Advanced Fuel Cycle Cost Basis Report: Supporting Document 6 A Proposed Methodology for Transformation of Reactor Cost Data to the 'What-It-Takes' Table

Nuclear Fuel Cycle and Supply Chain

Prepared for
U.S. Department of Energy
Systems Analysis and Integration
October 2023
INL/RPT-23-75635

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Fuel Fabrication Preface to FY 2021 Updates to the Supporting Documents

ACKNOWLEDGEMENT

This latest version of the *Supporting Document 6 A Proposed Methodology for Transformation of Reactor Cost Data to the 'What-It-Takes' Table* is the cumulative effort of many authors who have contributed to the *Advanced Fuel Cycle Cost Basis Report*). All the authors, including the four primary authors, 15 contributing authors, 12 contributors acknowledged, and the many other unacknowledged contributors from the 2017 report, have contributed various amounts to developing and writing this module prior to this current revision. Unfortunately, there is no history that allows us to properly acknowledge those that built the foundation that was updated and revised in this latest revision.

This update reformats previous work to the current format for rerelease of the entire report as individual modules so there is no primary technical developer or lead author. Jason Hansen (Idaho National Laboratory, jason.hansen@inl.gov) and Edward Hoffman (Argonne National Laboratory, ehoffman@anl.gov) can be contacted with any questions regarding this document.

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 following R-modules, the methodology was applied only in the analysis of the fast reactor (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.

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

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

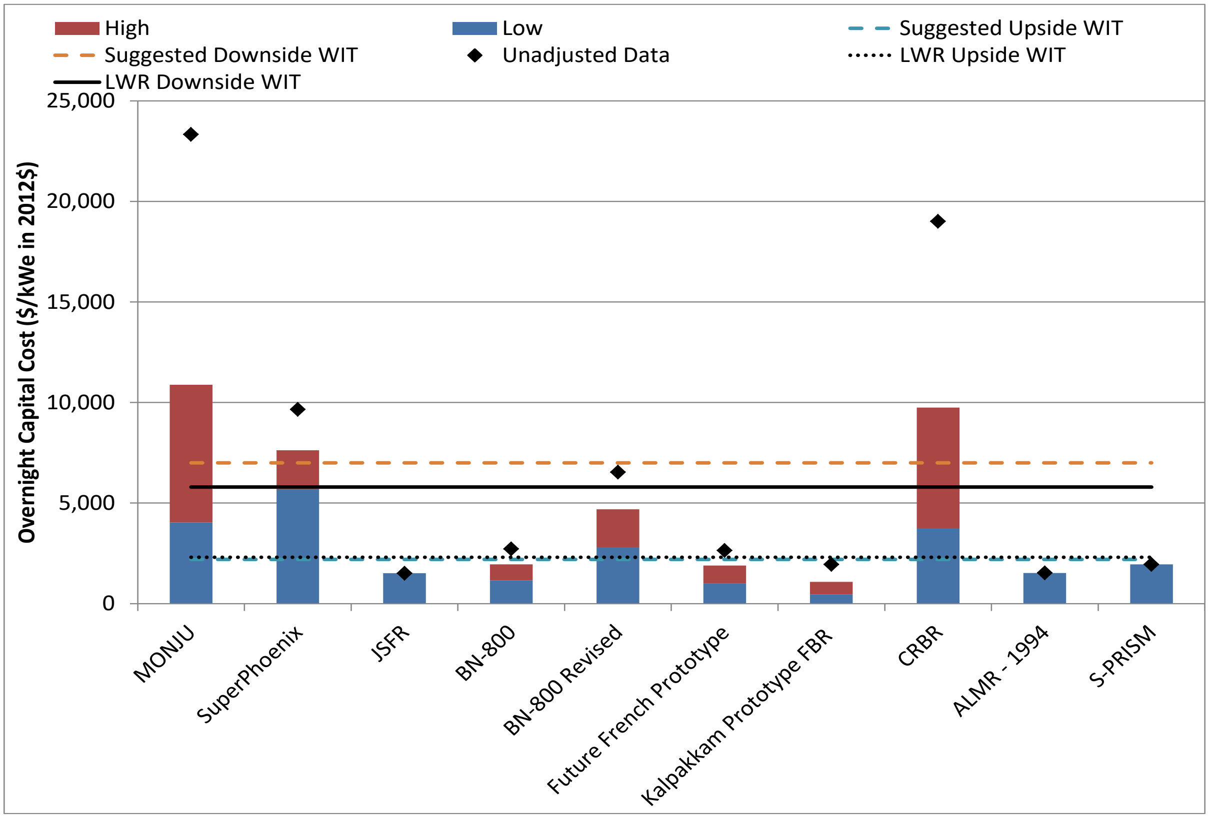

Figure 3-1. Specific Overnight Capital Cost Information.

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
    - done implicitly, but should have been made explicit

- foreign country to U.S. adjustment
    - 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
    - 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
    - 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

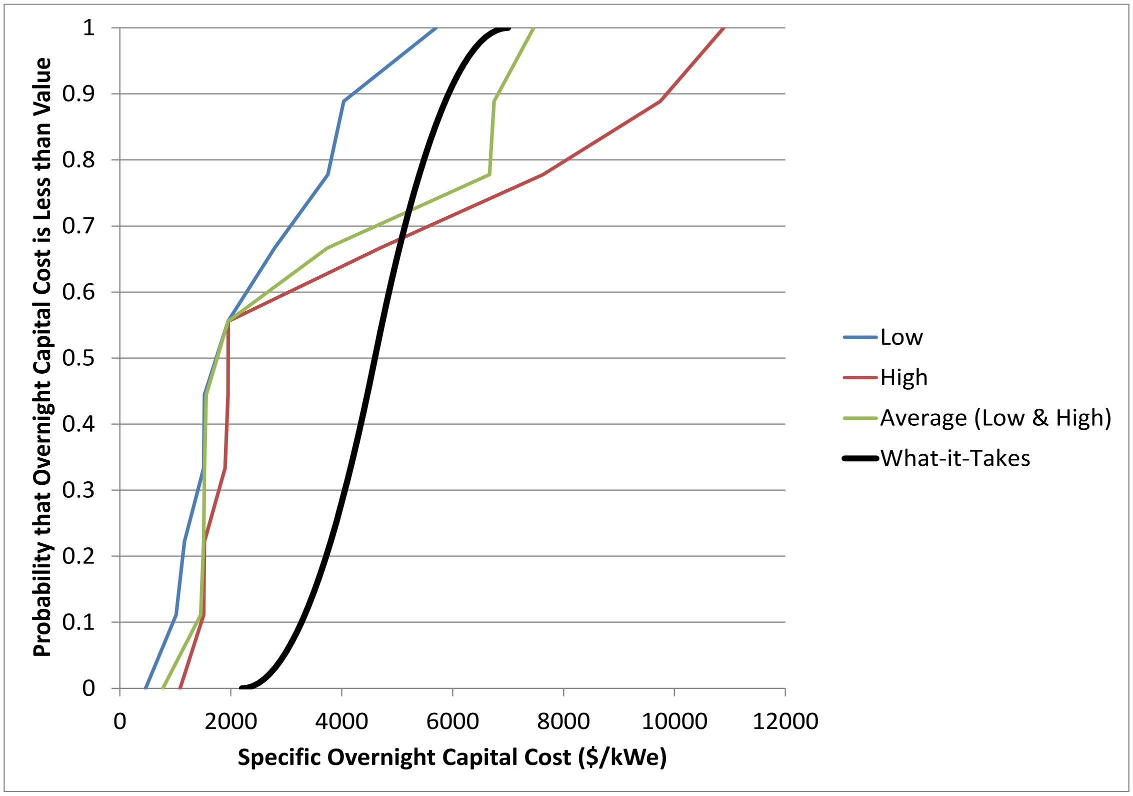

Figure 3-2. Cumulative Distribution Function for Low, High, Average of Low and High, and What-it-Takes Values.