation results in purer RU product than pyro techniques
- Shallow low level waste disposal sites probably not acceptable for most radioactive RU forms, such as from pyroprocessing.
- RU Forms will be more akin to “Greater-than-Class C” waste or ILW

Current unit RU disposal cost values* in *Advanced Fuel Cycle Cost Basis Report (2012 Update)*

- Geologic Disposal of Aq Reprocessing-derived U3O8
  - Low 61 $/kgRU If temp pkg could be emplaced
  - Most Likely 72 $/kgRU If repackaging & transport required
  - High 93 $/kgRU If regulatory & siting difficulties arise
- Geologic Disposal of Pyro Reprocessing-derived U metal
  - Low 75 $/kgRU If contamination level just above aq RU
  - Most Likely 93 $/kgRU If considerable addl handling req'd
  - High 150 $/kgRU If regulatory & siting difficulties arise

* Conversion and packaging costs not included

DU options can be considered for RU and general comments made on likely unit disposal costs

- DUCRETE not likely option for RU
  - Worker radiation exposure during cask manufacture could pose difficulties
- Other DGR DU options could be very suitable for aqueous reprocessing derived U3O8
  - Workers and operations can already accommodate higher radiation environments associated with packaged SNF or HLW, hence RU poses smaller burden
  - One could add 20% to DU disposal costs. This is analogous to LWR fuel fab, where reprocessed U derived fuel carries an ~20% cost premium above "virgin" LEU derived fuel
  - DGR probably only feasible option for pyro-derived RU-metal
    - Need for special pre-emplacement packaging could add at least 5 $/kgU to disposal cost

DU options for RU, cont'd

- Vault and shallow borehole options should be suitable for aqueous reprocessing-derived RU3O8
  - More robust packaging and higher radiation work environment might add a few $/kgU to DU costs
- Intermediate and deep boreholes could accommodate pyro or aqueous-derived RU at some additional cost vis-à-vis DU
  - Direct disposal of powder not feasible
  - Special disposal cans would need to be designed and qualified for borehole emplacement
  - Remote emplacement machine would be needed in higher radiation environment
  - A SWAG for the additional cost vis-à-vis DU might be $10/kgU for "aqueous" RU and $20/kgU for "pyro" RU

RU: Comparison to 2009 AFC-CBD Unit Costs (K-2 and K-3 modules)

- New analysis shows that 2009 AFC-CBD costs for aqueously-derived RU disposition are on high side
- 2009 AFC-CBD costs for pyro-derived RU disposition are reasonable, especially in light of high uncertainty associated with pyro fuel cycle
- Disposition of RU products in DGRs already handling SNF or HLW products is the lowest cost option, since operations costs and overheads are distributed over all emplaced forms

$/kg RU disposal cost summary

Option	Aqueous RU	Pyro RU
Packaged form in DGR (no excavation)	25	30
Packaged form in DGR (new excavation)	100	105
Shallow vault (similar to WCS)	4.5 to 6.5	n/a
Shallow borehole	3 to 5	
Intermediate depth borehole	21 to 25	30 to 25
Deep borehole	33-43	43-53

New 1300 Mwe PWR LCC with Low Enrichment Plant Tail Disposition Costs

		Unit Cost Values		Flowrates		One reactor COST		
Module	Description	Unit cost value	Units	Flow rate to support 1 reactor		1 reactor annual cost ($M/yr)	1 reactor $/kgHM contrib	1 reactor cost of electricity contribution ($/MWh)
A1	Uranium mining & milling	80 30.8	$/kgU $/lb U3O8	216512	kgU/yr	$17.32	703	1.69
A2	Thorium mining & milling	75	$/kgTh	0	kgTh/yr	$0.00	0	0.00
B	U3O8 to UF6 conversion	11	$/kgU	216512	kgU/yr	$2.38	97	0.23
C1	Uranium enrichment	105	$/SWU	159055	SWU/yr	$16.70	678	1.63
K1	Tails deconversion & disp	→ 10	$/kgDU	191867	kg DU/yr	$1.92	78	0.19
D	Fuel fabrication (U) Fuel fabrication (Th)	260	$/kgU	24645	kgU/yr	$6.41	260	0.62
E1 or E2	Pool or dry storage of spent fuel	100	$/kgHM	24645		$2.46	100	0.24
J	Low level waste C,P,&D							
	Total Fuel Cycle-related					**$47.19**	**$1,915**	4.60
R1	Thermal reactor (Non-fuel cycle related) Capital component O&M comp incl D&D Total reactor	see above diagram		24645	kgHM/yr	 $480.2 $101.7 **$581.8**		 $46.82 $9.91 **$56.73**
	Reactor and fuel cycle total					**$629.0 $M/yr**		**$61.33** $/MWh

One mill/kwh SNF disposal fee would add 416 $/kgU or HM to above costs

New 1300 Mwe PWR LCC with Very High Enrichment Plant Tails Disposal Cost

		Unit Cost Values		Flowrates		One reactor COST		
Module	Description	Unit cost value	Units	Flow rate to support 1 reactor		1 reactor annual cost ($M/yr)	1 reactor $/kgHM contrib	1 reactor cost of electricity contribution ($/MWh)
A1	Uranium mining & milling	80 30.8	$/kgU $/lb U3O8	216512	kgU/yr	$17.32	703	1.69
A2	Thorium mining & milling	75	$/kgTh	0	kgTh/yr	$0.00	0	0.00
B	U3O8 to UF6 conversion	11	$/kgU	216512	kgU/yr	$2.38	97	0.23
C1	Uranium enrichment	105	$/SWU	159055	SWU/yr	$16.70	678	1.63
K1	Tails deconversion & disp	85	$/kgDU	191867	kg DU/yr	$16.31	662	1.59
D	Fuel fabrication (U) Fuel fabrication (Th)	260	$/kgU	24645	kgU/yr	$6.41	260	0.62
E1 or E2	Pool or dry storage of spent fuel	100	$/kgHM	24645		$2.46	100	0.24
J	Low level waste C,P,&D							
	Total Fuel Cycle-related					**$61.58**	**$2,499**	6.00
R1	Thermal reactor (Non-fuel cycle related)	see above diagram		24645	kgHM/yr			
	Capital component					$480.2		$46.82
	O&M comp incl D&D					$101.7		$9.91
	Total reactor					**$581.8**		**$56.73**
	Reactor and fuel cycle total					**$643.4 $M/yr**		**$62.73 $/MWh**

Increases by 514 $/kgU or HM

One-mill per kwh SNF disposal adds $416/kgHM to above fuel cycle total

Some General Comments

- Transportation costs not included in most of above analyses
  - Low radiation levels keeps them low compared to other costs. Commercial transport can be used
- Siting and permitting costs can be very significant
  - Difficult to estimate since extent of regulatory and legal difficulties hard to predict
- There is some future benefit in having retrievable option for DU forms
  - Emplacement location can be “rich” U-mine for fleets of future fast breeder reactors
  - Potential energy potential of DU from 700,000 MT DUF6 US legacy is equivalent to over half of US coal reserves
    - Assumes breeder reactor fleet requires only make-up uranium
- DUF6 stockpile will continue to grow with commercial US enrichment providers (URENCO in New Mexico, future Idaho plant, possible CENTRUS (formerly USEC) capacity