Advanced Fuel Cycle Cost Basis Report: Supporting Documents 3 Cost Correlations

Nuclear Fuel Cycle and Supply Chain

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This is just a reformatting of previous work to the current format for rerelease of the entire report so there is no primary technical developer or lead author. J. Hansen (INL) and E. Hoffman (ANL) can be contacted with any questions regarding this document.

COST CORRELATIONS

A1-1.1. 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].

A1-1.2. 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.

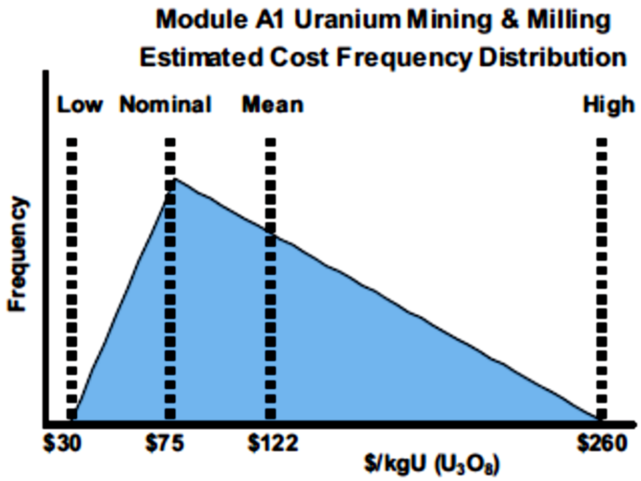


Figure 1. Example of cost distribution from the Advanced Fuel Cycle Cost Basis report: Uranium mining and milling.

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.

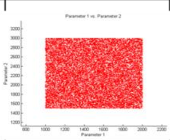
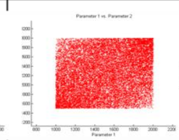
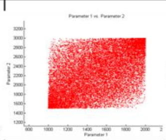
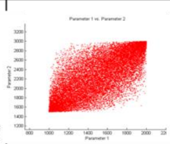
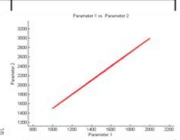
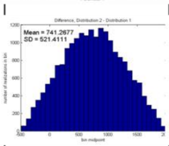
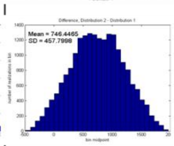
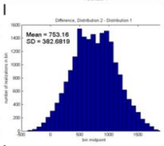
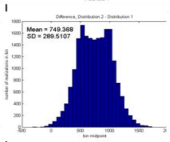
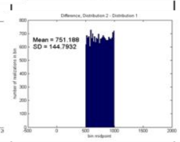
Correlation Coeff., ρ	0.0	0.25	0.5	0.75	1.0
Scatter Plot, Cost 1 vs. Cost 2					
Cost Difference Histogram					
Standard Deviation of Cost Difference	**$521**	**$458**	**$382**	**$290**	**$145**

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 0 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.

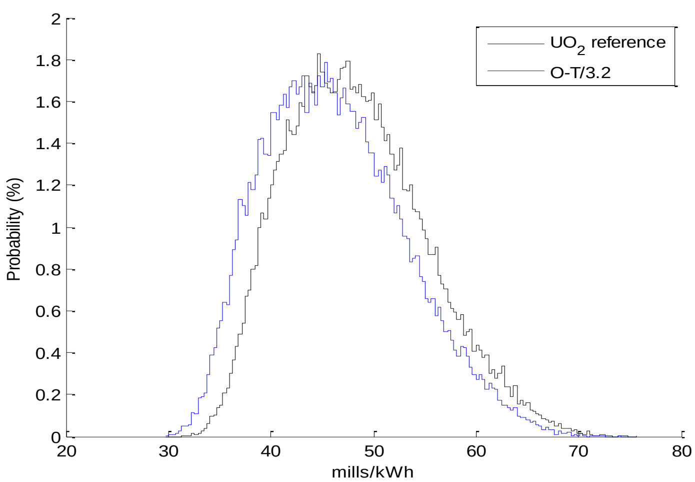


Figure 0. LCAE probability density functions (PDFs), reference once-through UO_2 cycle and O-T/3.2 cycle.

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 0 if all reactor and fuel cycle costs are assumed to be uncorrelated. Figure 3 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.

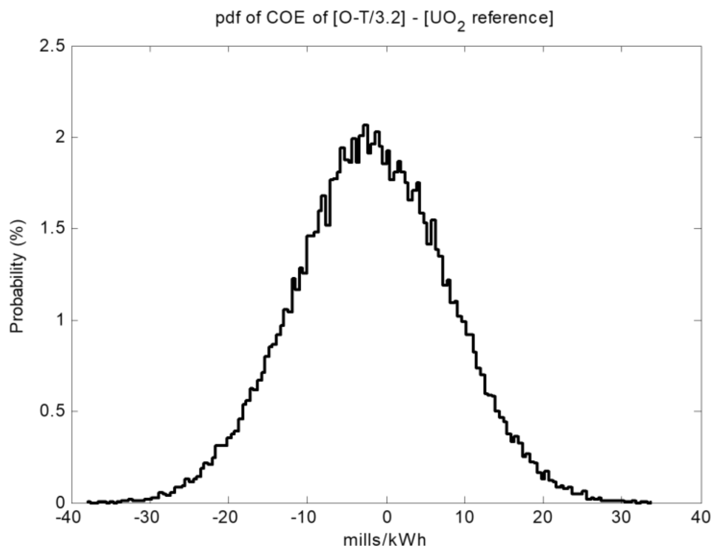


Figure 3. PDF of COE difference, O-T/3.2 minus UO_2 reference, no correlations.

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 4. 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.

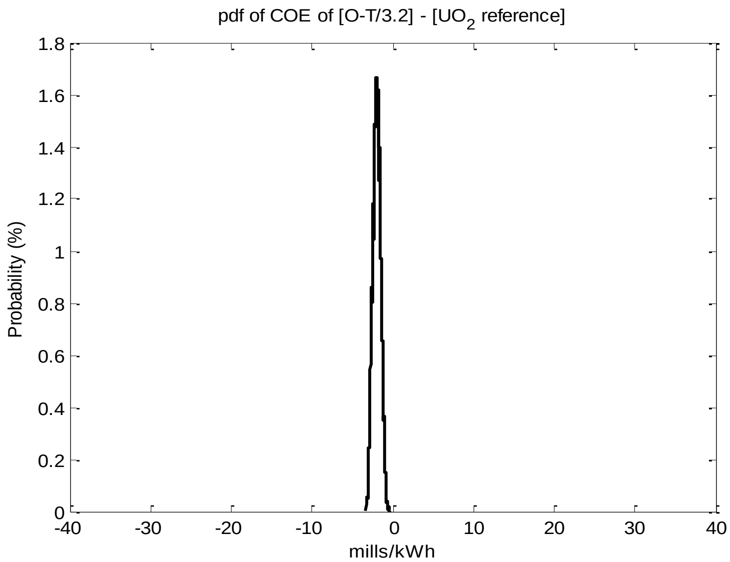


Figure 4. PDF of COE difference, O-T/3.2 minus UO_2 reference, correlations accounted for.

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 5. Uncertainties of differences with less similar systems (i.e., those that did not include the same reactor type present in EG01) were very large.

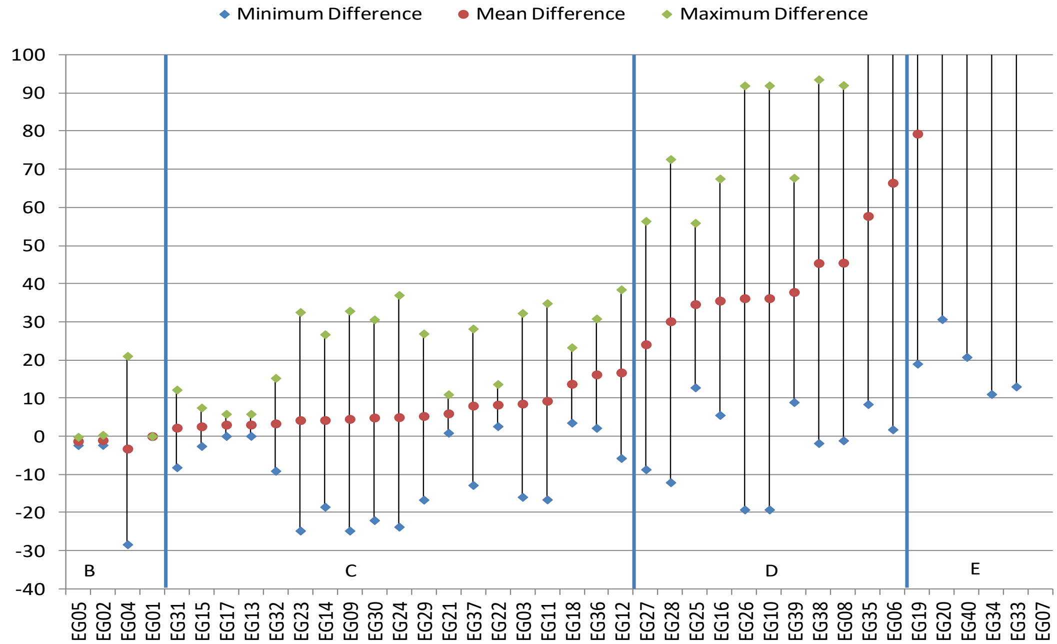


Figure 5. Fuel cycle evaluation and screening cases and their LCAE uncertainties.

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.

A1-1.3. 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 6.

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 7 shows the results, in which the coefficient values were generally lower than those from the internal trail.

Figure 8 and Figure 9 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.

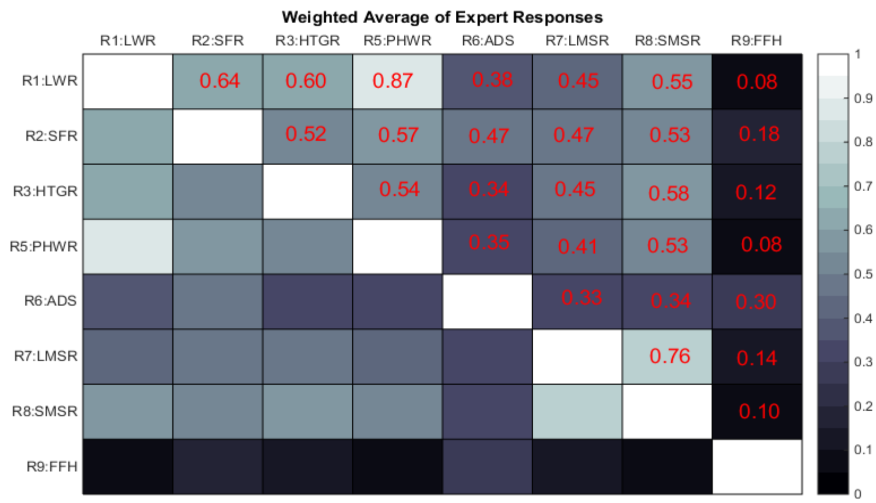


Figure 7. Elicited values of correlation coefficients.

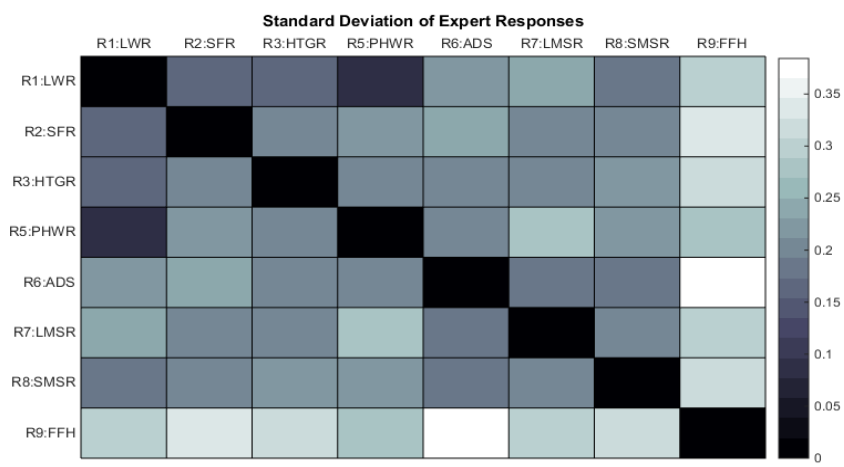


Figure 8. Standard deviation of participant responses.

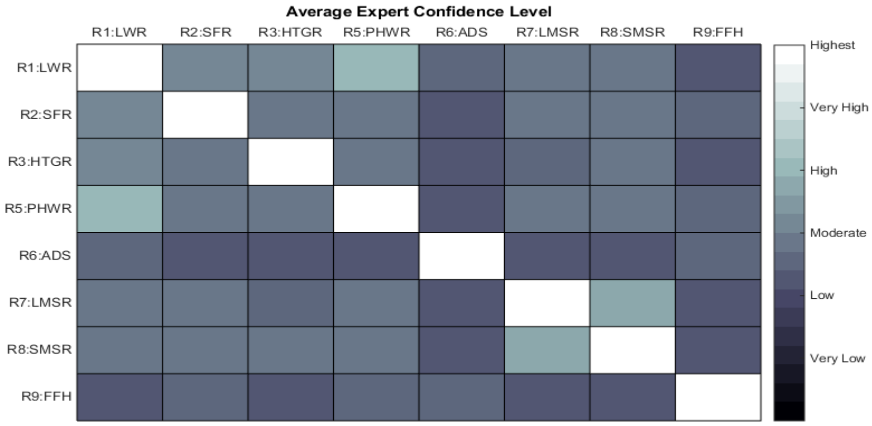


Figure 9. Average participant confidence level.

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

A1-1.4. 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.

A1-1.5. References

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