Report on the ACCERT Cost Algorithms Tool

Nuclear Fuel Cycle and Supply Chain

Prepared for
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Systems Analysis and Integration Campaign

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SUMMARY

This report presents the work, performed in FY19, dedicated to the improvement of the Algorithm for the Capital Cost Estimation of Reactor Technologies (ACCERT).

The overall ACCERT development, approach and methodology have been extensively discussed in Ganda (2018), and therefore it is not repeated here. Similarly, the cost models developed in FY18 have not been modified since Ganda (2018), and consequently are not discussed in the present report.

Ganda (2018) also included a complete evaluation of the expected construction cost of the ABR1000, with the primary objective of demonstrating the feasibility of the ACCERT approach for the estimation of the overnight capital cost of advanced concepts, as an example. Since that objective was fully achieved in Ganda (2018), and since a further demonstration was achieved with a full evaluation of the expected construction cost of the Versatile Test Reactor (VTR), no complete example evaluation of advanced systems has been performed in the current work.

The overall objective of this work was to increase the fidelity of the ACCERT algorithm, and consequently the usefulness and credibility of the evaluations performed with this tool. For this objective, the following has been accomplished in this work:

- Cost models of all the Nuclear Steam Supply System (NSSS)-supplied components were developed, for which costs were not provided in the reference cost databases (EEDB 1987), as discussed in Ganda (2018). This work was initiated and substantially advanced in FY18, with the development of detailed cost models for the eight largest and most expensive parts of the NSSS. The work in FY19 completed that task, with an inclusion of all the remaining NSSS-supplied components that were not analyzed in FY18. These include relatively minor, but numerous components, including rotating machinery, heat exchangers, demineralizers, tanks etc. for several important functions of nuclear power plants.
- The reasonableness of the NSSS cost models was checked, by summing the calculated costs derived from the models of this work and of Ganda (2018), and comparing the sum to the total aggregated NSSS costs, known from EEDB (1987). The agreement between the two was found to be excellent: the entire set of the NSSS components was calculated at $506 million in 2017 USD, versus the known aggregated cost of the total set of NSSS-supplied components from EEDB (1987), of $515 million in 2017 USD. In fact, this agreement exceeds the most optimistic expectations about this result before this work was initiated. Each of the cost models for the NSSS components was developed independently, regardless of the influence of each particular model on the total NSSS aggregated cost. This agreement should substantiate confidence in the cost models developed for the NSSS systems, at least at an aggregated level. This work offers, for the first time in the public domain, a complete set of models to evaluate the NSSS cost of advanced reactors systems.

- The number of cost models was substantially extended, in order to include all the costs that, in the preliminary list presented in Section 2, contribute at least 0.5% of the total direct costs of the reference PWR12-BE. In order to accomplish this, a total of 29 cost models were newly developed in FY19, including some of the NSSS-supplied components that contribute less than 0.5% to the total direct costs of the reference PWR12-BE. These, combined with the 31 cost models developed in FY17 and FY18, reach a total of 60 cost models, with a cumulative contribution to the total direct cost of the reference PWR12-BE of more than 95%. With only less than 5% of the direct cost of the reference design not directly quantified, the estimates performed with ACCERT have now a high degree of robustness and defensibility.
- New work was performed on the quantification of uncertainties of the cost estimates produced with the ACCERT algorithm, in Chapter 4. The cost models of the ACCERT algorithm produce deterministic estimates, which can be considered the "expected values" of cost estimates that are, in reality, uncertain. The shape and magnitude of the uncertainties were, however, unknown until the work performed here allowed their quantification, in a defensible and robust way. The standard deviation, and the functional form of the uncertainty distributions, are the new information that could be derived in this work for the first time, for well-executed construction projects, based on actual historical data on input cost uncertainty, such as labor, steel, concrete etc. As an example, it was possible to calculate that the standard deviation of the reference PWR containment's cost is 8.3% of the expected value. Therefore, in order to have a 95% confidence that the actual realized cost of a containment construction will be within the allocated budget, it is necessary to allocate a contingency of two standard deviations, or of 16.6%. This contingency would be sufficient to cover most of the uncertainty in input costs, which are outside of the control of the constructors. The uncertainty quantification methodology developed here is now an integral part of the ACCERT methodology.

In summary, the ACCERT methodology provides an efficient, transparent and defensible framework for estimating the expected construction costs, and associated uncertainties, of different reactor designs.

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TABLES

ACRONYMS

ACCERT	Algorithm for the Capital Cost Estimation of Reactor Technologies
ANL	Argonne National Laboratory
BE	Better Experience
BLS	Bureau of Labor and Statistics
BWR	Boiling Water Reactor
CFR	Code of Federal Regulation
CPI	Consumer Price Index
CSS	Containment Spray System
D&D	Decontamination and Decommission
DOE	Department of Energy
DOE-NE	Department of Energy, Office of Nuclear Energy
DOE-EM	Department of Energy, Office of Environmental Management
DU	Depleted Uranium
EAS	Engineering Alternative Study
EDF	Électricité de France
EEDB	Energy Economic Database
E&S	Nuclear Fuel Cycle Evaluation and Screening
EG	E&S Evaluation Group
EIA	U.S. DOE Energy Information Administration
FCO	Fuel Cycle Options – Systems Analysis & Integration
FCDP	Fuel Cycle Data Package
FR	Fast Spectrum Reactor
FY	Fiscal Year
GE	General Electric
GNP	Gross National Product
GWd	Giga-Watt-day
GW_e	Gigawatt Electric
GW_{th}	Gigawatt Thermal
HO	Home Office
IAEA	International Atomic Energy Agency
kgHM	kg of Heavy Metal
LLC	Limited Liability Company
LMR	Liquid Metal Fast Reactor
LWR	Light Water Reactor
MA	Minor Actinides
ME	Median Experience
MIT	Massachusetts Institute of Technology
MOX	Mixed Oxide Fuel
MT	Metric Tons
MW_e	Megawatt Electric
MW_{th}	Megawatt Thermal
NASAP	Nonproliferation Alternative Systems Assessment Program
NNS	Non-Nuclear Safety
NOAK	Nth of a Kind
NRC	Nuclear Regulatory Commission
NSSS	Nuclear Steam Supply System
O&M	Operation and Maintenance
PPI	Producer Price Index
PWR	Pressurized Water Reactor

RHR	Residual Heat Removal System
RU	Recovered Uranium
R&D	Research and Development
RWST	Refueling Water Storage Tank
SEC	Security and Exchange Commission
SFR	Sodium-cooled Fast Reactors
SIS	Safety Injection System
SWU	Separative Work Unit
TRU	Transuranic
UOX	Uranium Oxide Fuel
US	United States of America
USD	U.S. Dollars
USNRC	Nuclear Regulatory Commission
WEC	Westinghouse Electric Company LLC.

SYSTEMS ANALYSIS AND INTEGRATION CAMPAIGN REPORT ON THE ACCERT COST ALGORITHMS TOOL

1. INTRODUCTION

This report presents the work, performed in FY19, dedicated to the improvement to the Algorithm for the Capital Cost Estimation of Reactor Technologies (ACCERT).

The overall ACCERT development, approach and methodology have been extensively discussed in Ganda (2018), and therefore will not be repeated here. Similarly, the cost models developed in FY18 have not been modified since Ganda (2018), and consequently are not discussed in the present report. Instead, one important item that has been modified since the Ganda (2018) report is a revisited list of the direct cost breakdown of the reference PWR, in Section 2.1. The list has been updated and improved as compared to the one presented in Table 3 of Ganda (2018). Each account has been mapped to the corresponding account number of the Energy Economics Data Base (EEDB), and the cost of certain components that had incorrect costs in Section 2.3 of Ganda (2018) have been corrected, so that the sum of all the costs in the table has been verified to match exactly the total of the direct costs in the EEDB. Additionally, the revisited list of the direct costs of the present report includes a slightly different breakdown for certain complex components or systems, intended to facilitate the cost analysis of advanced concepts.

Ganda (2018) also included a complete evaluation of the expected construction cost of the ABR1000, with the primary objective of demonstrating the feasibility of the ACCERT approach for the estimation of the overnight capital cost of advanced concepts, as an example. Since that objective was fully achieved in Ganda (2018), and since a further demonstration was achieved with a full evaluation of the expected construction cost of the Versatile Test Reactor (VTR), no complete example evaluation of advanced systems has been performed in the current work.

The overall objective of this work is to increase the fidelity of the ACCERT algorithm, and consequently the usefulness and credibility of the evaluations performed with this tool. For this objective, the following has been accomplished in FY19:

- Cost models of *all* the Nuclear Steam Supply System (NSSS)-supplied components were developed, in Chapter 3, for which costs are not provided in the reference cost databases (EEDB 1987), as discussed in Ganda (2018).
- Further, the reasonableness of the NSSS cost models was checked, in Chapter 3, by summing the calculated costs derived from the models of this work and of Ganda (2018), and comparing the sum to the total aggregated NSSS costs, known from EEDB (1987). The agreement between the two was found to be excellent, as described in Section 3.20.
- The number of cost models was substantially extended, in Chapter 3, in order to include all the costs that, in the preliminary list presented in Section 2, contribute at least 0.5% of the total direct costs of the reference PWR12-BE.
- Cost models were developed, in Chapter 3, for relatively small mechanical components that are present both in reactors and in non-reactor fuel cycle facilities, such as rotating machinery, heat exchangers, demineralizers, tanks etc. Appendix A in particular includes an in-depth analysis of the cost of small and medium-sized pumps. With this set of information, work can continue in the future to develop detailed bottom-up estimates of non-reactor fuel cycle facilities.
- New work was performed on the quantification of uncertainties of the cost estimates produced with the ACCERT algorithm, in Chapter 4. The cost models of the ACCERT algorithm produce

deterministic estimates, which can be considered the "expected values" of cost estimates that are, in reality, uncertain. The shape and magnitude of the uncertainties were, however, unknown until the work performed here allowed their quantification, in a defensible and robust way. The standard deviation, and the functional form of the uncertainty distributions, are the new information that could be derived in this work for the first time, for well-executed construction projects, based on actual historical data on input cost uncertainty, such as labor, steel, concrete etc. Appendixes B, C and D provide additional information supporting the analysis of Chapter 4, including the Matlab code that performs the correlated sampling in Appendix D. The uncertainty quantification methodology developed here is now an integral part of the ACCERT methodology.

In summary, substantial improvements have been made to the ACCERT methodology in this work. However, it is also noted that the work on this tool is not complete, and that further efforts can improve the quality and robustness of the cost evaluations performed with the ACCERT tool, as well as expand its applicability beyond reactor systems, to other fuel cycle facilities. A summary of the most important achievements of this work, as well a discussion of the needed future work, are provided in Chapter 6.

2. METHODOLOGY and SORTED COMPONENTS OF THE REFERENCE DESIGN

The methodology for the ACCERT capital cost estimation of advanced reactor designs is described in detail in Ganda (2018), and therefore it will not be repeated here. However, this chapter presents an updated list of components for the reference PWR, sorted in decreasing order of fractional contribution to the total direct cost of the reference PWR.

2.1 Sorted Cost Components of the Reference PWR12-BE Plant

The main components of the reference PWR12-BE plant are listed in Table 3, in decreasing order of fractional contribution to the total direct costs. It is noted that the list has been updated and improved as compared to that presented in Table 3 of Ganda (2018). Each account has been mapped to the corresponding account number of the Energy Economics Data Base (EEDB), and the sum of all the costs in the table has been verified to match exactly the total of the direct cost in the EEDB (i.e. $904,576,232 in 1987 USD). The table includes the costs from EEDB (1987) for each account and sub-account, intentionally in 1987 USD, for the purpose of traceability and verifiability. The cost of certain components that had incorrect costs in Table 3 of Ganda (2018) have been corrected. However, since all the corrections were to low-cost components, for which models were not developed in Ganda (2018), there was no impact on the overall direct cost, as well as on previous models, or results, of the ACCERT algorithms and analyses. Additionally, several codes of accounts have been broken down in Table 1 into more detailed subaccounts, in order to facilitate the analysis of advanced reactor systems. These include accounts, 221 “Reactor Equipment”, 222 “Main heat transfer system”, 223 “Safeguard systems” and 226 “Other reactor plant equipment”, as well as the entire NSSS subsystems in account 220A, the cost of which is reported as an aggregated number in EEDB (1987).

For consistency, the costs of the NSSS components are taken from the preliminary breakdown of Holcomb (2011), even though it has been shown in Ganda (2018) that several of the costs need to be substantially modified as compared from Holcomb (2011). However, for the purpose of traceability and comparability with previous work, it was chosen to use the Holcomb (2011) preliminary breakdown of the NSSS components in Table 1.

A full revisit of the NSSS cost breakdown will be possible thanks to the work presented in this report, and is provided at the end of the report in Table 34, in Chapter 5. Table 34 and its content should be used as the starting point for future work on the ACCERT algorithm.

Table 1 – Cost contributors sorted by contributions for the PWR-12-BE; Cost Sources: (EEDB 1987); or (Holcomb 2011) for NSSS costs. Cost models for the items in blue were developed in Ganda (2018).

EEDB ACCOUNT NUMBER	DESCRIPTION	TOTAL COST (1987 USD)	FRACTION OF DIRECT COSTS	CUMULATIVE SUM
231	Turbine Generator	133,984,273	14.81%	14.8%
212	Reactor Containment Building	64,836,041	7.17%	22.0%
262	Condensing Systems Mechanical Equipment	44,648,245	4.94%	26.9%
233	Condensing Systems	28,981,986	3.20%	30.1%
252	Air Water & Service System	28,725,654	3.18%	33.3%
220A.211	Vessel Structure (NSSS)	28,694,400	3.17%	36.5%
211	Yardwork	24,992,519	2.76%	39.2%
234	Feed Heating System	23,588,801	2.61%	41.8%

213	Turbine Room & Heater Bay	23,152,330	2.56%	44.4%
235	Other Turbine Plant Equipment	22,323,194	2.47%	46.9%
245	Elect. Structure +Wiring Control	22,301,683	2.47%	49.3%
227	Reactor Instrumentation + Control	21,555,270	2.38%	51.7%
220A.223	Steam Generators (NSSS)	21,520,800	2.38%	54.1%
224	Rad-waste Processing	20,942,407	2.32%	56.4%
246	Power & Control Wiring	20,601,086	2.28%	58.7%
242	Station Service Equipment	20,163,388	2.23%	60.9%
226.7	Auxiliary Cool System	19,371,824	2.14%	63.1%
215	Prim Aux Building + Tunnels	18,472,145	2.04%	65.1%
218A	Control Rm/D-G Building	18,098,648	2.00%	67.1%
220A.221	Main Coolant Pumps (NSSS)	16,140,600	1.78%	68.9%
216	Waste Process Building	14,367,318	1.59%	70.5%
226.4	Coolant Treatment & Recycle	14,308,481	1.58%	72.1%
241	Switchgear	11,946,283	1.32%	73.4%
220A.2121	Lower Internals (NSSS)	10,760,400	1.19%	74.6%
220A.2122	Upper Internals (NSSS)	10,760,400	1.19%	75.8%
220A.2131	Control Rods (NSSS)	10,760,400	1.19%	76.9%
220A.2132	Control Rod Drives (NSSS)	10,760,400	1.19%	78.1%
217	Fuel Storage Building	9,879,103	1.09%	79.2%
220A.222	Reactor Coolant Piping (NSSS)	8,070,300	0.89%	80.1%
237	Turbine Plant Miscellaneous Items	8,045,900	0.89%	81.0%
218J	Main Steam & Feedwater Pipe Enclosure	7,867,164	0.87%	81.9%
228	Reactor Plant Miscellaneous Items	7,452,275	0.82%	82.7%
236	Turbine Instrumentation and Control	6,854,212	0.76%	83.5%
218B	Administration + Services Building	6,646,347	0.73%	84.2%
253	Communications Equipment	6,415,046	0.71%	84.9%
251	Transportation & Lifting Equipment	5,993,830	0.66%	85.6%
222.12	Reactor Coolant Piping System (Field Cost 222)	5,929,319	0.66%	86.2%
221.14	Transport To Site (Field Cost 221)	5,538,500	0.61%	86.8%
220A.224	Pressurizer (NSSS)	5,380,200	0.59%	87.4%
220A.2311	Residual Heat Removal Pumps And Drives (NSSS)	5,380,200	0.59%	88.0%
220A.2312	Residual Heat Removal Heat Exchanger (NSSS)	5,380,200	0.59%	88.6%
220A.2321	Safety Injection Pumps And Drives (NSSS)	5,380,200	0.59%	89.2%
223.4	Containment Spray System (Field Cost 223)	5,301,297	0.59%	89.8%
218T	Ultimate Heat Sink Structures	4,596,571	0.51%	90.3%
220A.251	Fuel Handling Tools (NSSS)	4,483,500	0.50%	90.8%
220A.254	Fuel Storage Racks (NSSS)	4,483,500	0.50%	91.3%
220A.27	Instrumentation And Control (NSSS)	4,483,500	0.50%	91.8%
220A.28	Standard NSSS Valve Package (NSSS)	4,483,500	0.50%	92.3%
261	Condensing Systems Structures	4,332,720	0.48%	92.8%
244	Protective Equipment	4,261,386	0.47%	93.2%
223.3	Safety Injection System (Field Cost 223)	3,643,982	0.40%	93.6%

225	Fuel Handling & Storage	3,167,160	0.35%	94.0%
222.11	Fluid Circulation Drive System (Field Cost 222)	3,015,496	0.33%	94.3%
255	Waste Water Treatment Equipment	2,831,384	0.31%	94.6%
254	Furnishing + Fixtures	2,735,984	0.30%	94.9%
220A.225	Pressurizer Relief Tank (NSSS)	2,690,100	0.30%	95.2%
220A.2322	Accumulator Tank (NSSS)	2,690,100	0.30%	95.5%
220A.2323	Boron Injection Tank (NSSS)	2,690,100	0.30%	95.8%
220A.2324	Boron Injection Surge Tank (NSSS)	2,690,100	0.30%	96.1%
220A.2325	Boron Injection Recirculating Pump & Drive (NSSS)	2,690,100	0.30%	96.4%
218E	Emergency Feed Pump Building	2,498,464	0.28%	96.7%
221.12	Vessel Structure (Field Cost 221)	2,469,806	0.27%	97.0%
223.1	Residual Heat Removal System (Field Cost 223)	2,390,058	0.26%	97.2%
220A.2611	Rotating Machinery (Pumps And Motors) (NSSS)	2,241,750	0.25%	97.5%
220A.2612	Heat Transfer Equipment (NSSS)	2,241,750	0.25%	97.7%
220A.2614	Purification And Filtration Equipment (NSSS)	2,241,750	0.25%	98.0%
243	Switchboards	2,048,898	0.23%	98.2%
226.3	Reactor Makeup Water Sys	1,492,582	0.17%	98.4%
221.11	Reactor Support (Field Cost 221)	1,372,273	0.15%	98.5%
214	Security Building	1,361,955	0.15%	98.7%
220A.2613	Tanks And Pressure Vessels (NSSS)	1,345,050	0.15%	98.8%
226.1	Inert Gas System	1,240,051	0.14%	99.0%
223.5	Combustible Gas Control System (Field Cost 223)	1,080,923	0.12%	99.1%
220A.262	Maintenance Equipment (NSSS)	896,700	0.10%	99.2%
222.13	Steam Generator Equipment (Field Cost 222)	839,491	0.09%	99.3%
218L	Technical Support Center	789,445	0.09%	99.4%
218S	Waste Water Treatment	767,292	0.08%	99.4%
218F	Manway Tnls. (Radiological Ctrl Access Tunnels)	761,901	0.08%	99.5%
226.9	Sampling Equipment	642,722	0.07%	99.6%
221.13	Vessel Internals (Field Cost 221)	597,953	0.07%	99.7%
221.21	Control Rod System (Field Cost 221)	538,347	0.06%	99.7%
218H	Non- Essential Switchgear Building.	535,897	0.06%	99.8%
226.8	Maintenance Equipment	530,847	0.06%	99.8%
218D	Fire Pump House, Including Foundations	426,826	0.05%	99.9%
218K	Pipe Tunnels	317,301	0.04%	99.9%
218P	Containment Equipment Hatch Missile Shield	219,928	0.02%	100.0%
226.6	Fluid Leak Detection System	173,004	0.02%	100.0%
222.14	Pressurizing System (Field Cost 222)	114,113	0.01%	100.0%
218V	Control Room Emergency Air Intake Building	89,133	0.01%	100.0%
218G	Electrical Tunnels	67,770	0.01%	100.0%
	TOTAL	**904,576,232**	**100%**	

2.2 Escalation and Cost Indices

In this study, data from different sources were used, with costs expressed in different year-dollars. While multiple sources have been used in this work, as well as in the previous reports (Ganda 2017 and 2018), a few references have been used more frequently throughout the report: (1) (Robertson 1971) with numbers in 1970-year dollars; (2) (Combustion Engineering 1978), with numbers in 1978-year dollars; (3) (EEDB 1987), with numbers in 1987-year dollars; and (4) (Holcomb 2011), with numbers in 2011-year dollars. A summary of the escalation indexes used in Ganda (2018), to January 2017 for the references mentioned above, is reproduced in Table 2 (from Ganda (2018)). Table 2 also includes an "above-inflation" escalation factor for each of the references: the logic and approach used to determine the "above-inflation" factors are discussed in Section 2.4 of Ganda (2018), and will not be repeated here.

Table 2 Summary of the escalation indexes used in Ganda (2018), to January 2017.

Source	**Year dollar**	**CPI index factor to January 2017**	**Above inflation escalation factor**	**Total escalation factor**
(Robertson 1971)	1970	6.42	2.16	13.84
(Combustion Engineering 1978)	1978	3.95	1.70	6.72
(EEDB 1987)	1987	2.20	1.30	2.87
(Holcomb 2011)	2011	1.10	1.00	1.10

In order to maintain consistency between the cost models of Ganda (2018) and those generated in this report (since the work in this report is a continuation and extension of the work of Ganda (2018)), it was chosen to retain the escalation factors used in Ganda (2018), and reproduced in Table 2, also in this report. Future updates of this work could update the cost models to the then-current year dollars. Additionally, future updates could switch the general inflation index from the CPI, used in Ganda (2018) and consequently here, to the GNP-deflator index, which would be consistent with the assumptions for the general inflation of EEDB (1987).

3. DEVELOPMENT OF COST MODELS

In this Chapter, the work performed in Ganda (2018) with the development of cost models for the 31 most expensive components, contributing at least 1% of the total direct cost of the reference PWR, is continued and substantially expanded. For each cost model, a description is provided of the basis, assumptions and approximations utilized to arrive at the recommended models.

In this Chapter, 29 additional cost models are developed for cost accounts comprising at least 0.5% of the total direct cost of the reference PWR (please see Table 1), thus reaching a cumulative contribution of 92%, plus all the NSSS-supplied components for which models were not previously developed in Ganda (2018), even if their individual contribution is lower than 0.5%. This was done in order to complete the analysis of all the components of the NSSS, and to be able to verify how the aggregated cost of the ACCERT NSSS models compares to the known aggregated NSSS cost from EEDB (1987). This comparison is performed at the end of this Chapter, in Section 3.20.

Additionally, cost models for the "field costs" of the *residual heat removal system* and of the *combustible gas control system* were developed, even though these two accounts contribute only 0.26% and 0.12% to the total direct costs of the reference PWR. This is done in order to complete the assessment of the cost of those components, even if the cost of installation ranks substantially lower than that of other components.

The total cumulative contributions of the cost models analyzed in this work and in Ganda (2018) is more than 95% of the total direct costs of the reference PWR.

3.1 Turbine Plant Miscellaneous Items (Account 237)

The turbine plant miscellaneous items (which is about 0.9% of total direct costs) includes the cost of field painting, the cost of qualifying welders and the cost of insulation of pipes, equipment and of NSSS-supplied components.

The cost breakdown of the reactor plant miscellaneous items into factory equipment, cost of site labor and of site material, from EEDB (1987), is shown in Table 3.

Table 3 – PWR12-BE account 237 costs, in 1987 USD, from (EEDB 1987)

	Factory equipment	**Site labor**	**Site material**	**Total**
237.1 Field Painting	-	$1.05 million	$0.28 million	$1.33 million
237.2 Qualification of Welders	-	$1.52 million	$0.23 million	$1.75 million
237.31 Pipe Insulation	-	$1.54 million	$2.20 million	$3.74 million
237.32 Equipment Insulation	-	$0.50 million	$0.73 million	$1.23 million
TOTAL		**$4.61 million**	**$3.44 million**	**$8.05 million**

The cost of this account for advanced reactor designs is estimated in first approximation using a scaling law of 0.8, as for other turbine-related equipment, as suggested by Phung (1987), according to the following Equation (in 1987 USD).

$$C_{226} = \$8.05 \text{ million } \cdot \left(\frac{\text{MW}_{th}}{3431}\right)^{0.8}$$

The corresponding equation in 2017 USD is:

$$C_{226} = \$23.10 \text{ million } \cdot \left(\frac{\text{MW}_{th}}{3431}\right)^{0.8}$$

3.2 Main Steam and Feedwater Pipe Enclosures (Account 218J)

The Main Steam and Feedwater Pipe Enclosures is one of the major Seismic Category I structures. It houses the Seismic Category I sections of the main steam and feedwater piping external to the reactor containment building, and protects the containment piping penetrations.

The dimensions of these structures are derived from EEDB (1988b), as follows: *"The floors are located 17 feet below grade with the walls extending to competent rock for support except in the portion of the north tunnel near the containment where the roof of the mechanical penetration area forms the floor of the enclosure. The mechanical penetration area is 39 feet high and founded on rock 56 feet below grade. The enclosures are each 18 feet wide (20 feet wide on the north side), 115 feet long and 59 feet high, with a total volume of approximately 245,000 cubic feet. The mechanical penetration area is approximately 25 feet wide and 90 feet long and is also a reinforced concrete Seismic Category I structure."*

It is noted that, based on the description, there are two separate pipe enclosures (on the north and south sides of the containment building, respectively) of 115ft x 59 ft x18 ft each, and one mechanical penetration area below the north enclosure of the building of dimension 90ft x 39 ft x 25 ft.

The cost of these structures is calculated using the containment construction model and the above-specified dimensions, with the additional assumptions of 2 ft thick walls (which is consistent with other buildings with similar functions, such as the turbine building) and a 95% internal void fraction (utilizing a number similar to the containment). The calculated combined construction costs was found to be very close (about 6.5% lower) to the reported value in EEDB (1987), as shown in Table 4.

Table 4 – PWR12-BE account 228 costs, from EEDB (1987)

	Total cost (in 1987 USD)
Each of the Two Feedwater Pipe enclosures	$2.74 million ea.
Mechanical penetration building	$1.88 million
TOTAL	**$7.36 million**
Cost of Account 218J from (EEDB 1987)	**$7.87 million**

Therefore, in order to estimate the cost of the Feedwater Pipe Building for advanced systems, if this structure is present, it is recommended to reduce by 6.5% the value calculated using the containment building model from Ganda (2018) for the specific dimensions of this building.

3.3 Reactor Plant Miscellaneous Items (Account 228)

The reactor plant miscellaneous items (which are about 0.8% of total direct costs) include the cost of field painting, the cost of qualifying welders, and the cost of insulation of pipes and equipment.

The cost breakdown of the reactor plant miscellaneous items in factory equipment, cost of site labor and of site material, from EEDB (1987), is shown in Table 5.

In general, it is recommended to keep the costs of field painting and of the qualification of welders unchanged for different reactor technologies. However, for system for which the total external surface of the NSSS is known, and different from that of the reference PWR12-BE, the cost of insulation can be scaled linearly. For example, pool-type Na fast reactors, may require less insulation than pipe-type plants, since most of the components will be submerged in Na, and therefore will not require insulation.

Table 5 – PWR12-BE Account 228 costs, from EEDB (1987) in 1987 USD.

	Factory equipment	**Site labor**	**Site material**	**Total**
228.1 Field Painting	-	$0.50 million	$0.16 million	$0.66 million
228.2 Qualification of Welders	-	$2.53 million	$0.38 million	$2.91 million
228.41 Pipe Insulation	-	$0.65 million	$1.04 million	$1.69 million
228.42 Equipment Insulation	-	$0.12 million	$0.38 million	$0.50 million
228.43 NSSS Insulation	-	$0.47 million	$1.21 million	$1.68 million
TOTAL		**$4.27 million**	**$3.17 million**	**$7.44 million**

In general, if the design is not mature enough to provide the required geometrical details, it is recommended to use the same cost of the reference PWR12-BE for the entire Account 228. The cost breakdown of the reactor plant miscellaneous items in factory equipment, cost of site labor and of site material, from EEDB (1987), is shown in Table 6, in January 2017 USD.

Table 6 – PWR12-BE Account 228 costs, from EEDB (1987) in January 2017 USD.

	Factory equipment	**Site labor**	**Site material**	**Total**
228.1 Field Painting	-	$1.44 million	$0.46 million	$1.89 million
228.2 Qualification of Welders	-	$7.26 million	$1.09 million	$8.35 million
228.41 Pipe Insulation	-	$1.87 million	$2.98 million	$4.85 million
228.42 Equipment Insulation	-	$0.34 million	$1.09 million	$1.44 million
228.43 NSSS Insulation	-	$1.35 million	$3.47 million	$4.82 million
TOTAL		**$12.25 million**	**$9.10 million**	**$21.35 million**

3.4 Turbine Instrumentation and Control (Account 236)

The Turbine Instrumentation and Control (which is about 0.76% of total direct costs) provides "*monitoring and protection for plant, personnel and equipment. It enables the operator to start up, operate and shut down the turbine plant in conjunction with the reactor plant*" (EEDB 1988b).

The cost breakdown of the Turbine Instrumentation and Control account in factory equipment, cost of site labor and of site material, in 2017 USD from EEDB (1987), is shown in Table 7, dominated by the labor cost for the installation.

Table 7 – PWR12-BE account 227 costs, from EEDB (1987) (escalated to 2017 USD)

	Factory equipment	**Site labor**	**Site material**	**Total**
Account 227	$5.36 million	$13.18 million	$1.13 million	**$19.67 million**

In general, it is recommended to keep the costs associated with this account unchanged for different reactor technologies, at $19.67 million, since the cost of the instrumentation and control is not likely to change substantially with a change in the power level or other technical parameters of the turbine.

3.5 Administration and Services Building (Account 218B)

The administration and services building is described as *"a Non-Seismic Category I structure located north of the turbine building and heater bay. The building is a two story steel frame structure 176 feet wide, 270 feet long and 38 feet high. The building volume is approximately 1,500,000 cubic feet."* (EEDB 1988b).

The functions of this structure are described as follows in EEDB (1988b): *"The building houses the auxiliary boilers, equipment rooms, service shops, storage areas, locker and change rooms, showers, toilet rooms, lunch room, laboratories, general offices and conference rooms."*

The approach adopted for a preliminary estimation of the cost of this structure is analogous to that adopted for accounts 215, 218A, 216 and 217 in Ganda (2018): the containment cost model is utilized to estimate the cost of this structure, and afterwards an "adjustment factor" is derived from the ratio of the actual cost of this structure from EEDB (1987) and of the cost calculated by the containment cost model, which generally overestimates the cost for non-containment buildings.

Afterwards, the cost of this structure for advanced reactor designs can be estimated using the containment model for the particular design of this building for each advanced design, and then correcting with the adjustment factor derived in this section.

With the reported dimensions, plus the assumption of 1 ft thick exterior and interior walls, foundations and roof, and an internal void fraction of 98%, the building cost would be $51.08 million, in 2017 USD, if it was built as a containment building. However, the actual cost of this structure according to EEDB (1987) is of only $19.07 million in 2017 USD.

Therefore, the calculated adjustment factor is 0.373.

3.6 Communication Equipment (Account 253)

The communication equipment account includes the following sub-systems:

- Local communications system (including telephone lines, and intercommunication, paging and loudspeaker systems);
- Fire detection system;
- Security system (including both access control to various plant areas, as well as various closed circuit cameras and other various monitoring and surveillance devices).

This set of systems will be generally needed for any advanced reactor system. Therefore, it is recommended to utilize the reference cost of this set of systems (of $18.41 in 2017 USD) for other advanced concepts as well. The cost breakdown of this system is provided in Table 8, in both 1987 USD from EEDB (1987), and in millions of 2017 USD.

Table 8 Cost of factory-supplied equipment, labor and material for Account 253, in 1987 USD (from EEDB (1987)) and in 2017 USD.

Year dollars		Factory	Labor	Material	Total
1987 USD (EEDB 1987)		$1,948,800	$3,873,139	$593,107	$6,415,046
2017 USD		$5.59 million	$11.12 million	$1.70 million	$18.41 million

3.7 Transportation and Lifting Equipment (Account 251)

The transportation and lifting equipment (Account 251), is part of the "miscellaneous plant equipment" under account 25 of EEDB.

In particular, Account 251 includes major cranes and other hoist. Three major cranes are included in this account (EEDB 1987b):

- A 420-ton bridge polar crane inside the containment building, with a bridge span of 103 ft and an auxiliary hoist of 50 ton (Account 251.12);
- A 210-ton traveling bridge crane inside the turbine building, with a bridge span of 126 ft and an auxiliary hoist of 30 tons (Account 251.111);
- A 100-ton traveling bridge crane inside the feed-water heater area, with a bridge span of 61 ft and an auxiliary hoist of 15 tons (Account 251.112).

In addition, several smaller cranes are also listed under Account 251 (EEDB 1988b):

- One monorail hoist with capacity of 5 tons and 1 monorail hoist with capacity of 10 tons in various parts of the plant;
- Two 5-ton traveling bridge cranes in the diesel-generator part of the auxiliary building.

Table 9 shows a summary of the factory, labor and material cost of the major cranes and hoist contained in Account 251, in 2017 USD, together with the gross lifting capacity of each crane. Aggregated lifting capacities are shown for the multiple cranes/hoist included in accounts 251.16 and 251.17.

Table 9 Cost of the major cranes and hoist in Account 251, in 2019 USD, and gross lifting capacity of each crane (aggregated lifting capacity are shown for the multiple cranes/hoist included in accounts 251.16 and 251.17).

Account	2019 USD	Factory cost	Installation Labor Cost	Material Cost	Total Cost	Max gross load (MT)	Factory cost/gross load ($/ton)
251.12	Cont. build	$7.30 million	$1.19 million	$0.12 million	$8.61 million	420	17,391
251.111	Turbine room	$3.65 million	$0.42 million	$0.04 million	$4.11 million	210	17,391
251.112	Heater bay	$1.46 million	$0.17 million	$0.02 million	$1.65 million	100	14,608
251.16	Various	$0.88 million	$0.56 million	$0.06 million	$1.49 million	55	15,936
251.17	Diesel building	$1.23 million	$0.10 million	$0.01 million	$1.33 million	10	122,710

It is noted that the factory costs per ton of gross lifting capacity is a rather constant number, ranging approximately between $14,600/ton and $17,400/ton for all the various cranes, except for the very small bridge cranes of the diesel building, which is substantially more expensive at $122,700/ton. The large unit cost of the diesel building cranes is likely due to the size of the bridge, while the lifting capacity is still being dimensioned for a comparatively minor load. Additionally, the labor cost for the installation of the cranes range from 11% of factory costs to 16% of factory costs for large cranes, and has a high value of 64% for the small monorail hoists of 5-10 tons. This large incidence of labor cost is expected for the small cranes that still require substantial installation labor in order to secure the rails.

In conclusion, it is recommended to use a unit factory cost of $17,000/ton for the large cranes that may be needed for advanced reactor concepts, and a labor cost of 15% of the factory costs. Material costs were added as 10% of labor costs in EEDB (1987): the same approach is recommended also for other reactor concepts.

Alternatively, in the absence of sufficient details to know the lifting requirements of the cranes for advanced concepts, it is recommended to use the aggregated cost of this account for the reference PWR12-BE, of $17.20 million in 2017 USD.

3.8 Transport to Site, Field Cost (Account 221.14)

This account includes the cost of transporting the major NSSS equipment (several weighting tens or even hundreds of ton) from the factory to the construction site. The account includes the cost of constructing a barge unloading dock, as well as the cost of the lifting and transportation equipment (EEDB 1988b).

The construction of the barge unloading dock, as well as the cost of the lifting and transportation equipment, will be relatively insensitive to the combined mass of equipment to be transported, even though it will be somewhat sensitive to the mass of the heaviest single piece of equipment to be transported. However, very little information is provided in EEDB (1987) on the contribution of the various parts to the total cost of this account, which is listed simply as a "material" cost of $5.54 million in 1987 USD, or $15.89 million in 2017 USD.

Therefore, it is recommended to utilize a transportation cost of $15.89 million, as for the reference PWR12-BE, for advanced concepts needing heavy pieces of equipment, except for those designs specifically intended to reduce transportation costs, e.g. through the use of parts that are all light and compact enough to not require any special lifting equipment, by design. In those special cases the cost of this account can be reduced, possibly even to zero.

3.9 Residual Heat Removal System (Account 223.1)

The Residual Heat Removal (RHR) system is described under Account 223.1 of (EEDB 1987 and 1987b), where the costs of installation (site labor and materials) and most of the factory-fabricated equipment are described. Account 223.1 is referred-to as "RHR system field cost", while two large pumps and heat exchangers are provided by the vendors as part of the NSSS system, and therefore are accounted-for separately under accounts 220A.2311 and 220A.2312, respectively.

Account 223.1 amounts to only about 0.26% of the direct cost of the reference PWR, and therefore it would not have been considered in the present report, since the cutoff for inclusion was set at components giving a contribution of at least 0.5% (please see the discussion in Section 2). However, an important goal of this work is to develop cost models of *all* the NSSS-supplied parts, for which cost data have so far been un-available in the public domain Ganda (2018). For this objective, accounts 220A.2311 and 220A.2312 had to be included in this work. Since the technical parameters of the components in accounts 220A.2311 and 220A.2312 are included in the description of account 223.1 in EEDB (1987b), and the cost of installation of those components are included in Account 223.1 in EEDB (1987), it is evident that accounts 223.1, 220A.2311 and 220A.2312 are strongly intertwined. For these reasons, and for the sake of completeness, it was decided to include an analysis of account 223.1 in the present work, despite its low contribution to the total cost of the reference PWR. The inclusion of account 223.1 will additionally make it easier, for users of the ACCERT algorithm, to perform a complete analysis of the cost of the RHR system, or even to exclude the entire cost of the RHR system for those plants that may not include such a system.

Cost models for the pumps and drives, for the heat exchangers and for the field cost of the RHR systems, are developed in Sections 3.9.1, 3.9.2 and 3.9.3, respectively.

3.9.1 RHR System's Pumps and Drives (NSSS) (Account 220A.2311)

Account 220A.2311 includes the pumps, and associated motors, that are part of the "residual heat removal system" and that are supplied by the vendors as part of the NSSS system. Consequently, no cost information on these components is available in EEDB (1987), as for the other components that are supplied as part of the NSSS (Ganda 2018).

In order to develop cost estimates for the pumps and drives in Account 220A.2311, the general approach developed in Appendix A to estimate the cost of small and medium-sized pumps is utilized.

EEDB (1987b), under account 223.111, provides the technical specifications of the two pumps of account 220A.2311. Those technical specifications, together with cost information, are provided in Table 10. According to the approach proposed in Appendix A, two pumps of similar characteristics (reference pumps) as the ones to be estimated were found in accounts 226.7111 (cooling tower pump) and 226.7211 (primary component pump), shown in Table 10.

Table 10 – RHR pump and drive cost estimates.

EEDB Account	226.7111	226.7211	223.111
	Cooling Tower Pump (CTP)	Primary Component Pump (PCP)	RHR Pump
Type	Centrifugal	Centrifugal	Centrifugal
Orientation	Vertical	Horizontal	Vertical
Speed (rpm)	1,180	1,200	N/A
Volumetric flow rate (gpm)	13,000	11,000	3,800
Head (feet of head)	170	200	350
Design pressure (psig)	150	150	600
Design temperature (F)	200	200	400
Material	Stainless Steel	Cast Carbon Steel	Stainless Steel
Safety Class	3	3	2
Seismic Category	1	1	1
Design Code	ASME III, Class 3	ASME III, Class 3	ASME III, Class 2
C/H factor (gpm*feet)	2,210,000	2,200,000	1,330,00
Factory equipment cost (2017 USD)	$1.26 million	$0.42 million	Not Provided
Calculated equipment cost using C/H with exponent 0.52 Phung (1987) and cost of CTP	$1.26 million	$1.26 million	$0.97 million
Calculated equipment cost using C/H with exponent 0.52 Phung (1987) and cost of PCP	$0.43 million	$0.42 million	$0.33 million
Calculated using Figure 23 Phung Curve	$0.13 million	$0.13 million	$0.10 million
Calculated using Figure 23 EEDB Data Fit Curve	$0.44 million	$0.44 million	$0.31 million

While both reference pumps have a similar C/H[a] and identical pressure, temperature and safety class, their factory cost is substantially different. It is also noted that the cooling tower pump is made of stainless steel, while the primary component pump is made of carbon steel: this may explain some of the difference in cost, even though it is clear from the analysis in Appendix A that the type of steel is generally not a major cost drivers for small and medium pumps.

The RHR pump is made of stainless steel and is a higher safety class (class 2) than both the cooling tower pump and the primary component pump (both class 3). Additionally, while the C/H of the RHR pump is

[a] C/H is defined as the product between the volumetric flow rate and the pressure drop as (Ganda 2018):

$$\frac{C}{H} = \text{flow\_rate}\ [gpm] \cdot \text{pressure\_drop}\ [psi]$$

smaller, its design pressure and temperature are substantially higher than both reference pumps. The higher pressure will require thicker walls of the pump casing, and more complex sealing, which will increase the factory cost of the RHR pump. Those factors indicate that the choice of the reference pump, as the starting point of the cost estimate, should be "biased" toward the more expensive of the two reference pumps: i.e. the cooling tower pump appears to offer a more defensible starting point.

Using the 0.52 scaling exponent from Phung (1987), the factory equipment cost of the RHR pump would be estimated at \$0.97 million, according to the following equation:

$$C_{pump} = C_{pump,ref}\left(\frac{C/H_{pump}}{C/H_{pump,ref}}\right)^{0.52} = 1.26\,million\left(\frac{1{,}330{,}000}{2{,}210{,}000}\right)^{0.52} = 0.97\,million$$

Since there are two RHR pumps, the estimated cost of factory equipment included in the NSSS allocation is \$1.94 million, in 2017 USD.

For advanced plants, if a detailed design is available for the RHR system, the technical specifications of the main RHR pumps should be used to identify a pump with similar characteristics and for which cost information are available. The cost of the reference pump should then be used to scale the cost of the pump, as shown in this section.

3.9.2 Residual Heat Removal Heat Exchangers (Account 220A.2312)

Account 220A.2312 includes two large heat exchangers, that are part of the "residual heat removal system" and that are supplied by the vendors as part of the NSSS system. Consequently, no cost information on these components is available in EEDB (1987), as for the other components that are supplied as part of the NSSS (Ganda 2018).

The specifications provided in EEDB (1987b), under account 223.1, are used to arrive at a cost estimate for these components, utilizing the approach developed in Section 3.8 of Ganda (2018).

From Account 223.121 in EEDB (1987b), it is known that the dry weight of the RHR heat exchangers is 29,000 lb, and that the shell is made of carbon steel and the tubes of stainless steel. However, no information is provided in EEDB (1987b) on the fractional weight of the tubes and of the shell. Therefore, those were determined by utilizing, in first approximation, the fractional weight of tubes and shell of the ABR1000 steam generators, from (Grandy 2007), since the information could be readily calculated from the information available in (Grandy 2007) and from Section 4.1.7.2 of Ganda (2018).

The calculated volume information are shown in Table 11: it is observed that the weight of the tubes (including the tube sheets) constitute 61% (rounded as 60%) of the component, while the shell and heads constitute 39% (rounded as 40%) of weight of the component.

Table 11 Weight and fractional weight of the steam generators of the ABR1000, from parameters derived from (Grandy 2007)

	Weight [t]	
Tubes	84.0	
Shell	47.3	
Tube Sheet	4.3	
Both Heads	8.6	
Shell + Head	55.9	39% of total
Tubes + Tube Sheets	88.3	61% of total
Total	144.2	

Therefore, utilizing unit cost of $75,000/ton for plate-fabricated carbon steel (for the shell and heads) and of $310,000/ton for stainless steel for the tubes and tube sheets (Ganda 2018), the total cost of each of the heat exchangers could be calculated at $3.13 million. Since there are two of these components under account 220A.2312 for each reference PWR, the estimated total cost of this account is $6.26 million in 2017 USD.

3.9.3 RHR System, Field Cost (Account 223.1)

This Section provides an approach to compute the cost of the RHR field costs (Account 223.1), including that for other advanced nuclear energy systems. Table 12 provides the cost information of the RHR system that is part of the Field Cost (Account 223.1) in 1987 USD, from EEDB (1987). The factory equipment costs of the pumps and heat exchangers are included in the NSSS, and are discussed in Sections 3.9.1 and 3.9.2, respectively.

Table 12 – Residual heat removal system cost breakdown (in 1987 USD) from EEDB (1987).

	Account	Factory equipment	Site labor	Site material	Total
Pumps and Drives	223.11	Included in NSSS	50,250	5,025	55,275
Heat transfer equipment	223.12	Included in NSSS	30,725	3,073	33,798
Piping	223.15	881,381	1,139,130	108,181	2,128,692
RHR valves	223.16	42,999			42,999
Piping - misc. items	223.17	48,364			48,364
Instrumentation + control	223.18	69,548	10,840	542	80,930
TOTAL		**1,042,292**	**1,230,945**	**116,821**	**2,390,058**

It is observed that the field costs of the RHR is dominated by the cost of piping, which comprise about 90% of the costs directly included in Account 223.1. Obviously, this makes generalizations of the costs of this account difficult, since the piping in general will strongly depend on the configuration and arrangement of the system.

Therefore, it is proposed here to instead adopt an approach that is based on the total field cost (of $7.02 million in 2017 USD) as a fraction of the combined cost of the NSSS-included components, namely “pumps and drives” and “heat transfer equipment”.

From Sections 3.9.1 and 3.9.2, where cost models for these components were developed, it was estimated that the NSSS cost of the pumps and drives (Account 220A.2311) is $1.94 million, and that the cost of heat transfer equipment (Account 220A.2312) is of $6.26 million. Therefore, the total combined cost of the NSSS-supplied equipment is $8.20 million, as shown in Table 13.

Table 13 – RHR system cost breakdown, including NSSS-supplied components and field costs (in 2017 USD)

Account #	Parts of the RHR system	Cost (2017 USD)
220A.2311	Pumps and Drives (NSSS Cost)	$1.94 million
220A.2312	Heat transfer equipment (NSSS Cost)	$6.26 million
	Pumps and Drives + Heat transfer equipment (NSSS Cost)	$8.20 million
223.1	RHR System, Field Cost (Account 223.1)	$7.02 million (85% of total costs)

Therefore, the RHR system field cost of $7.02 million is 85% of the combined cost of the related NSSS supplied equipment. It is recommended to use this fraction as a first approximation approach to estimate the field cost of the RHR system, absent a detailed design that allows a bottom-up costing of the necessary equipment, including piping.

3.10 Containment Spray System (Account 223.4)

The Containment Spray System (CSS), in Account 223.4, comprises about 0.6% of the total direct cost for the reference PWR12-BE. It is a safety feature of the containments that is not included in the containment construction costs (Account 212), which instead is treated in detail in Ganda (2018).

The CSS is normally activated only in the case of an accident, and is used *"as an active containment heat removal system in conjunction with the RHR system to limit the containment pressure to values below the design pressure, in compliance with General Design Criterion 38 of Appendix A to 10CFR50."* (EEDB 1988b) and for *"removing sufficient containment airborne iodine to limit external doses to values below those set by 10CFR100, in compliance with General Design Criterion 41 of Appendix A to 10CFR50."* (EEDB 1988b). Additionally, the CSS *"consists of two independent, redundant trains with the exception of the common [Refueling Water Storage Tank] RWST and spray additive tank"* and it *"first functions on water from the RWST and then on water recycled from the containment sump."* (EEDB 1988b). In other words, no major tanks are required for this system, which instead relies primarily on the separate refueling water storage tank and on water from the containment sump. Therefore, as expected, the cost of this system is dominated by the factory equipment and installation labor cost of the piping, which comprise almost 80% of the total cost of this system, as can be seen in Table 14.

Table 14 – Containment Spray System cost breakdown (in 1987 USD) from EEDB (1987).

	Account	Factory equipment	Site labor	Site material	Total
Rotating machinery	223.41	254,295	55,275	5,528	315,098
Heat Transfer Equipment	223.42	251,011	23,650	2,365	277,025
Tanks and Pressure Vessels	223.43	159,256	23,635	2,364	185,255
Piping	223.45	1,990,084	1,936,512	195,076	4,121,672
Valves and Fittings	223.46	172,098	5,610	561	178,269
Piping - misc. items	223.47	113,000			113,000
Instrumentation + control	223.48	99,595	10,840	542	110,977
TOTAL		**3,039,339**	**2,055,522**	**206,436**	**5,301,297**

The size of the system for advanced concepts is related to the detailed accident scenarios for the particular advanced nuclear energy system. Some advanced concepts may not need this system: in that case, the cost of this system will obviously be zero. On the other hand, other concepts may require additional components as compared to the ones listed in Table 14, especially tanks for water or other cooling fluids, if large tanks of cooling fluids (such as the refueling water storage tank in the case of the PWR12-BE) are not already installed in the plant to support other systems.

Therefore, in order to provide an accurate estimate of the cost of this system, it will be necessary to calculate the cost of the components, including factory equipment and installation, from the detailed design of this system for each advanced design studied. However, absent detailed engineering designs for this system, or in order to provide an initial, first order estimate, the containment free volume can be used to scale linearly the cost of the CSS. The containment free volume for the reference PWR-BE is 86,488 m^3 (Ganda 2018), resulting in a unit cost of \$61.3/m^3 in 1987 USD, and of \$175.9/m^3 in 2017 USD. The following equation can be used to calculate the cost of the containment spray system:

$$C_{223.4} = \$175.9 \cdot \left(C_{free\_volume}\ [m^3]\right)^{1.0}$$

3.11 Safety Injection System (Account 223.3)

The Safety Injection System (SIS) is described under Account 223.3 of (EEDB 1987 and 1987b), where the costs of installation (site labor and materials) and most of the factory-fabricated equipment are described. Account 223.3 is referred-to as “SIS field cost”, while several tanks and pumps (which are also important parts of the SIS) are provided by the vendors as part of the NSSS system, and therefore are accounted-for separately under accounts 220A.2321 to 220A.2325.

Account 223.3 amounts to only about 0.4% of the direct cost of the reference PWR, and therefore it would not have been considered in the present report, since the cutoff for inclusion was set at components giving a contribution of at least 0.5% (please see the discussion in Section 2). However, an important goal of this work is to develop cost models of *all* the NSSS-supplied parts, for which cost data have so far been unavailable in the public domain (Ganda 2018). For this objective, accounts 220A.2321 to 220A.2325 had to be included in this work. Since the technical parameters of the components in accounts 220A.2321 to 220A.2325 are included in the description of account 223.3 in EEDB (1987b), and the cost of installation of those components are included in Account 223.3 in EEDB (1987), it is evident that accounts 223.3, 220A.2321, 220A.2322, 220A.2323, 220A.2324 and 220A.2325 are strongly intertwined. For these reasons, and for the sake of completeness, it was decided to include an analysis of account 223.3 in the present work, despite its low contribution to the total cost of the reference PWR. The inclusion of account 223.3 will additionally make it easier, for users of the ACCERT algorithm, to perform a complete analysis of the cost of the SIS, or even to exclude the entire cost of the SIS for those plants that may not include such a system.

Cost models for the pumps and drives, for the tanks and for the field cost of the SIS systems, are developed in Sections 3.11.1, 3.11.2 and 3.11.3, respectively.

3.11.1 SIS’s Pumps and Drives (NSSS): Accounts 220A.2321: Safety Injection Pumps and Drives and 220A.2325: Boron Injection Recirculating Pumps and Drives

Accounts 220A.2321 and 220A.2325 include the pumps, and associated motors, that are part of the “safety injection system” and that are supplied by the vendors as part of the NSSS system. Consequently, no cost information on these components is available in EEDB (1987), as for the other components that are supplied as part of the NSSS (Ganda 2018).

In order to develop cost estimates for the pumps and drives in Accounts 220A.2321 and 220A.2325, the general approach developed in Appendix A to estimate the cost of small and medium-sized pumps is utilized.

For advanced plants, if a detailed design is available for the RHR system, the technical specifications of the main RHR pumps should be used to identify a pump with similar characteristics, and for which cost information are available. The cost of the reference pump should then be used to scale the cost of the pump, as shown in this section.

3.11.1.1 Account 220A.2321: Safety Injection Pumps and Drives (NSSS allocation)

EEDB (1987b), under accounts 223.311, provides the technical specifications of the two “safety injection system” pumps of account 220A.2321. Those technical specifications, together with cost information, are provided in Table 15. According to the approach proposed in Appendix A and already illustrated in Section 3.9.1, two pumps of similar characteristics (reference pumps) as the ones to be estimated were found in accounts 226.7111 (cooling tower pump) and 226.7211 (primary component pump), shown in Table 15. While both reference pumps have a similar C/H and identical pressure, temperature and safety class, their factory cost is substantially different. It is also noted that the cooling tower pump is made of stainless steel, while the primary component pump is made of carbon steel: this may explain some of the difference in cost, even though it is clear from the analysis in Appendix A that the type of steel is generally not a major cost drivers for small and medium pumps.

The safety injection system pumps are made of stainless steel, and are a higher safety class (class 2) than both the cooling tower pump and the primary component pump (both class 3). Additionally, while the C/H of the safety injection system pumps is about half, its design temperature, and especially its design pressure, are substantially higher than both reference pumps. The substantially higher pressure will require thicker walls of the pump casing, and more complex sealing, which will increase the factory cost of the safety injection system pumps. Those factors indicate that the choice of the reference pump, in order to perform the cost estimate, should be "biased" toward the more expensive of the two reference pumps: i.e. the cooling tower pump appears to offer a more defensible starting point.

Using the 0.52 scaling exponent from Phung (1987), the factory equipment cost of each of two the safety injection system pumps would be estimated at \$0.86 million, according to the following equation:

$$C_{Safety\_inj\_pump} = C_{pump,ref}\left(\frac{C/H_{pump}}{C/H_{pump,ref}}\right)^{0.52} = 1.26\,million\left(\frac{1{,}062{,}500}{2{,}210{,}000}\right)^{0.52} = 0.86\,million$$

Since there are two safety injection system pumps, the estimated cost of factory equipment included in the NSSS allocation is \$1.72 million, in 2017 USD.

Table 15 – Safety Injection Pumps and Drives cost estimates (2017 USD).

EEDB Account	226.7111	226.7211	223.311
	Cooling Tower Pump	Primary Component Pump	Safety Injection System Pump
Type	Centrifugal	Centrifugal	Centrifugal, 10 Stage Diffuser
Orientation	Vertical	Horizontal	Horizontal
Speed (rpm)	1,180	1,200	N/A
Volumetric flow rate (gpm)	13,000	11,000	425
Head (feet of head)	170	200	2,500
Design pressure (psig)	150	150	1750
Design temperature (F)	200	200	300
Material	Stainless Steel	Cast Carbon Steel	Stainless Steel
Safety Class	3	3	2
Seismic Category	1	1	1
Design Code	ASME III, Class 3	ASME III, Class 3	ASME III, Class 2
C/H factor (gpm*feet)	2,210,000	2,200,000	1,062,500
Factory equipment cost (2017 USD)	\$1.26 million	\$0.42 million	Not Provided
Calculated equipment cost using C/H with exponent 0.52 Phung (1987) and cost of CTP	\$1.26 million	\$1.26 million	\$0.86 million
Calculated equipment cost using C/H with exponent 0.52 Phung (1987) and cost of PCP	\$0.43 million	\$0.42 million	\$0.29 million
Calculated using Figure 23 Phung Curve	\$0.13 million	\$0.13 million	\$0.09 million
Calculated using Figure 23 EEDB Data Fit Curve	\$0.44 million	\$0.44 million	\$0.26 million

3.11.1.2 Account 220A.2325: Boron Injection Recirculating Pumps and Drives (NSSS allocation)

EEDB (1987b), under accounts 223.312, provides the technical specifications of the two boron injection recirculating pumps of account 220A.2325. Those technical specifications, together with cost information, are provided in Table 16. According to the approach proposed in Appendix A and already utilized in previous Sections, two pumps of similar characteristics (reference pumps) as the ones to be estimated were found in accounts 218A.23121 (the hot water circulation pump) and 218B.22123 (primary component pump), shown in Table 15. The boron injection recirculating pumps are small pumps that fall within the bulk of the fitted data utilized in Appendix A, with the cost likely in the range of a few thousand dollars. Both reference pumps have identical design pressures and temperature as the boron injection recirculating pumps, which however is made of stainless steel as opposed to carbon steel, and has a higher safety class, seismic category and design code. Between the two reference pumps, the hot water circulation pump appears to be the closest to the boron injection recirculating pumps in terms of C/H, and with a similar heads and flow rates. Therefore, the “base estimate” of the factory cost of each of the two boron injection recirculating pumps will be performed using hot water circulation pump as reference, and the 0.52 scaling exponent from Phung (1987), according to the following equation:

$$C_{Boron\_inj\_pump} = C_{pump,ref}\left(\frac{C/H_{pump}}{C/H_{pump,ref}}\right)^{0.52} = \$1{,}435\left(\frac{2000}{1190}\right)^{0.52} = \$1{,}880$$

However, in order to correct for the higher safety class, seismic category and design code, as well as for the fact that the boron injection recirculating pumps are made of stainless rather than of carbon steel, a factor 10 in the estimated cost of each pump is introduced, somewhat arbitrarily but conservatively, thus resulting in a cost of $18,800 for each of the two boron injection recirculating pumps.

Since there are two boron injection recirculating pumps in the SIS of the reference PWR12-BE, the estimated cost of factory equipment included in the NSSS allocation is $37,600, in 2017 USD.

Table 16 – Boron Injection Recirculating Pumps and Drives and drive cost estimates (2017 USD).

EEDB Account	218A.23121	218B.22123	223.312
	Hot water circulation pump	Primary hot water circulation pump	Boron Injection Pump
Volumetric flow rate (gpm)	14	230	20
Head (feet of head)	85	30	100
C/H factor (gpm*feet)	1,190	6,900	2,000
Design pressure (psig)	150	150	150
Design temperature (F)	250	250	250
Material	Carbon Steel	Carbon Steel	Stainless Steel
Safety Class	NNS	NNS	3
Seismic Category	None	None	1
Design Code	-	-	ASME III, Class 3
Factory equipment cost (2017 USD)	$1,435	$5,023	Not Provided
Calculated equipment cost using C/H with exponent 0.52 (Phung 1987) and cost of hot water circ. pump	$1,435	$3,579	$1,880
Calculated equipment cost using C/H with exponent 0.52 (Phung 1987) and cost of primary hot water circ. pump	$2,014	$5,023	$2,638
Calculated using Figure 23 Phung Curve	$3,518	$8,178	$4,513
Calculated using Figure 23 EEDB Data Fit Curve	$1,707	$6,256	$2,506

3.11.2 SIS Tanks (NSSS allocation): Accounts 220A.2322: Accumulator Tank, 220A.2323: Boron Injection Tank and 220A.2324: Boron Injection Surge Tank

Account 220A.2322 to 220A.2324 include several tanks that are part of the SIS and that are supplied by the vendors as part of the NSSS system. Consequently, no cost information on these components is available in EEDB (1987), as for the other components that are supplied as part of the NSSS (Ganda 2018).

The specifications provided in EEDB (1987b), under account 223.33, are used to arrive at a cost estimate for these components, utilizing the approach developed in Section 3.6 of Ganda (2018).

From Account 223.33 in EEDB (1987b), it is known that the dry weight of the each of the tanks are, 80,000 lbs, 20,000 lbs and 325 lb for respectively the Accumulator Tank, the Boron Injection Tank and the Boron Injection Surge Tank, as shown in Table 17, together with other relevant technical data.

Table 17 – Technical parameter, and resulting costs, of the

Account	223.331	223.332	223.333
Description	Accumulator Tank	Boron Injection Tank	Boron Injection Surge Tank
Quantity	4	1	1
Material	Carbon Steel	Carbon Steel	Stainless Steel
Liner	Stainless Steel	Stainless Steel	None
Dry weight (lb)	80,000	20,000	325
Tank volume (ft^3)	1350	900	75
Design pressure (psig)	700	2735	atmospheric
Approximate Wall Thickness (cm)	7.36	9.22	0.78
Approximate Stainless Steel Fraction	13%	10%	100%

3.11.2.1 Account 220A.2322: Accumulator Tank

Each of the four accumulator tanks operates at a design pressure of 700 psig. This should result in a relatively thick-walled tank, with a stainless steel liner inside a carbon steel tank (Table 17), resulting in a total dry mass of 80,000 lbs. Since the cost of stainless and carbon steel components are substantially different (Ganda 2018), the fraction of each needs to be obtained to provide a robust estimate of the cost of these tanks. However, since the thicknesses of the liner and of the carbon steel walls of the tank are not provided in EEDB (1988b), the same liner thickness of the SS liner of the primary vessel of the reference PWR12-BE, of 0.95 cm (please see Section 3.6.4 of Ganda (2018)), was utilized as a first approximation. Additionally, the overall thickness of the tank needs to be estimated, since EEDB (1988b) does not provide this information. Therefore, in first approximation, a right circular cylindrical geometry was assumed, with the known volume of 1,350 ft^3, resulting in a total thickness of approximately 7.36 cm, which leads to an approximate fractional weight of 13% stainless steel and 87% carbon steel. Using the unit costs of \$75,000/ton for plate carbon steel and of \$310,000/ton for stainless steel (Ganda 2018), each tank is estimated to cost \$3.82 million. The combined cost of the four accumulator tanks is therefore calculated at \$15.3 million.

3.11.2.2 Account 220A.2323: Boron Injection Tank

The boron injection tank operates at a design pressure of 2,735 psig. The same approach as the accumulator tank, in Section 3.11.2.1 was used. The total weight is 20,000 lbs and the volume is 900 gallons (EEDB 1987b), or 3.4 m^3. The estimated thickness is 9.22 cm, which leads to an approximate fractional weight of 10% stainless steel and 90% carbon steel. Using the unit costs of \$75,000/ton for plate carbon steel and of \$310,000/ton for stainless steel (Ganda 2018), the boron injection tank is estimated to cost \$0.90 million.

3.11.2.3 Account 220A.2324: Boron Injection Surge Tank

The boron injection surge tank is a small stainless steel tank that operates at atmospheric pressure. The same costing approach as for the accumulator tank, described in Section 3.11.2.1 is used here: the total weight is 325 lbs and the volume is 75 gallons (EEDB 1987b), or 0.28 m^3. The estimated thickness is 0.78 cm. Using a unit costs of $310,000/ton for stainless steel (Ganda 2018), the boron injection tank surge is therefore estimated to cost $45,700, or 0.05 million.

3.11.3 Safety Injection System, Field Cost (Account 223.3)

This Section provides an approach to compute the SIS field costs (Account 223.3), including for other advanced nuclear energy systems. Table 12 provides the cost information of the SIS accounts that are part of the Field Cost (in account 223.3) in 1987 USD, from EEDB (1987). The factory equipment costs of the rotating machinery and of the tanks and pressure vessels are included in the NSSS-supplied components, and are discussed separately in Sections 3.11.1 and 3.11.2, respectively.

Table 18 – Residual heat removal system cost breakdown (1987 USD) from EEDB (1987).

	Account	Factory equipment	Site labor	Site material	Total
Rotating machinery	223.31	Included in NSSS	47,741	4,775	52,516
Tanks and Pressure Vessels	223.33	Included in NSSS	160,717	161,272	321,989
Piping	223.35	803,157	1,778,490	167,810	2,749,457
Valves	223.36	314,628			314,628
Piping - misc. items	223.37	54,240			54,240
Instrumentation + control	223.38	141,591	9,106	455	151,152
TOTAL		**1,313,616**	**1,996,054**	**334,312**	**3,643,982**

It is observed that the field cost of the SIS is dominated by the cost of piping, which comprises about 75% of the total costs directly included in Account 223.3. Obviously, this makes generalizations of the costs of this account difficult, since the cost of piping in general will depend on the configuration and arrangement of the system.

Therefore, two approaches are proposed here instead:

- Scaling of the cost of Account 223.3 in proportion to the mass of the primary coolant, based on the logic that the amount of injection capacity required will be, in first approximation, a function of the inventory of primary coolant. Since the inventory of primary coolant of the reference PWR12-BE is 0.57 million lb of light water, the scaling relationship will be as follows (in 2017 USD):

  $$C_{tanks} = \$10.46\, million \left(\frac{M_{Primary\ Coolant}}{0.57\, million\ lb}\right)$$

  This approach is applicable if the reactor is a pressurized water system, and the mass of primary coolant is known.

- Calculating the cost of account 223.3 as a fraction of the cost of the NSSS components associated with this account, as was done in Section 3.9.3 for the field cost of the RHR system. This approach is applicable more generally than that proposed in the previous bullet, even though it will generally yield less defensible results. This approach will also work if the reactor does not need a SIS, since it will yield a cost of $0 in that case.

  From Sections 3.11.1 and 3.11.2, where cost models for the SIS NSSS components were developed, it was estimated that their cost is $18.01 million, as shown in Table 13. Therefore, the SIS field cost of $10.46 million is 58% of the combined cost of the related NSSS supplied equipment. It is recommended to use this fraction as a first approximation approach to estimate the field cost of the SIS system, absent a detailed design that allows a bottom-up costing of the necessary equipment, including piping.

Table 19 – SIS system cost breakdown, including NSSS-supplied components and field costs (2017 USD)

Account #	Parts of the SIS system	Cost (2017 USD)
220A.2321 and 220A.2325	Safety Injection, and Boron Injection Recirculating Pumps and Drives (NSSS Cost)	$1.76 million
220A.2322	Accumulator tanks (NSSS Cost)	$15.30 million
220A.2323	Boron Injection Tank (NSSS Cost)	$0.9 million
220A.2324	Boron Injection Surge Tank (NSSS Cost)	$0.05 million
	SIS Pumps and Drives + Tanks (NSSS Cost)	$18.01 million
223.3	SIS System, Field Cost	$10.46 million (58% of total costs)

3.12 NSSS-related parts of the Coolant Treatment and Recycle System (Accounts 220A.2611, 220A.2612, 220A.2613, 220A.2614)

The field costs of the Coolant Treatment and Recycle System (Account 226.4) have been discussed in Section 3.18 of Ganda (2018), both for the reference PWR and for SFRs. Therefore, the focus of this section will be exclusively on the NSSS components that are part of the Coolant treatment and recycle systems, but are not included in the field cost (Account 226.4). Those include:

- Rotating Machinery Pumps and Motors (NSSS allocation) – Account 220A.2611;
- Heat Transfer Equipment (NSSS allocation) – Account 220A.2612;
- Purification and Filtration Equipment (NSSS allocation) – Account 220A.2614;
- Tanks and Pressure Vessels (NSSS allocation) – Account 220A.2613;

It is noted that the *coolant treatment and recycle system* is composed of two subsystems (as shown in Table 20):

- The *chemical and volume control system*, which is a complex system that includes the NSSS-provided equipment; and
- The *boron recycle system*, the entire cost of which is included in Account 226.4 as field cost.

3.12.1 Rotating Machinery – NSSS Allocation (Account 220A.2611)

The coolant treatment and recycle system, under Account 226.411, includes several pumps that are supplied as part of the NSSS. The two "charging" pumps of accounts 226.4111 and 226.4112 have a relatively small flow rate, but extremely large heads, of 5800 ft, resulting in a large C/H.

Additionally, because of the large design pressure (2800 psig), their cost is likely estimated more realistically starting from relatively expensive pumps in the reference set, such as the one of account 226.7111, as shown in Table 21, using Phung (1987) correlation, as described in Chapter 5:

$$C_{pump} = C_{pump,ref}\left(\frac{C/H_{pump}}{C/H_{pump,ref}}\right)^{0.52}$$

Table 20 – Coolant treatment and recycle system cost breakdown (1987 USD) from EEDB (1987).

	Account	**Factory equipment**	**Site labor**	**Site material**	**Total**
Chemical & volume control	*226.41*	*3,321,027*	*4,986,568*	*573,874*	*8,881,469*
Rotating machinery	226.411	**Included in NSSS**	54,031	5,403	59,434
Heat transfer equipment	226.412	**Included in NSSS**	9,754	977	10,731
Tanks & press vessels	226.413	**Included in NSSS + $556**	125,746	137,514	263,816
Purification & filtration equipment	226.414	**Included in NSSS**	74,635	7,464	82,099
Piping	226.415	2,225,867	4,688,361	420,195	7,334,423
Chem. & vol. control valves	226.416	734,132	0	0	734,132
Piping - miscellaneous items	226.417	167,440	8,708	871	177,019
Instrumentation + control	226.418	187,938	21,681	1,084	210,703
Foundations/skids	226.419	5,094	3,652	366	9,112
Boron recycle system	*226.42*	*3,502,593*	*1,548,698*	*375,721*	*5,427,012*
Rotating machinery	226.421	20,852	10,056	1,006	31,914
Tanks & press vessels	226.423	273,089	103,051	170,851	546,991
Purification & filtration equipment	226.424	1,525,661	355,813	35,582	1,917,056
Piping	226.425	1,051,699	1,036,415	166,114	2,254,228
Bor. rec. sys. valves	226.426	244,633	0	0	244,633
Piping - miscellaneous items	226.427	203,400	0	0	203,400
Instrumentation + control	226.428	183,259	43,363	2,168	228,790
TOTAL	**226.4**	**6,823,620**	**6,535,266**	**949,595**	**14,308,481**

The complete set of pumps, including the cost and technical data of the reference pumps, is shown in Table 21 and Table 22.

Table 21 – Parameters and cost estimates (in 2017 USD) of the rotating machinery (NSSS allocation) of account 226.411 (subaccounts 226.4111, 226.4112 and 226.4113).

(EEDB 1987b) Account #	**226.4111**	**226.4112**	**226.4113**	**226.4113**
Description	Centrifugal charging	Positive displacement charging	Boric acid transfer	Boric acid transfer
Number of Pumps	2	1	1	1
Type	Centrifugal	Positive displacement	Centrifugal/ Canned	Centrifugal/ Canned
Orientation	Horizontal	Horizontal	Horizontal	Horizontal
Volumetric flow rate (gpm)	150	98	35	100
Head (feet of head)	5800	5800	250	200
Design pressure (psig)	2800	2800	150	150
Design temperature (F)	300	300	250	250
Material	Stainless Steel	N/A	Stainless Steel	Stainless Steel
Safety Class	2	N/A	3	3
Seismic Category	Yes	N/A	I	I
Design Code	ASME III, Class 2	N/A	ASME III, Class 3	ASME III, Class 3
C/H factor (gpm*feet)	870,000	568,400	8,750	20,000
Reference pump Account #	226.7111	226.7111	226.4211	226.4211
C/H of the Reference Pump	2,210,000	2,210,000	9,600	25,000
Cost of the reference pump	1,259,119	1,259,119	10,461	10,461
Estimated Pump Cost – each pump	775,413	621,445	9,969	9,315
Combined cost of all pumps in the account (2017 USD)	**1,550,825**	**621,445**	**9,969**	**9,315**

It is observed that there are a total of 9 pumps, with 3 large and expensive ones (the charging pumps) and 6 small ones. The total calculated cost of all the pumps in this account is $2.22 million, largely dominated by the high head and pressure charging pumps of accounts 226.4111 and 226.4112.

Figure 1 shows the estimated costs of the rotating machinery analyzed in this Section, as compared to other pumps in the reference set, as described in Appendix A.

Table 22 – Coolant treatment and recycle system pump cost estimate.

EEDB Account	26.4114	26.4115	26.4115
Description	Chiller pump	Boron injection	Boron injection
Number of Pumps	2	1	1
Type	Centrifugal	Centrifugal / Canned	Centrifugal / Canned
Orientation	Horizontal	Horizontal	Horizontal
Volumetric flow rate (gpm)	400	35	100
Head (feet of head)	150	250	200
Design pressure (psig)	150	150	150
Design temperature (F)	200	250	250
Material	Carbon Steel	Stainless Steel	Stainless Steel
Safety Class	NNS	N/A	N/A
Seismic Category	None	N/A	N/A
Design Code	ASME VIII	N/A	N/A
C/H factor (gpm*feet)	60,000	8,750	20,000
Reference pump Account #	226.311	226.4211	226.4211
C/H of the Reference Pump	54,000	9,600	25,000
Cost of the reference pump (2017 USD)	5,855	10,461	10,461
Estimated Pump Cost (2017 USD) – each pump	6,185	9,969	9,315
Combined cost of all pumps in the account (2017 USD)	**12,369**	**9,969**	**9,315**

3.12.2 Heat Transfer Equipment – NSSS Allocation (Account 220A.2612)

The NSSS allocation for the coolant treatment and recycle system includes 6 different heat exchangers and 2 chillers, as shown in Table 23 and Table 24. The cost of the heat transfer equipment is estimated here using the method in Section 3.8 of Ganda (2018), which is based on the mass of the materials within the heat exchangers, and on the assumption (derived and discussed in Section 3.9.2 of this report), that the weight of the shell is about 40% and the tubes 60% of the total mass, for shell and tube heat exchangers.

From Ganda (2018), the recommended costs of plate carbon steel and of stainless steel are $75,000/ton and $310,000/ton, respectively.

Table 23 – Coolant treatment and recycle system heat transfer equipment technical parameters and cost estimates (2017 USD).

Account	**226.4121**	**226.4122**	**226.4123**	**226.4124**
	Moderating HX	**Main Coolant Pump Seal H2O**	**Chiller**	**Regenerative HX**
Quantity	1	1	1	1
Shell Material	Stainless Steel	Carbon Steel	N/A: Assumed Carbon Steel	Stainless Steel
Tube Material	Stainless Steel	Stainless Steel		Stainless Steel
Dry weight (lb)	2600	2700	9590	3170
Assumed weight of shell (lb)	1040	1080	3836	1268
Assumed weight of tubes (lb)	1560	1620	5754	1902
Unit cost shell ($/ton)	310,000	75,000	75,000	310,000
Unit cost tubes ($/ton)	310,000	310,000	75,000	310,000
Total cost of item (2017 USD)	**365,595**	**264,535**	**326,246**	**445,745**

Table 23 and Table 24 provide the cost estimates for the coolant treatment and recycle system heat transfer equipment included with the NSSS-supplied equipment, of $2.45 million in (2017 USD).

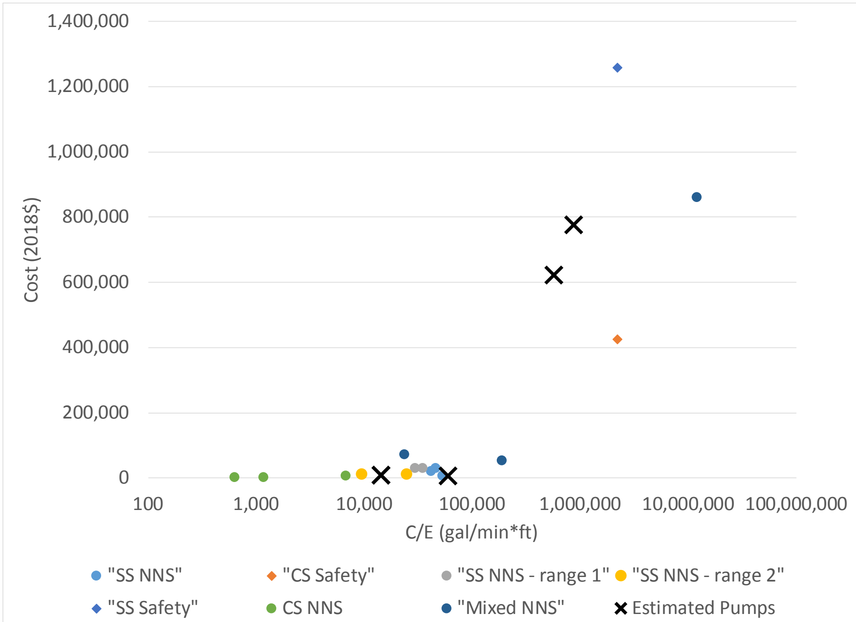

Figure 1 – Coolant treatment and recycle system pump cost estimates compared with other pumps in the EEDB.

Table 24 – Coolant treatment and recycle system heat transfer equipment technical parameters and cost estimates (2017 USD).

Account	226.4125	226.4126	226.4127	226.4128
	Letdown (Non-Regenerative) HX	Excess Letdown HX	Letdown Chiller HX	Letdown Reheat HX
Quantity	1	1	1	1
Shell Material	Carbon Steel	Carbon Steel	Carbon Steel	Stainless Steel
Tube Material	Stainless Steel	Stainless Steel	Stainless Steel	Stainless Steel
Dry weight (lb)	5000	1800	3300	420
Assumed weight of shell (lb)	2000	720	1320	168
Assumed weight of tubes (lb)	3000	1080	1980	252
Unit cost shell ($/ton)	**75,000**	**75,000**	**75,000**	**310,000**
Unit cost tubes ($/ton)	**310,000**	**310,000**	**310,000**	**310,000**
Total cost of item (2017 USD)	**489,879**	**176,357**	**323,320**	**59,058**

3.12.3 Tanks and Pressure Vessels – NSSS Allocation (Account 220A.2613)

The NSSS allocation for the coolant treatment and recycle system includes 4 tanks and pressure vessels, as shown in Table 25. The cost of this equipment is estimated here using the method in Section 3.8 of Ganda (2018) which is based on the mass of the materials within the tanks and pressure vessels.

Table 25 provides the cost estimates for the coolant treatment and recycle system tanks and pressure vessels included with the NSSS-supplied equipment, of $1.14 million in (2017 USD).

Table 25 – Coolant treatment and recycle system tanks and pressure vessels technical parameters and cost estimates (2017 USD).

Account	226.4133	226.4134	226.4135	226.4131
Description	Chiller surge tank	Boric acid batch tank	Chemical mixing tank	Volume control tank
Quantity	1	1	1	1
Material	Stainless Steel	Carbon Steel	Stainless Steel	Stainless Steel
Liner	None	None	None	None
Dry weight (lb)	4,750	1,300	3,000	80
Unit cost ($/ton)	310,000	75,000	310,000	310,000
Estimated Cost (2017 USD)	667,914	44,225	421,841	11,249

3.12.4 Purification and Filtration Equipment – NSSS Allocation (Account 220A.2614)

The NSSS allocation for the coolant treatment and recycle system includes 8 demineralizers and 2 filters, as shown in Table 26. The demineralizers are essentially tanks filled with resins. The cost of the resins is expected to be substantially smaller than those of the tanks themselves, and in general it is allocated as an O&M cost rather than as a capital cost. Therefore, the cost of the demineralizers is estimated here using the method in Section 3.8 of Ganda (2018) which is based on the mass of the materials within the tanks of the demineralizers.

The filter costs, as a function of the flow rate, is shown in Figure 2 for a number of filters from accounts 252, 224, and 226.4, for which the cost was provided in EEDB (1987). The flow rate for these filters is derived from information in EEDB (1987b). The plot does not show a cost dependence on the flow rate, indicating therefore that other parameters, beside the flow rate, contribute to the filter cost. However, it is also noted that all the filters have relatively modest costs, in the range of $2,000 to $16,000, in 1987 USD, or about $6,000 to $45,000 in 2017 USD.

Table 26 provides the cost estimates for the coolant treatment and recycle system demineralizers and 2 filters included with the NSSS-supplied equipment, of $2.45 million in (2017 USD).

Table 26 – Coolant treatment and recycle system purification equipment technical parameters and cost estimates (2017 USD).

Account	226.4141	226.4142	226.4143	226.4144	226.4145
Description	Mixed bed demineralizer	Cation demineralizer	Process filters	Seal water injection filter	Thermal regen. demineralizer
Quantity	2	1	1	1	5
Material	Stainless Steel	Stainless Steel	N/A	N/A	Stainless Steel
Liner	None	None	N/A	N/A	None
Dry weight (lb)	1,565	1,565	N/A	N/A	2,500
Unit cost ($/ton)	310,000	310,000	N/A	N/A	310,000
Estimated Unit Cost (2017 USD)	220,060	220,060	17,000	17,000	351,534
Total Cost (2017 USD)	440,120	220,060	17,000	17,000	1,757,669

The cost of the filters is assumed here to be about in the average of other filters included in Figure 2, of about $17,000 per filter in 2017 USD.

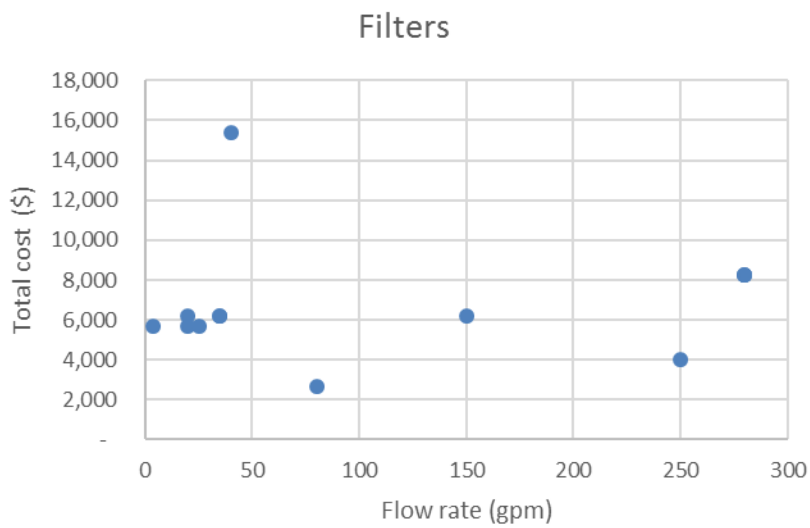

Figure 2 – Total cost of filters as a function of the flow rate (1987 USD)

3.13 Ultimate Heat Sink Structure (Account 218T)

The ultimate heat sink structure building is described as *"a Seismic Category I reinforced concrete structure located southwest of the main plant structures and supported on a reinforced concrete foundation which has a thickness of four feet. The base mat is founded on rock 32 feet below grade, except for the east bay which is founded at grade. The building is 50 feet wide, 176 feet long and 77.5 feet high. The building volume is approximately 650,000 cubic feet. The exterior and interior walls, floor slabs and roof slab are reinforced concrete. The exterior walls are a minimum of two feet thick."* (EEDB 1988).

The approach used for the calculation of the cost of this structure for advanced designs is the same as that described in Section 3.5 for the administration and services building.

With the reported dimensions, including the assumption of 2 ft thick exterior and interior walls and roof, 4 ft thick foundations, and an internal void fraction of 98%, the building cost would be $24.24 million if it was built as a containment building. However, the actual cost of this structure according to EEDB (1987) is instead of $13.19 million in 2017 USD.

Therefore, the calculated adjustment factor is 0.544. This adjustment factor can be utilized to estimate the cost of this structure for advanced designs, starting from the value calculated using the containment building model from Ganda (2018) for the specific dimensions of this building.

3.14 Fuel Handling Tools (NSSS) (Account 220A.251)

Two fuel handling tools (Account 220A.251) must be present in each nuclear plant: one in the containment building, in order to shuffle the assemblies inside the reactor vessel, and to transfer the assemblies between the reactor vessel and the refueling canal, and one in the fuel storage building, in order to move both the new and used fuel assemblies between storage racks, and between the refueling canal and the storage pool.

The fuel handling tools are complex but compact components. For example, from (WEC 2015) the tools appear to be about 20x20x40 cm in dimensions. If, for conservativeness, each tool was solid steel with the above-mentioned dimensions, it would weigh about 100-150 kg. With a standard cost of stainless steel components of $310,000/ton, the cost of the tool would therefore be between $31,000 and $46,500. Even if adjusted by a factor 4, to correct for the fact that the cost of this equipment is highly uncertain, the total cost would be between $124,000 and $186,000.

Therefore, it is proposed here to utilize a cost for the fuel handling tool of $200,000, and $400,000 for both tools combined, with the caution that these numbers are highly uncertain. It is also recommended to use these costs also for other advanced reactor designs, since no better estimate for this account is available at this time. The recommended costs are likely overestimating the costs of the fuel handling tools for standard PWR, but costs may be higher for advanced designs, such as Na-cooled reactors, because of the complexity associated with the different cooling fluids. Actual quotes from vendors will be required to refine this estimate in the future.

3.15 Fuel Storage Racks (NSSS) (Account 220A.254)

From EEDB (1988b), it is known that 280 "seismic category I" and "safety class 3" storage racks will be provided as part of the NSSS system for the reference PWR. Combustion Engineering (1978) includes the cost of storage racks for the LMFBR, of $374,000 in 1978 USD, which is equivalent to $2.51 million in 2017 USD, according to the conversion factor of Section 2.2. This cost, which was developed specifically for Na-cooled reactors, is likely too high for PWRs systems: *"High LMFBR refueling costs reflect the penalties due to the reactive sodium coolant. A sealed environment complete with a forced convection cooling system is required for transport of spent subassemblies, and fuel handling operations must be performed remotely. Refueling at high temperatures places restrictions on machine fabrication due to differential thermal expansion.*" (Combustion Engineering 1978).

IAEA (1994) provides the cost of installing new fuel storage racks for PWRs, with estimates of the "installation cost" of new racks provided by the German government, of 0.5-0.7 USD/kgU. Considering that a typical PWR assembly contains about 500 kgU, each rack would cost between $250 and $350, in 1994 USD. Using a factor 1.66 to convert 1994 USD to 2017 USD (https://data.bls.gov/cgi-bin/cpicalc.pl), the cost of each rack would be between $415 and $580, in 2017 USD. This would amount to a total cost of $0.12 to $0.16 million for the 280 storage racks, which is more than an order of magnitude lower than the value obtained from Combustion Engineering (1978). Moreover, IAEA (1994) only references to this cost as the cost of "installation" of the racks, and it is therefore not clear this includes the purchase cost of the racks. For this reason, this data-point is considered of lower quality than that of Combustion Engineering (1978).

In conclusion, for conservativeness, it is recommended to use the high value applicable to LMFBR (of $2.51 million in 2017 USD) for both conventional and advanced designs, unless actual quotes from vendors can be obtained for these components.

3.16 Instrumentation and Control (NSSS) (Account 220A.27)

The "instrumentation and control" system for the reference PWR12-BE is divided in 3 parts:

- The NSSS control board, which is discussed under Account 227 and was addressed in Ganda (2018);
- The turbine plant control board, which is discussed in Section 3.4 of this report under Account 236;
- The main generator and auxiliary electric power system control board, which is treated under Account 243 and comprises only 0.23% of the total direct cost of the reference PWR12-BE, according to EEDB (1987). Because of the small fractional cost of this account, it has not been addressed yet among the ACCERT cost models.

From a detailed analysis of the accounts involved, it appears that none of the control equipment or instrumentation is supplied as part of the NSSS package, from EEDB (1987). Consequently, account

220A.27 is quantified as zero (i.e. its costs are accounted elsewhere), and the sum of the values of accounts 227, 236 and 243, dominated by account 227, is considered complete for the purpose of estimating the cost of the instrumentation and control.

3.17 Standard Valve Package (NSSS) (Account 220A.28)

No information was found on the type and quantities of valves typically included in the "standard valve package" supplied as part of the NSSS system. Further, from an analysis of the various accounts associated with the NSSS installation in EEDB (1987), no mentions of valves supplied as part of the NSSS was found. All the valves found in these systems appear to be purchased either as individual components (for large valves) or as "site material" (for small valves).

Consequently, according to the accounting approach adopted in EEDB (1987), account 220A.28 is quantified as zero, as all the various valves appear to be included as part of the "field costs" of the relevant accounts.

3.18 Maintenance Equipment (NSSS) (Account 220A.262)

Multiple items under the Maintenance Equipment account are supplied as part of the NSSS:

- Remotely controlled tools;
- Radioactive maintenance facilities;
- Portable shielding;
- Tools and equipment for reactor vessel;
- Core-tools and fixtures;
- Decontamination equipment;
- Laundry equipment;
- Hot change area;
- Sampling equipment.

Considering the long list and heterogeneity of the items in this account, it is clear that a credible and defensible estimate of the cost of this account can only be obtained from vendor quotes that are specific for each reactor technology. Additionally, each contract may differ in the amount and types of items provided under each of the items in the above list, even for the same reactor technology.

Also, it was not possible to obtain a value for the costs in this account from (Combustion Engineering 1978), since the "maintenance equipment" was intentionally excluded from the NSSS estimate in (Combustion Engineering 1978).

Consequently, it was not possible to develop a meaningful cost model for this account at this stage, nor an approach for determining this cost for alternative reactor design. Detailed estimates of the construction costs of advanced reactor designs will have to rely on vendors' quotes for this account. In general, the actual cost of this account is expected to be minor as compared to that of other major NSSS components, and the absence of an estimated value for this account is not expected to impact the outcome of cost analyses of advanced systems in a significant way.

3.19 Pressurizer Relief Tank (Account 220A.225)

The pressurizer relief tank is delivered as part of NSSS system, under account 220A.225. The technical details of the pressurizer relief tank are found under account 222.1432 of EEDB (1987b), and the cost of the installation of the tank is found under account 222.1432 in EEDB (1987).

The pressurizer relief tank is a 1800 ft^3 non-nuclear safety (NNS) tank, made of stainless steel 304, operating at low pressure (100 psig, or 6.8 atm) (EEDB 1988b). The thickness of the tank is not provided in EEDB (1988b). However, considering the low design pressure, a thickness of 1 cm is assumed as a first approximation.

If the tank is cylindrical, with height equal to the diameter in order to minimize the tank surface for a given volume, the radius would be approximatively 2 meters and the height approximatively 4 meters. This would result in a surface of 76.1 m^2, which with a SS weight of 7.85 g/cm^3 would result in a weight of 5.97 tons. With a stainless steel unit cost of 310,000 \$/ton (Ganda 2018), the total cost of the tank is estimated at \$1.85 million.

3.20 Summary of the Total Cost of the NSSS Components Analyzed in This Work for the PWR12-BE

The work in this report completes the development of cost models for the NSSS components initiated in FY18, for which cost information was not provided directly in EEDB (1987). Detailed cost models, for among other things, the eight largest and most expensive parts of the NSSS, were developed in Ganda (2018). In the present report, cost models for 17 additional parts of the NSSS, all of relatively minor importance, were developed[b].

Concluding this analysis, it is very important to check the reasonableness of the cost models developed in this work, as compared to the total aggregated cost of the NSSS-supplied system, known from EEDB (1987). For this reason, in Table 27, the results of the cost models for the reference PWR12-BE were summed and compared to the total NSSS cost as known from EEDB (1987). It is observed that the total cost of the entire set of the NSSS components was calculated at \$505.52 million in 2017 USD: this is in excellent agreement with the known aggregated cost of the total set of NSSS-supplied components from EEDB (1987), of \$514.71 million in 2017 USD.

In fact, this agreement exceeds the most optimistic expectations about this analysis before this work was initiated. Each of the cost models for the NSSS components was developed independently, regardless of the influence of each particular model on the total NSSS aggregated cost.

This agreement should substantiate confidence in the cost models developed for the NSSS systems, at least at an aggregated level.

Additionally, this work offers – for the first time in the public domain – a complete set of models to evaluate the NSSS cost of advanced reactors systems.

[b] It was not possible to develop cost models for the Maintenance Equipment supplied with the NSSS, as explained in Section 3.18, because of the long list and heterogeneity of the items in this account, and because no reference was found on the costs of this account.

Table 27 Total cost of the NSSS components developed in Ganda (2018), in black, and in this work, in blue, for the reference PWR12-BE, as compared to the known aggregated cost of the entire set of NSSS-supplied components from EEDB (1987).

Account #	Account Description (Complete List of NSSS-Supplied Components)	Cost (Millions of 2017 USD)	Reference
220A.211	Vessel	70.00	(Ganda 2018)
220A.221	Pumps	125.24	(Ganda 2018)
220A.223	Steam Generators	149.80	(Ganda 2018)
220A.212	Internals (Upper And Lower)	63.55	(Ganda 2018)
220A.2131	Control Rods	3.10	(Ganda 2018)
220A.2132	Control Rod Drives	34.90	(Ganda 2018)
220A.224	Pressurizer	8.30	(Ganda 2018)
220A.222	Piping	11.40	(Ganda 2018)
220A.2311	Residual Heat Removal Pumps and Drives	1.94	Section 3.9.1
220A.2312	Residual Heat Removal Heat Exchanger	6.26	Section 3.9.2
220A.2321	Safety Injection Pumps and Drives	1.72	Section 3.11.1.1
220A.251	Fuel Handling Tools	0.40	Section 3.14
220A.254	Fuel Storage Racks	2.51	Section 3.15
220A.27	Instrumentation and Control	0.00	Section 3.16
220A.28	Standard NSSS Valve Package	0.00	Section 3.17
220A.225	Pressurizer Relief Tank	1.85	Section 3.19
220A.2322	Accumulator Tank	15.30	Section 3.11.2.1
220A.2323	Boron Injection Tank	0.90	Section 3.11.2.2
220A.2324	Boron Injection Surge Tank	0.05	Section 3.11.2.3
220A.2325	Boron Injection Recirculating Pump and Drive	0.04	Section 3.11.1.2
220A.2611	Rotating Machinery (Pumps and Motors)	2.22	Section 3.12.1
220A.2612	Heat Transfer Equipment	2.45	Section 3.12.2
220A.2614	Purification and Filtration Equipment	2.45	Section 3.12.4
220A.2613	Tanks and Pressure Vessels	1.14	Section 0
220A.262	Maintenance Equipment	Unknown	Section 3.18
	TOTAL CALCULATED COST (Except Maintenance Equipment)	**505.52**	**(Calculated)**
	TOTAL REFERENCE COST (Including Maintenance Equipment)	**514.71**	**(EEDB 1987)**

4. UNCERTAINTY QUANTIFICATION OF THE ACCERT COSTS AND EXAMPLE APPICATION TO THE CONTAINMENT BUILDING

4.1 Introduction

This Section introduces new work on the quantification of uncertainties of the cost estimates produced with the ACCERT algorithm.

The ACCERT algorithm produces deterministic estimates, which can be considered the "expected values" of cost estimates that are, in reality, uncertain. The shape and magnitude of the uncertainties were, however, unknown until the work performed here allowed their quantification, *for well-executed projects*, in a defensible and robust way, as explained below.

The methodology for uncertainty quantification developed in this work has been applied in this Chapter to the reactor containment cost model, described in Section 3.2 of Ganda (2018), as an example. The uncertainty distribution quantified for the reactor containment can then be extended to the cost of the entire reactor system, as a simplifying assumption, until similar uncertainty models will be developed specifically for other components.

The uncertainty quantification methodology developed here is now a part of the ACCERT methodology.

4.2 Uncertainty in Nuclear Construction Cost Estimates

In the literature on investment under uncertainty, there are two categories used to characterize project cost uncertainties*: input cost uncertainty* and *technological uncertainty* (Pindyck 1993, Pindyck 2001).

- **Input cost uncertainty** is defined as *"external to what the firm does. It arises when the prices of labor, land, and materials needed to build a project fluctuate unpredictably."* (Pindyck 1993). This uncertainty is un-avoidable even for well-executed projects, since it is outside of the control of the constructors. It rather depends on factors affecting the entire economy.
- **Technological uncertainty** is defined as *"relating to the physical difficulty of completing a project. Assuming prices of construction inputs are known, how much time, effort, and materials will ultimately be required?"* (Pindyck 1993). The technological uncertainty can be considered zero for well-executed projects, by definition. It can also be called "avoidable" uncertainty in the context of this work. It is noted that other disruptive forces such as regulatory interventions, supply chain disruptions etc… are also external to the firm constructing the project and can cause disastrous cost escalation. However, those are still classified as "avoidable" in the context of this work, since it is assumed that with careful planning and advanced procurement (in the case of supply chain disruptions), and with a predictable and stable regulatory regime (in the case of regulatory interventions), for example, those disruptions could be largely avoided. It is also clear, however, that avoiding those issues, in some cases, requires an effort that involves more entities than just the firms constructing the project, especially in the example of regulatory interventions.

Because the focus of the ACCERT tool is on quantifying the construction costs of well-executed projects, this document outlines an approach to quantify *input cost uncertainty* rather than technological uncertainty. Input cost uncertainty captures uncertainty from those external, economic factors, which impact the final cost of well-executed projects, and is an "un-avoidable" uncertainty. Independently of the amount of planning, correct execution, excellent project management and other best practices, the *input cost uncertainty* will be present in every nuclear construction project.

Subsection 4.3 described the data used to generate the parameters that drive the input cost uncertainty, including the de-trending of seasonal and escalation factors. The outcome of this analysis is a set of probability distributions for labor, steel, concrete, welding and other materials, based on actual historical data and including the relevant parameters and equations, and a correlation matrix quantifying the interdependencies of those uncertainties.

Afterwards, the utilization of this information and methodology is demonstrated, arriving at a quantification of the *input cost uncertainty* for the containment building of the reference PWR, as an example. This work shows for the first time what would be the "intrinsic" uncertainty, based on the historical uncertainty in input costs, for a fully well-executed construction project (the containment building is utilized as an example here), in a defensible and robust way. The defensibility and robustness of the analysis is based both on the quality of the input data, and on the robustness of the methodological assessment. The Matlab code used to generate the uncertainty distributions for the containment building, including the correlated sampling, is attached in Appendix D for full transparency.

4.3 Approaches, Data and Methodology

Modeling input cost uncertainty takes as a beginning point a deterministic cost estimate around which uncertainty can be propagated. This Section present the methodological approach to arrive at *input cost uncertainty distributions*, in a robust and defensible manner, around deterministic cost estimates produced with the ACCERT algorithm.

As an example, Table 12 through Table 15 of Section 3.2 of Ganda (2018) present a series of cost estimates for different structures of the reactor containment. In each table the costs of raw materials are separated by quantity, labor cost, and material cost. Let C_{jk} stand for a deterministic cost estimate from any of those tables, where j indexes construction activities (i.e. the rows of the tables, such as installation of formwork, of reinforcement steel, etc.) and k indexes cost categories where l stands for labor cost m for material cost. Labor inputs, such as number of man-hours, and material inputs, such as cement, rebar, and welding supplies are used for the various construction activities, so that costs can be differentiated by labor inputs and material inputs. For modeling purposes, it is assumed that labor cost (l) uncertainty is not differentiated across activities, but materials cost are subdivided in the following categories: concrete (c), steel (s), welding (w), and other materials (m). This convention enables the cost analyst to model uncertainty for a given activity by labor cost uncertainty, and by the cost uncertainty of the primary input material.

Converting the deterministic C_{jk}, taken from the Tables in Section 3.2 of Ganda (2018), to a stochastic variable $\tilde{C}_{jk}$ requires the multiplication of a random variable such that:

$$\tilde{C}_{jk} = \lambda_{jk} C_{jk} ,$$

Where λ_{jk}, a random variable, reflects input cost uncertainty. In this arrangement $\lambda_{jk}>0$ holds, which means that λ_{jk} is a factor that, when multiplied, converts the deterministic cost estimate to one which is stochastic.

In other words, the uncertainty in λ_{jk} is imposed on the deterministic cost estimate from Ganda (2018). As an example, let us consider the labor cost for formwork given in Table 12 of Ganda (2018), listed at \$154,906, while material cost is listed at \$22,000. Imposing uncertainty on these two cost estimates means that $\tilde{C}_l = \lambda_l * \$154,906$ for labor cost and $\tilde{C}_{mc} = \lambda_{mc} * \$22,000$ for material cost. For materials cost, two subscripts denote materials and the primary input material, in the example here, concrete.

4.3.1 Input Cost Uncertainty Data Sets

As discussed in Section 4.2, input cost uncertainty captures the fact that construction costs for a nuclear facility are, in part, uncertain due to economic factors. In order to develop an approach to capture and model input cost uncertainty, data sets are needed that contain variations which are reasonable approximations of input cost uncertainty that would likely be observed in estimates of labor and materials in a nuclear construction project. That is, input cost uncertainty should account for economic uncertainty that impacts the cost of labor and materials, respectively. There are a few data sets which could serve as candidates.

Ideal data sets for this analysis would be: (1) one which tracks labor costs paid to workers in nuclear construction over time and (2), another which records the cost of inputs used in nuclear construction, also over time. Because this Section focuses on cost uncertainty in reactor containment as an example, if such data sets were specific to construction of reactor containments, that would be even better. Such data sets would allow the analyst to find the economic uncertainties in labor and material costs, specific to nuclear construction and reactor containments, by removing the underlying trends so that the intrinsic variation in the data might be captured. Based on detailed searches for such data sets, performed by this Section's authors, the ideal data sets do not appear to exist. Instead, what were found are several different indices and data series published by statistical agencies of the U.S. government, which are generally not nuclear-specific. The issue, then, is selecting appropriate data to model input cost uncertainty for the reactor containment. Two important criteria in selecting such data are (1) that the data series be of sufficient size so that variation can be measured, and (2) that the data series be as close to construction in the nuclear industry as possible.

The next sub-sections describe potential data sources and the selected data source used to model input cost uncertainty for labor and materials, respectively.

4.3.1.1 Labor (L) Data Sets

Several data sources could be utilized to approximate uncertainty for labor costs. The Bureau of Labor Statistics (BLS) publishes several data sets, based on surveys and statistical analyses, from which economic uncertainty could be extracted and utilized to represent labor input cost uncertainty (BLS 2019). For example, the often-used Consumer Price Index (CPI) reflects changes in prices across the economy based on a "basket of goods" whose prices are tracked across time. A limitation of the CPI is that the basket of goods does not reflect how changes in demand for goods impacts changing prices levels. To account for this, the Chained-CPI updates the basket consistently with changing patterns of consumer demand for goods and services. While a long time series exists for the CPI, from which variation could be extracted, the focus of the CPI is on economy-wide price changes, not on price changes specific to nuclear construction. Alternatively, the Current Employment Statistics (CES) can be deconstructed, using the NAICS (North American Industry Classification System) code relating the nuclear construction (NAICS 237130: Power and Communication Line Related Structures Construction, (NAICS 2019)), to find data on how hours worked and levels of employment have changed across time. The fact the data are on hours worked and not on costs, disqualify the CES as a good candidate data source. This is because modeling input cost uncertainty, for the analysis at hand, requires variation in prices to approximate uncertainty, not variation in hours worked. Utilizing a data series on hours worked might be utilized, with various manipulations, if a better candidate series were not available. However, the BLS publishes other data series, which allow the analyst to capture price variation directly.

Two other BLS data sets that could be utilized for modeling labor input uncertainty are: the *Employment Cost Index* (BLS 2019) and the *Employer Cost for Employer Compensation* (BLS 2019). The latter data records average weekly wages, and using the NAICS code for nuclear construction listed above, can be down selected to construction workers in the industry. These data, collected quarterly beginning in 2001, are in current dollars, which means that before utilizing them, the series must be converted to constant dollars. This data series satisfies the two important criteria mentioned above: (1) the series is sufficiently large to capture variation and (2) it reflects labor cost changes in the nuclear construction industry. Because the *Employer Cost for Employer Compensation* data records can be down-selected to reflect nuclear construction, it is a better measure than the *Employment Cost Index*. While the latter reflects construction, it does not reflect nuclear construction specifically.

The raw data from the *Employer Cost for Employer Compensation* data are shown graphically in Figure 3, and are listed in Table 36 of Appendix B.

4.3.1.2 Materials data set: Materials-Material (mm)

The disaggregated category of materials-material (*mm*) is included for the following reason. If, for a construction activity listed in the containment model of Ganda (2018), the primary material input is not in any of the other materials categories for which specific indexes were identified, the uncertainty for materials input can be modeled using this category. Like other data sources, selecting the appropriate source of data must follow the two criteria noted above: (1) data series of sufficient size to capture variation and (2) data series relevant to nuclear construction.

Published by the BLS, the Producer Price Index (PPI) can be down-selected to various industries and categories. Selecting for nuclear, returns a series that may be applicable to capturing uncertainty on costs if the focus of the analysis were on nuclear instrumentation and control.[c] Additionally, several series explicitly state that nuclear applications are excluded. Since the focus of this example is on the reactor construction, this data is not applicable, and instead alternative but relevant data series within the PPI should be selected. An option is to select the PPI for commodities used in the construction of new, industrial buildings: the *Producer Price Index by Commodity for New Construction: New Industrial Building Construction*. Figure 4 and Table 37 of Appendix B includes the raw data from this series. These data are recorded quarterly and begin in 2001. Because a nuclear power plant, and the reactor containment therein, is an example of an industrial construction, the variation in the commodities index approximates reasonably well the uncertainty in material input costs.

4.3.1.3 Materials data set: Concrete (mc)

Concrete is an important cost for nuclear construction: therefore, it is modeled as an input with cost uncertainty. In order to find a suitable index that allows the quantification of the input cost uncertainties related to concrete, the index titled *Industrial Production Durable Goods: Cement* (FRED 2019) from the St. Louis Federal Reserve was utilized. It corresponds to NAICS code 32731, for *cement manufacturing*. Although the index does not specify concrete used in nuclear construction, it does index cement prices, on a monthly basis, in the U.S. dating back to 1972. Consequently, the variations observed in this index approximate the input cost uncertainty for concrete used in nuclear construction. See Figure 5 and Table 38 in Appendix B for the raw data.

4.3.1.4 Materials data set: Steel (ms)

Similar to the index for cement discussed in Section 4.3.1.3, the Board of Governors has been tracking steel prices in the U.S., monthly, since 1972. And similar to the cement market, the PPI does not reflect these prices changes directly. The index published by the Board of Governors, *Industrial Production Durable Goods: Raw Steel* represents real price changes in the U.S. steel market (FRED 2019). Thus, the variation observed in its time series approximates reasonably well the input cost uncertainty for steel used in nuclear construction and specifically in the reactor containment. Figure 6 as well as Table 39 of Appendix B, show the raw data of the time series.

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[c] PPI industry data for other measuring and controlling device mfg-nuclear radiation detection and monitoring instruments, not seasonally adjusted. https://beta.bls.gov/dataViewer/view/timeseries/PCU3345193345195

4.3.1.5 Materials data set: Welding (mw)

Welding is included as an uncertainty input because of its primary importance in several activities related to nuclear construction Ganda (2018). The BLS publishes a monthly welding index, dating back to 1972. This index (in Figure 7) reflects price changes in supplies and equipment in welding activities, as well as metal. The raw data for this series are in Table 40 of Appendix B.

4.3.2 Time Series Analysis: De-Trending the Data

Modeling input cost uncertainty, using the data sources listed above, requires capturing the variation in each time series. One approach to capturing uncertainty would be to simply compute the mean and standard deviation of each data series: however, in this case the underlying components of *seasonality and trend* would be left in the data. This means that the data would be defined as *non-stationary*. Because the focus of this analysis is to capture the underlying, uncertain, stochastic process in each series these data must be made stationary. Time series analysis is a method to accomplish that.

Given a historical, time series data set Y_t, where t denotes the time where data on Y are recorded, then Y_t is composed of a seasonal component, S_t, an underlying trend, T_t, and an irregular component, I_t. Time series analysis enables the analyst to identify each of these components, then in the case of forecasting, systematically reflect each component in a way that preserves the underlying stochastic process. For the purposes of this analysis, I_t captures the variation in each series needed to model input cost uncertainty.

Two fundamental approaches exist for deconstructing a time series into its component parts: additive decomposition and multiplicative decomposition (Hanke, Reitsch et al. 2001). The factor that points to which method is best suited, is how the variation in the time series behaves over time. If the variation is relatively constant over time, then additive decomposition is the recommended approach. On the other hand, if the variation grows over time, then multiplicative decomposition is the recommended method. Because the variance in the datasets listed above does not increase with time, additive decomposition is the method followed. The non-increasing variance can be observed in Figure 3 through Figure 7, by looking at the red line relative to the blue line in each figure. The red lines plot the irregular component and its relation to the underlying data, the blue line, is neither increasing nor decreasing over time. This means that for each data series the following time series equation must be decomposed into each of the four parts.

$$Y_t = T_t + S_t + I_t \,.$$

For additive decomposition, the first step was to adjust the data series for seasonality. In some cases, the U.S. statistical agencies provide data that have been seasonally adjusted. This is the case for the data series used to model variation in concrete and steel listed above. The other data series had to be seasonally adjusted for this work. For the series representing labor, materials and welding, first a moving average was computed according to the data frequency. If the data are recorded quarterly, then a four-period moving average is typically applied, and if the data are monthly then a twelve-period moving average is typically computed. The next step involved computing a moving average over eight periods for quarterly data and 24 periods for monthly data. Then a seasonality index was computed by finding the ratio of the original data series with the eight or 24 periods moving average, as applicable. Then the seasonality index was found by quarter or by month; e.g. quarter 1 has a distribution of seasonality index made up of all quarter 1 data in the series and, if monthly, then each month has its own distribution of seasonality indexes.

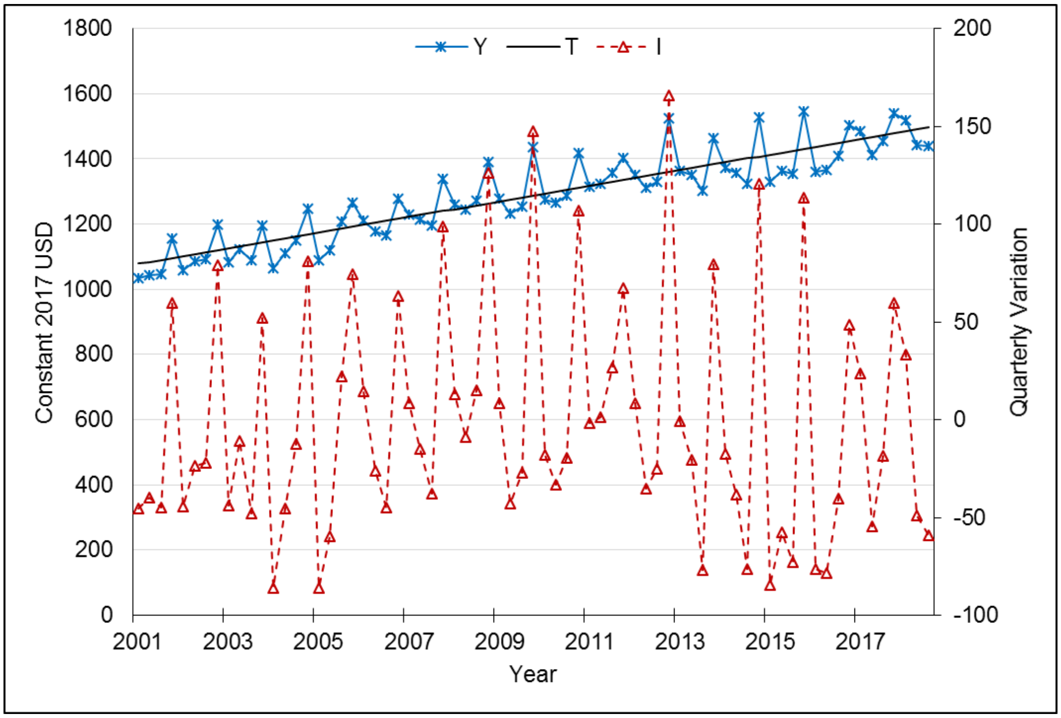

Figure 3 Average Weekly Wages in Power and Communication Construction

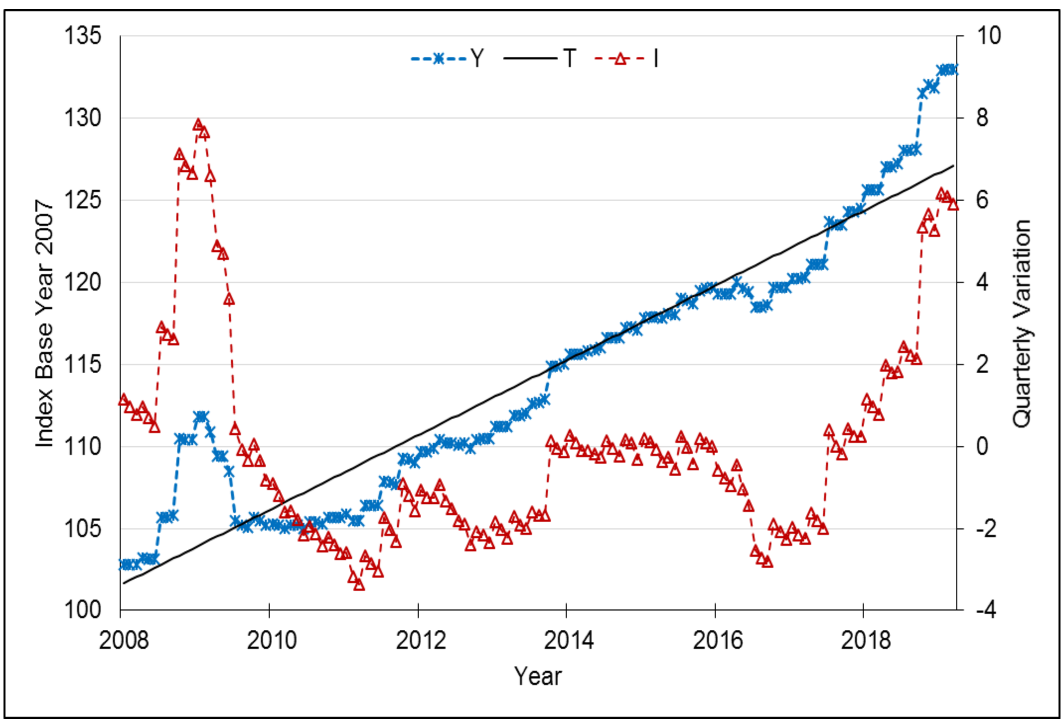

Figure 4 Producer Price Index by Commodity for New Industrial Construction

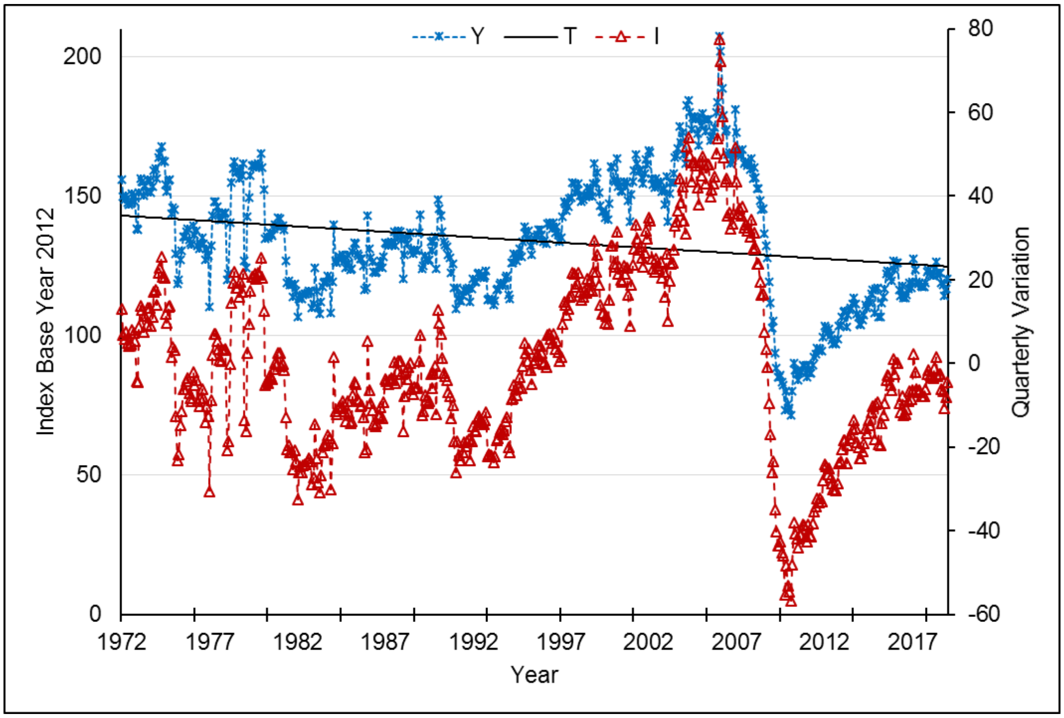

Figure 5 Industrial Production: Durable Goods – Cement

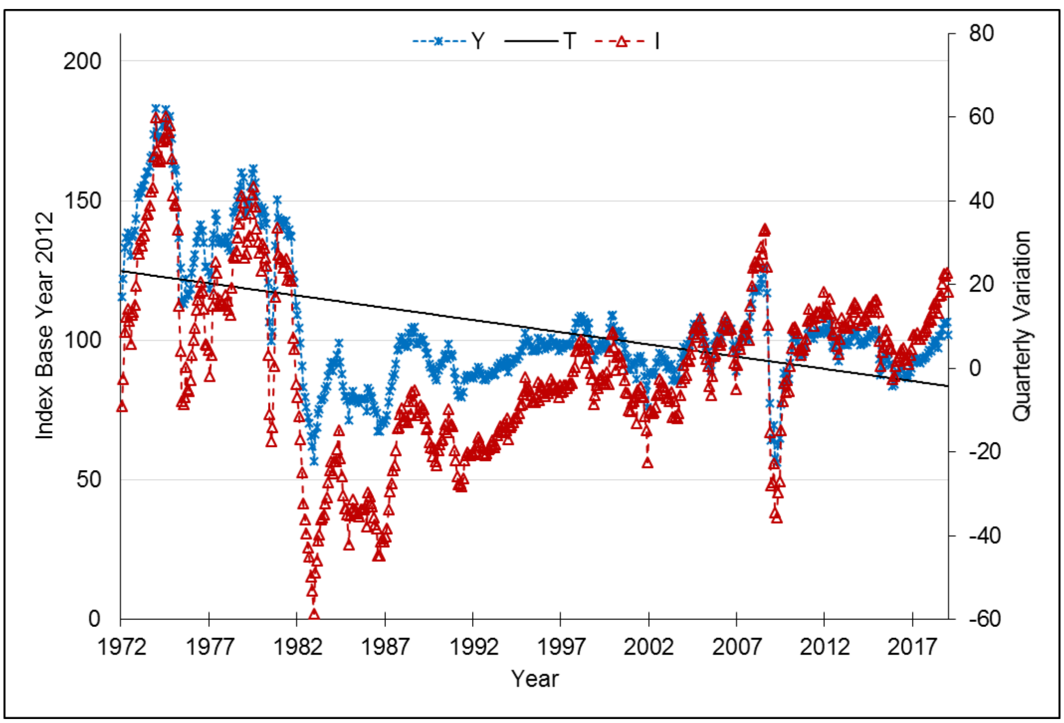

Figure 6 Industrial Production: Durable Goods – Raw Steel

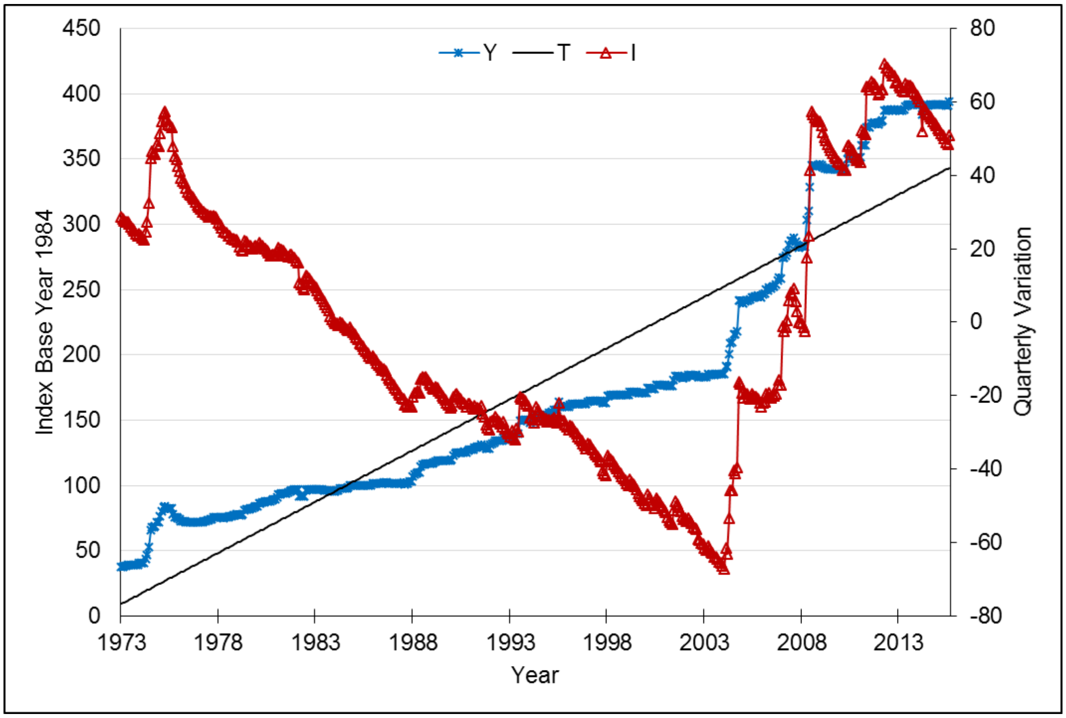

Figure 7 Producer Price Index: Welding and Soldering Equipment Manufacturing, Metal

From each of these distributions, the median seasonality index was found, and then used to compute a seasonality factor for each time component. *"Quarter 1 to Quarter 4"* each has its own seasonality factor, as does *"January to December"*. Then the original data series is adjusted by the seasonality factor that corresponds to each data observation. Once this process is complete, the original data are said to be seasonally adjusted. With seasonality dealt with in the time series, then the underlying trend must be extracted. (The interested reader is referred to Hanke, Reitsch et al. (2001), p. 179 for more on seasonally adjusted data.)

Identifying the time trend in each data series requires performing regression analysis on each series. In the regression, the seasonally adjusted data series becomes the left-hand variable and time, (1 … t) where t, the number of time observations in each series, becomes the right-hand side variable. The following Equation illustrates which equation is to be estimated with regression.

$$T_t = \beta_0 + \beta_1 \text{TIME}$$

In the Equation, T_t is the variable to be estimated; it is the underlying time trend. The data used to perform the regression include the seasonally adjusted series mentioned earlier, S_t, and the observation time. From these data, the regression estimates β_0 and β_1, which are the coefficients needed to predict T_t,, are attained. Then these two coefficients, together with TIME are employed to estimate the trend T_t in the original data series. Table 28 shows the regression results for each data series. The estimated coefficients shown in the table are inserted into the Equation, with the time series, and the result is a series T_t, which is the underlying time trend of each data series.

With the data adjusted for seasonality, and the trend identified, it was possible to extract de-trended information, which can then be used in uncertainty modeling. Figure 3 through Figure 7 show the results of the time series analysis on each data series. Each figure contains three plots: Y, the seasonally adjusted data series, T the time trend estimated with the parameters in Table 28, and the irregular component in each series, I. It is this irregular component for each series that can be utilized to model input cost uncertainty. It represents the intrinsic stochastic process in each series – absent seasonal and time variation. One can think of it as the 'pure randomness' in each series.

The irregular component of each series is the source of variation used to model input cost uncertainty, but I_t is not the needed parameter by itself. That is, $I_t \neq \lambda_{jk}$. The following equation instead allows I_t to be utilized to calculate λ_{jk}, which in turn is used to approximate uncertainty.

$$\lambda_{jkt} = 1 + \frac{I_t}{Y_t}$$

In the next section, the parameters λ_{jkt} for each series are accumulated into a distribution, such that the time subscript is no longer applicable. Instead, for each input cost uncertainty, the distribution of λ_{jk} is the basis upon which to generate the probability density function for each input.

Table 28 Statistical Results from De-Trending Data Series

Data series for:	Coefficient (β_1)	Intercept (β_0)	R^2 Adj. R^2	Obs.
labor	4.35	780. 78	0.56	71
	(0.46)	(19.14)	0.56	
materials	0.19	100.14	0.89	135
	(0.01)	(0.49)	0.89	
concrete	-0.03	143.02	0.05	565
	(0.01)	(1.88)	0.05	
steel	-0.07	124.83	0.25	565
	(0.01)	(1.73)	0.25	
welding	0.65	8.56	0.87	512
	(0.01)	(3.28)	0.87	

(standard errors)

4.4 Probability density functions from the de-trended input uncertainty data

This Section presents the histograms generated for each input uncertainty, as well as the analytical form of an approximating probability density function.

A plug-in to Microsoft Excel called @Risk (Palisade 2016) is used to analyze the data and to generate output data. Figure 8 to Figure 12 are results from applying @Risk to the data generated as discussed in Section 4.3.2. In each figure, the blue histogram shows the distribution of the λ_{jk} and the red line shows the continuous, probability density function (pdf) that best fits the input data. The *"Akaike Information Criterion"* is used to evaluate how well a set of probability density function fit the input data. For the data series under analysis, the possible best-fit distributions included the triangular, the beta general, the extreme value minimum, the Pierson 5, the logistic and the lognormal. However, the pdfs shown in the figures reflect the lognormal, and in two cases the logistics distribution. For these two cases the lognormal was invalid because of the potential for negative values.

In each of the figures, a legend showing a summary statistics grid is included. It shows the descriptive statistics of the histogram and of the pdf. The statistics of mean and standard deviation from the histograms are used to populate the lognormal distribution for each data series. The log-normal excludes the possibility of non-positive values and is a better approximation of cost uncertainty in cost estimating. Further, previous research has shown that cost uncertainty in construction follows a lognormal distribution (Touran and Wiser 1992, Moret 2011). Thus, based on these considerations, it was chosen to utilize log-normal distribution for all the input cost uncertainties in this study. Other functional forms of the pdfs can easily be utilized, if found more appropriate, in future work, by simply swapping the instructions in the code, reported in Appendix D, related to the pdfs sampling.

Comparing the distributions, it is observed that uncertainty in steel and in welding have the largest variations, as measured by evaluating the minimum and maximum values of each distribution. Conversely, the histograms for materials and labor costs, show the least variation based on the min-max range.

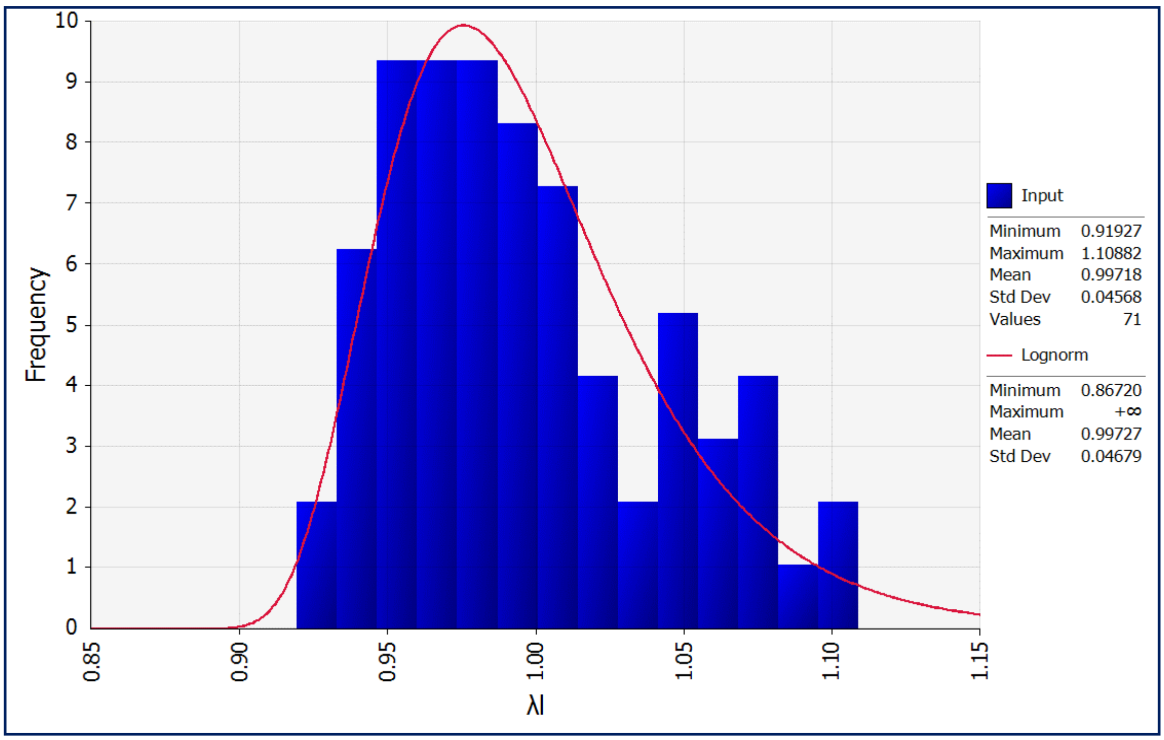

Figure 8 Uncertainty Factor in Labor Cost

The following equation shows the functional form of lognormal probability density functions (Wackerly, Mendenhall et al. 2002):

$$f(y) = \frac{1}{\sigma y \sqrt{2\pi}} e^{-(\ln(y)-\mu)^2/(2\sigma^2)}$$

where μ is the location parameter and σ is the shape parameter. In this equation, and based on the reference Wackerly, Mendenhall et al. (2002), the location and shape parameters are taken as the mean and standard deviation of the data series. Table 29 shows the pdf that can be utilized to model uncertainty for each input and the parameters for each distribution.

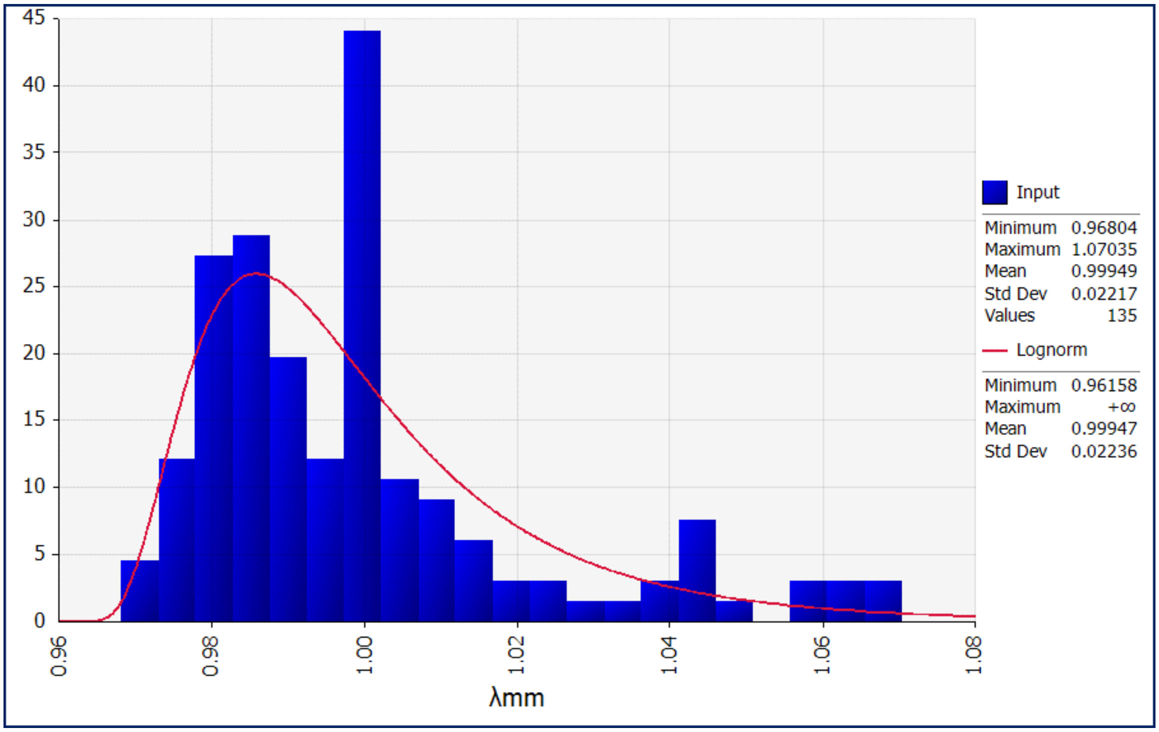

Figure 9 Uncertainty Factor in Materials-Materials Cost

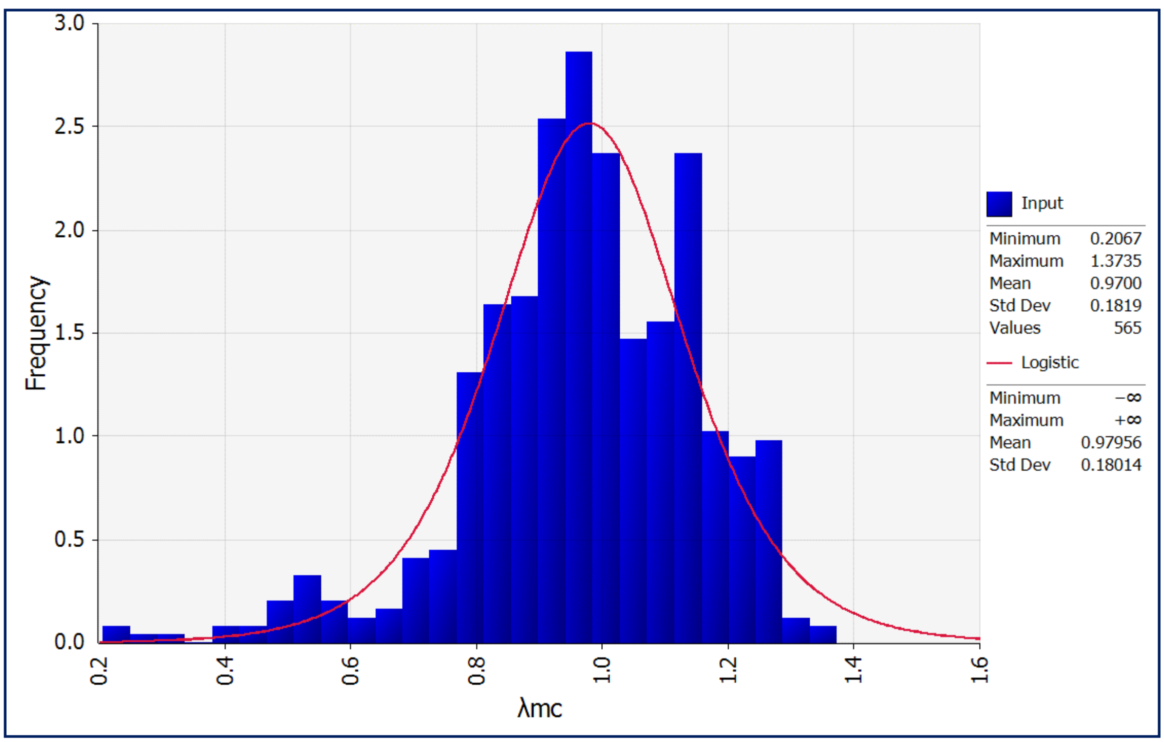

Figure 10 Uncertainty Factor in Materials-Concrete Cost

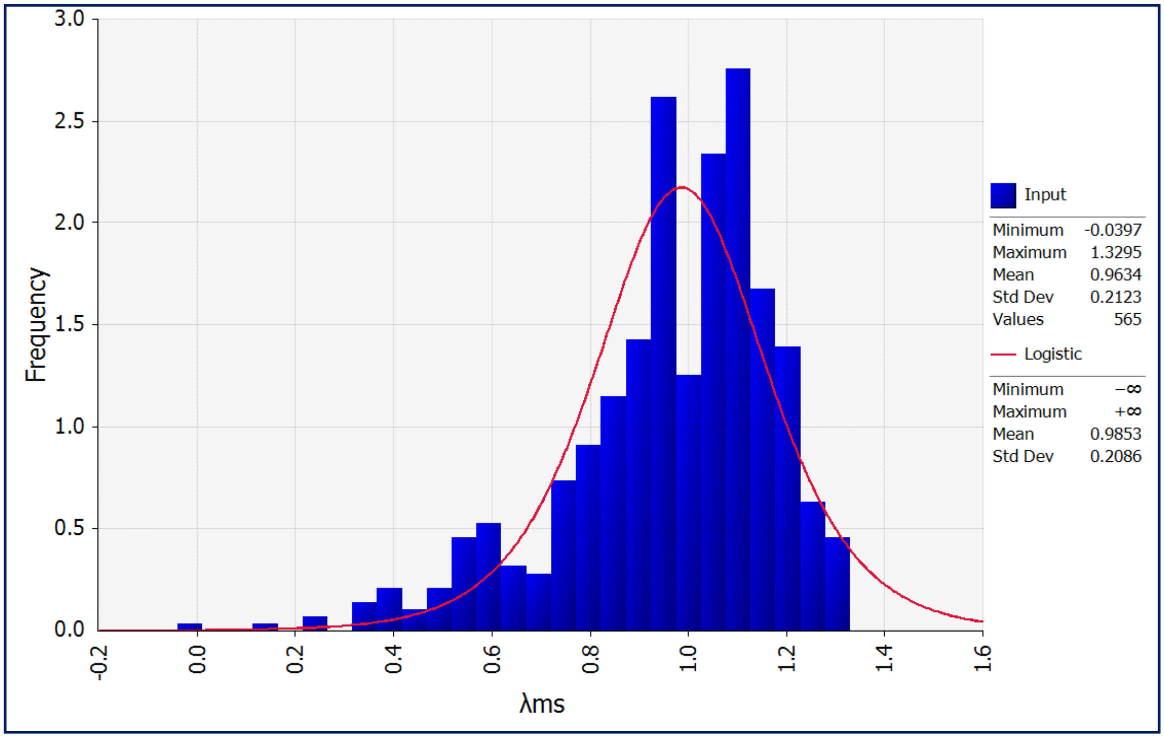

Figure 11 Uncertainty Factor in Materials-Steel Cost

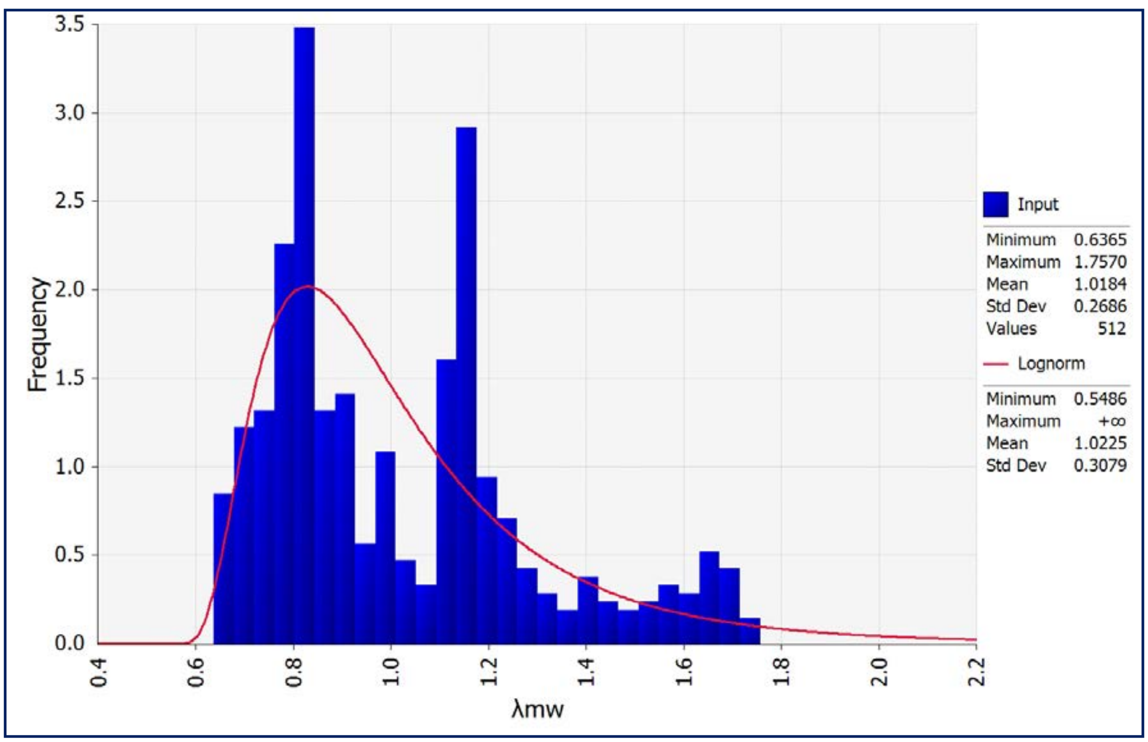

Figure 12 Uncertainty Factor in Materials-Welding Cost

Table 30 shows the correlation matrix that quantifies the correlation between each of the distributions of Table 29. The correlation matrix, as calculated with the actual historical de-trended data, was found to be valid (i.e. it was found to be positive semi-definite, or with non-negative eigenvalues), and therefore it did not require any adjustment in order to be used for this work.

It is observed that all the materials have a negative correlation to labor costs: this is somewhat understandable, based on the fact that when labor is expensive, construction activity is likely to slow down, thus yielding to lower demand for construction materials, and therefore to lower prices for construction materials. Additionally, it is observed that steel is positively correlated to concrete − since the two are often used together in reinforced concrete, for example − and to welding, since welding is used only for steel, so the demand (and therefore the price) for welding will be higher when the demand (and therefore the price) for steel is higher. Similarly, "other construction materials" are positively correlated to concrete, since there will be high demand (and therefore higher prices) for both simultaneously, when there is high construction activity.

Appendix C of this chapter contains a matrix of scatter plots. The plots and correlation shown in Appendix C correspond to the measured correlation shown in Table 30.

Table 29 Probability Density Functions with Estimated Parameters from Figure 8 to Figure 12

Input Cost Category	$f(y)=$	μ	σ
Labor	$\frac{1}{0.115y}e^{-(\ln(y)-1)^2/0.004}$	0.997	0.046
Materials	$\frac{1}{0.056y}e^{-(\ln(y)-1)^2/0.001}$	1.000	0.022
Concrete	$\frac{1}{0.456y}e^{-(\ln(y)-1)^2/0.066}$	0.970	0.182
Steel	$\frac{1}{0.532y}e^{-(\ln(y)-1)^2/0.090}$	0.963	0.212
Welding	$\frac{1}{0.673y}e^{-(\ln(y)-1)^2/0.144}$	1.018	0.269

Table 30 Calculated correlation matrix, quantifying the correlation between each of the distributions of Table 29.

	λl	λmc	λms	λmw	λmm
λl	1.000				
λmc	-0.196	1.000			
λms	-0.038	0.362	1.000		
λmw	-0.033	0.110	0.323	1.000	
λmm	-0.154	0.459	0.073	0.070	1.000

4.5 Example application to the containment building: construction cost uncertainty quantification

The de-trended uncertainty distributions for labor, steel, concrete, welding and other materials were utilized in this section to arrive at an uncertainty distribution for the construction cost of the entire containment building, as an example.

The containment building of the reference PWR-12BE has a cost of $185.87 million in 2017 USD (Ganda 2018, Section 3.2). Since the containment model of the ACCERT algorithm is a bottom-up model, it is possible to obtain a detailed breakdown of the various cost contributions to the total cost. These needed to be organized according to the categories listed above of:

- Labor;
- Steel;
- Concrete;
- Welding;
- Other Materials;

as shown in Table 31.

Table 31 Detailed breakdown of the total cost of the PWR12-BE containment building, with each cost attributed to one of the uncertainty distributions categories.

Total Costs (Material and Labor)	**Million of 2017 USD**	**Uncertainty distributions category**
Formwork	14.63	Other materials
Reinforcing steel	39.94	Steel
Concrete	9.97	Concrete
Embedded Steel	10.89	Steel
Rubbing Surfaces	0.79	Concrete
Waterproofing	0.08	Concrete
Cadwelds	11.02	Welding
Construction Joints	1.07	Concrete
Welded Wire Fabric	0.07	Welding
Major Support Embedments	7.81	Steel
Reactor Cavity Liner	3.97	Steel
Structural Steel	2.86	Steel
Miscellaneous Steel Frames	1.83	Steel
Floor Grates Handrail Stairs	0.93	Steel
Containment Liner	59.46	Steel
Painting	10.20	Other materials
Plumbing & Drains	1.13	Steel
Special HVAC	4.94	Other materials
Lighting & Power	3.67	Other materials
Other Equipment	0.62	Other materials
TOTAL	**185.88**	

It is noted that the attribution of each of the costs to some of the categories is subjected to a certain degree of subjectivity. For example, it can be debated whether the uncertainty around the "Welded Wire Fabric" costs should be related to the uncertainty around welding, or whether it should be quantified with the steel uncertainty, since welded wire fabric is made of steel but also requires a large amount of welding at the factory. Nevertheless, the purpose of this exercise is to demonstrate the methodology, and to arrive at a quantification of the expected uncertainty in nuclear construction costs for well executed projects. The attribution to each of the categories can easily be changed, and the exercise easily repeated with the methodology developed here: the quantitative conclusions are not expected to change substantially with slightly different allocations of the cost categories.

As mentioned in Section 4.3.1 when discussing the data sources, the uncertainty around the cost of construction labor is assumed to be applicable to all the various construction activities. For this reason, labor costs are not shown separately in Table 31.

The expected, summed values of the five cost categories utilized for the input cost uncertainty quantification are shown in Table 32 for the containment of the PWR12-BE. It is noted that the containment costs are dominated by the labor costs, followed by the steel costs. The other categories have relatively minor roles in the expected total costs.

Table 32 Expected values of the five cost categories utilized for the input cost uncertainty quantification for the containment of the PWR12-BE

Uncertainty distributions category	Expected value of Cost (Million of 2017 USD)
Labor Cost	101.95
Other Materials	7.58
Concrete Materials	4.53
Steel Materials	68.03
Welding Materials	3.79

Afterwards, a correlated Monte Carlo sampling approach was utilized, with the same logic discussed in detail in Chapter 6 of Ganda (2014), based on the Iman Conover approach for correlated sampling (Ganda 2014). For this reason, the methodological and mathematical details are not repeated here.

The sampled probability density functions of the "labor", "other materials", "concrete materials", "steel materials" and "welding materials" costs for the construction of the containment of the PWR12-BE, are shown in Figure 13 to Figure 17.

The functional forms of each these distributions is sampled from a log-normal distribution according to the corresponding "best fit" listed in Table 29, and with an expected value obtained from Table 32. Therefore, the Labor cost (in Figure 13) will have an expected value of \$101.95 million, and a standard deviation of 0.046 x \$101.95 million, or \$4.69 million. The sampling is performed according to the following equation:

$$\frac{1}{0.115y}e^{-(\ln(y)-1)^2/0.004}$$

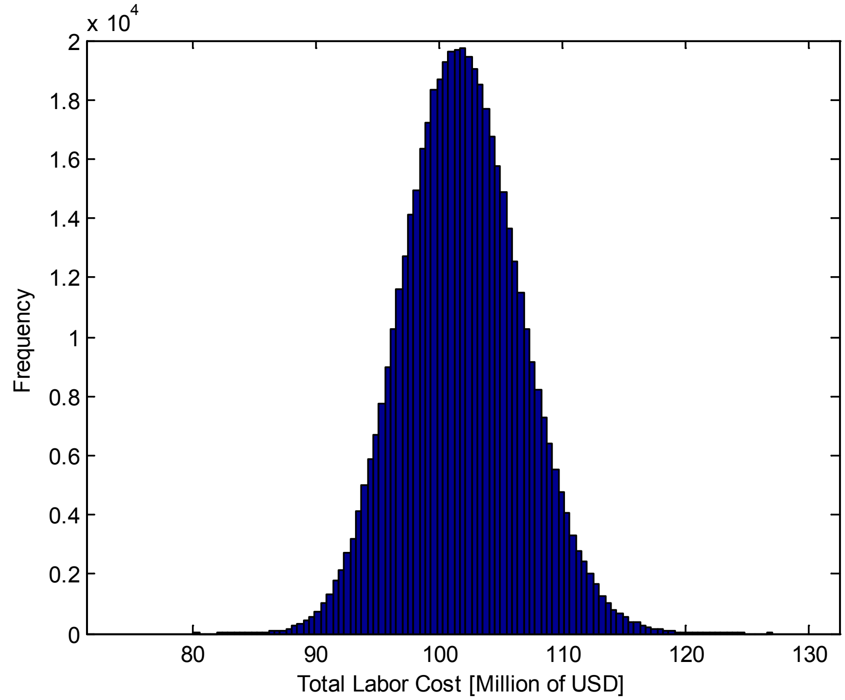

Figure 13 Sampled probability density function of the "labor" costs for the construction of the containment of the PWR12-BE, based on the equation of Table 29 and on the costs of Table 32.

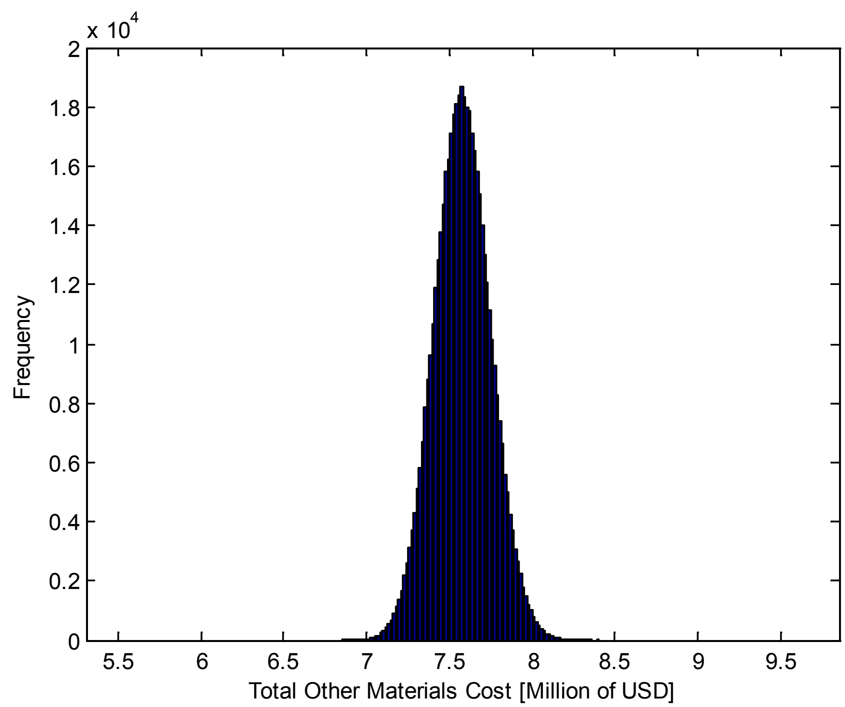

Figure 14 Sampled probability density function of the costs of "other materials" for the construction of the containment of the PWR12-BE, based on the equation of Table 29 and on the costs of Table 32.

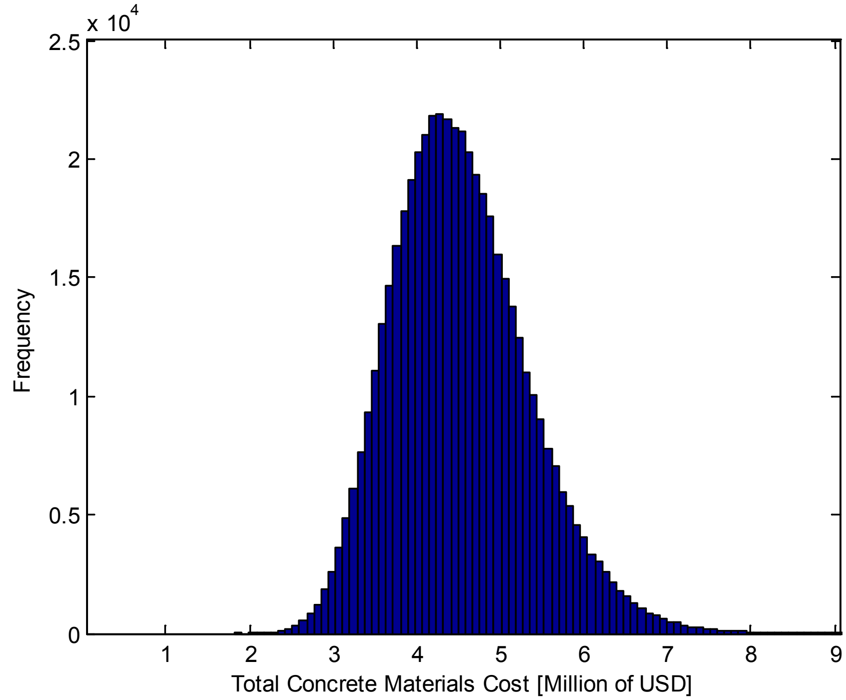

Figure 15 Sampled probability density function of the “concrete materials” costs for the construction of the containment of the PWR12-BE, based on the equation of Table 29 and on the costs of Table 32.

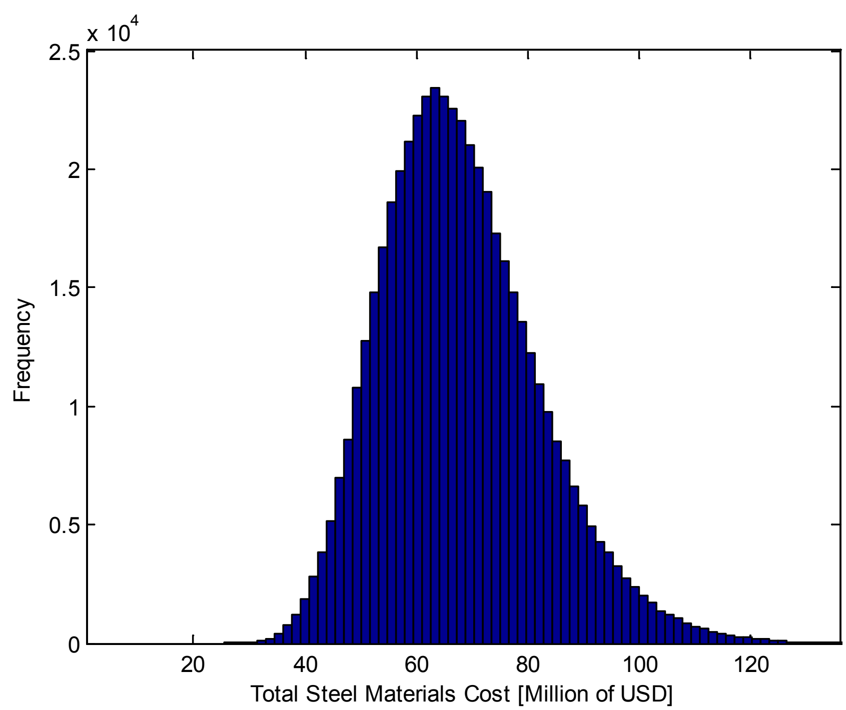

Figure 16 Sampled probability density function of the “steel materials” costs for the construction of the containment of the PWR12-BE, based on the equation of Table 29 and on the costs of Table 32.

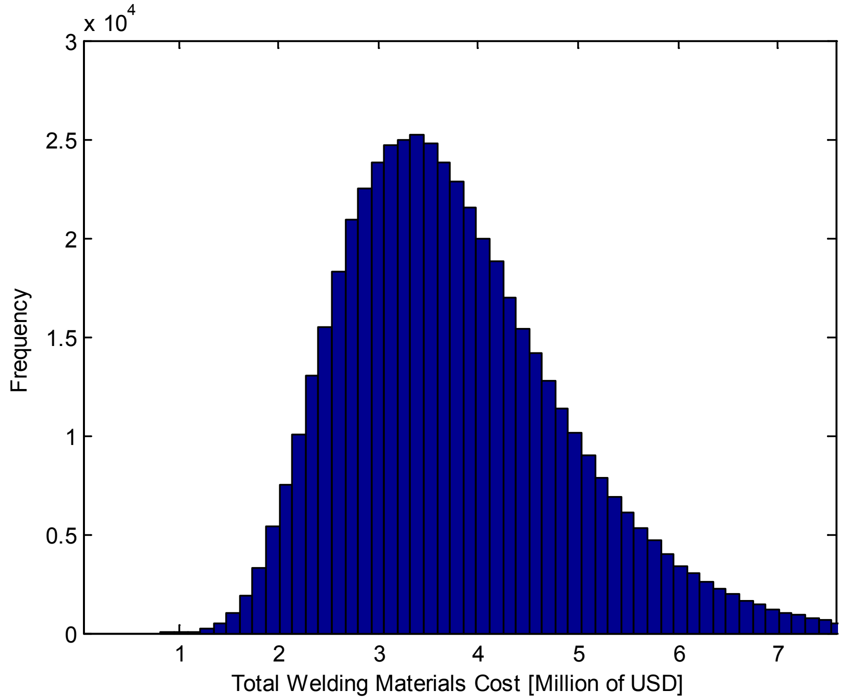

Figure 17 Sampled probability density function of the "welding materials" costs for the construction of the containment of the PWR12-BE, based on the equation of Table 29 and on the costs of Table 32.

The sampled log-normal distributions shown in Figure 13 to Figure 17 should be correlated, according to the correlation matrix shown in Table 30. The actual resulting correlation matrix, for the calculations performed here, is shown in Table 33: it is observed that, as desired, the sampled correlation matrix is close to the target of Table 30. Each time the uncertainty sampling is repeated, because of the random nature of the Monte Carlo calculations, the sampled correlation matrix will, in general, be different from that of Table 33.

As an example, the scatter plot of the cost of concrete and steel, which have a positive correlation coefficient of about 0.36, is shown in Figure 18, while that of labor and concrete, which have a negative correlation coefficient of about -0.19, is shown in Figure 19.

Table 33 Actual correlation matrix, for the sampled data of Figure 13 to Figure 17: it is, as desired, very close to the target correlation matrix of Table 29.

	Labor Cost	**Concrete Materials**	**Steel Materials**	**Welding Materials**	**Other Materials**
Labor Cost	**1**	-0.1957	-0.0374	-0.0327	-0.1497
Concrete Materials	-0.1957	**1**	0.3598	0.1096	0.4496
Steel Materials	-0.0374	0.3598	**1**	0.3197	0.0718
Welding Materials	-0.0327	0.1096	0.3197	**1**	0.0683
Other Materials	-0.1497	0.4496	0.0718	0.0683	**1**

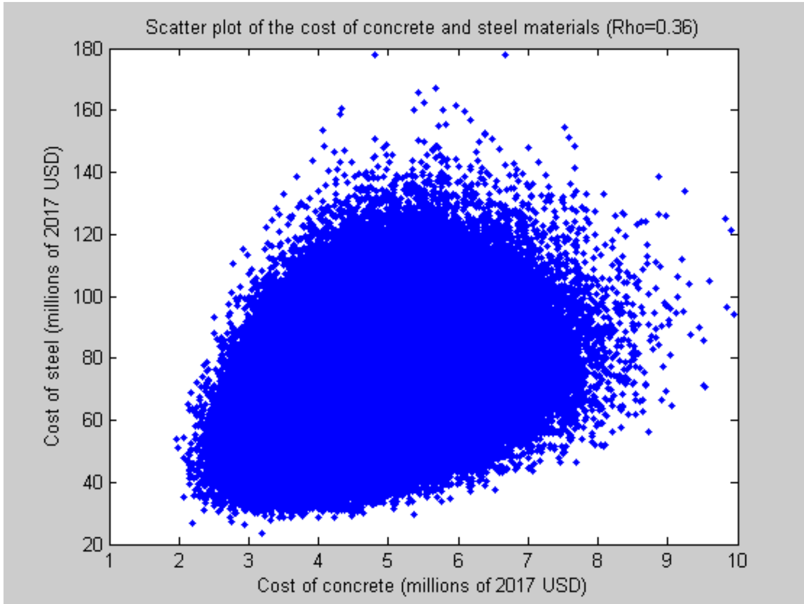

Figure 18 Scatter plot of the sampled distributions of steel and concrete (in millions of 2017 USD), which have a positive correlation coefficient of about 0.36.

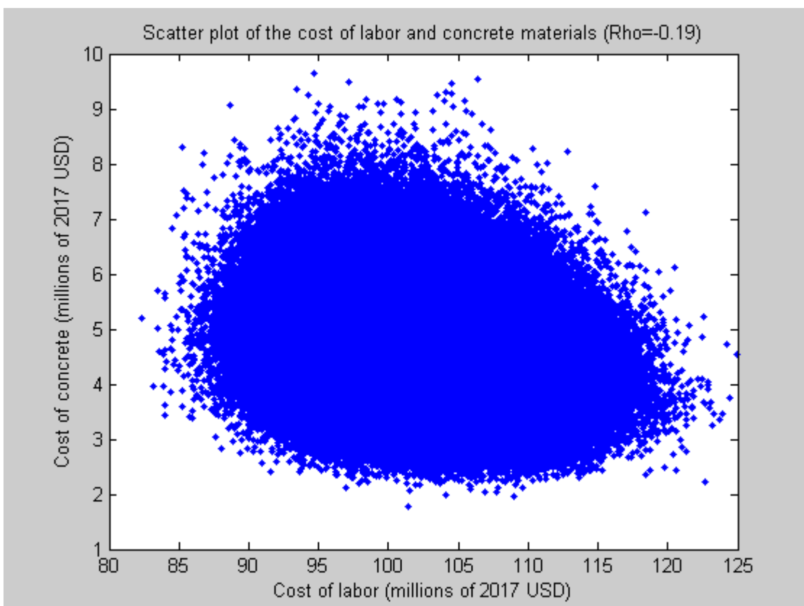

Figure 19 Scatter plot of the sampled distributions of labor and concrete (in millions of 2017 USD), which have a negative correlation coefficient of about -0.19.

4.5.1 Results: the un-avoidable uncertainty in construction cost for the containment building

The total uncertainty in construction costs for the containment building of the PWR12-BE is shown in Figure 20, as calculated with the methodology and data described in this Section.

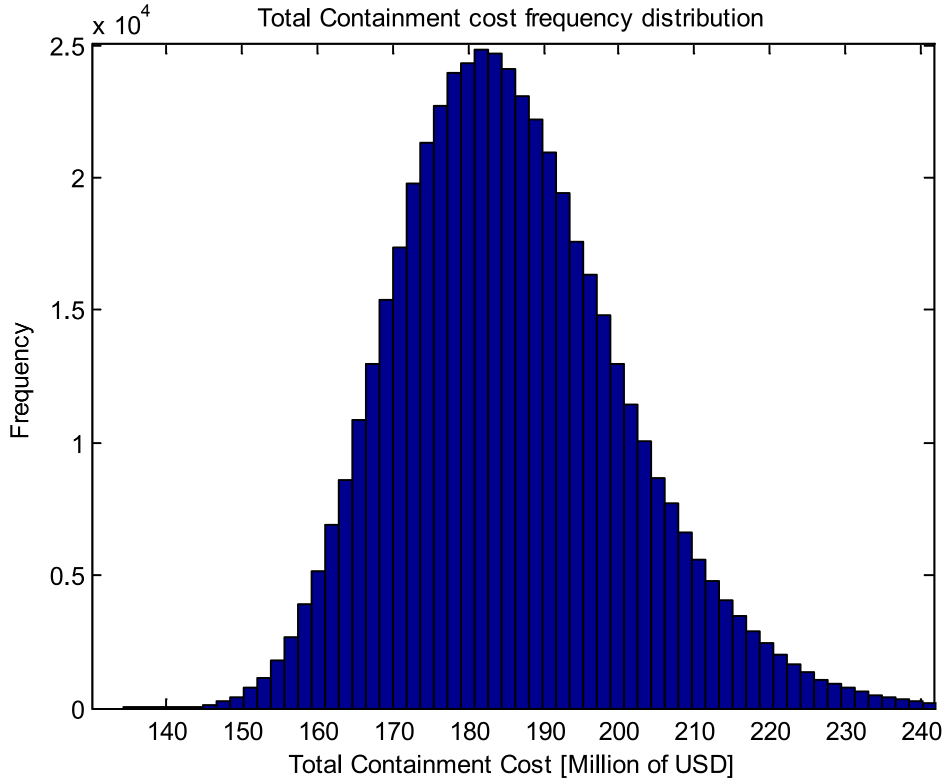

Figure 20 Total resulting uncertainty in containment construction costs for the PWR12-BE

It is observed that the expected value of the containment cost, from the sampled data, is of $185.89 million, consistent from the ACCERT deterministic calculation of $185.88 million.

The standard deviation, and the functional form of the uncertainty distribution, are the new information that could be derived in this chapter for the first time, for well-executed construction projects, based on actual historical data on input cost uncertainty.

The standard deviation of the containment uncertain cost in Figure 20 is of $15.44 million, or 8.3% of the expected value. Therefore, in order to have a 95% confidence that the actual realized cost of a containment construction will be within the allocated budget, it is necessary to allocate a contingency of two standard deviations, or of 16.6%. This contingency would be sufficient to cover most of the oscillations in input costs, which are outside of the control of the constructors.

While the calculations in this chapter were performed for the containment building, it is recommended to use the σ/μ (ratio of the standard deviation to the expected construction cost) obtained for the containment, as an approximation of the expected un-avoidable uncertainty for the entire plant construction. This is based on the consideration that other parts of the plant typically have similar types of input costs, including construction labor, steel etc…. Future work may be dedicated to applying the technique developed here, to other parts of the plant, and progressively refine this approximation. It is noted, however, that the uncertainty calculated here was derived in a very robust and defensible way: using actual historical data, properly de-trended, and a rigorous mathematical method for the calculation of the containment uncertainty. This same rigor may not be equally applicable to other costs centers for which less is known in terms of cost breakdown (e.g. the large mechanical components, and other components described both in this report and in Ganda (2018)).

It is noted that each reactor design employing a different containment may have different expected values of the containment costs, uncertainty distributions and standard deviations. The methodology developed in this chapter is easily applicable to any alternative reactor design, and even to other fuel cycle facilities, by utilizing the building models for the construction cost of massive concrete/steel buildings housing large fuel cycle facilities, developed in Ganda (2018). For other design, it is sufficient to run the ACCERT models for the containment building of each design, in order to obtain the contributions to the total costs of each of the large cost components categories utilized in this chapter for input cost uncertainty: namely “labor”, “other materials”, “concrete materials”, “steel materials” and “welding materials”. Afterwards, it is sufficient to change those at the beginning of the input of the uncertainty model of the ACCERT code reported in Appendix D, and to re-run the uncertainty model. A new uncertainty quantification for the new building (and by extension for the new plant) will be immediately produced.

5. UPDATED SUMMARY TABLE OF DIRECT COSTS FOR THE REFERENCE PWR12-BE

This section includes a summary table of the total direct costs for the reference PWR12-BE, in millions of 2017 USD.

- Table 34 is similar to Table 1 of Section 2.1. However, in Table 34 all the NSSS cost inputs reflect the results of the models developed in this work and in Ganda (2018).
- Accounts for which models were generated in Ganda (2018) and in this work are in blue: 60 in total, reaching a cumulative contribution of more than 95%. In black are accounts for which models have not been developed yet, which contribute cumulatively the remaining 5% to the total direct costs of the reference PWR.
- The third column, greyed, contains the costs contributions from Holcomb (2011) for the NSSS, which were used as placeholders prior to the present work and prior to Ganda (2018).
- The 4th column contains the results of the cost models develped in this work and in Ganda (2018), as applied to the reference PWR12-BE. The cost contributions are sorted according to this column.
- In the grey-shaded raws, are NSSS cost models developed in this work and in Ganda (2018). The cost of those are the same as in Table 27.

Table 34 and its content should be used as the starting point for future work on the ACCERT algorithm.

Table 34 – Summary table of the total direct costs (in millions of 2017 USD) sorted by contributions for the PWR-12-BE.

Account # (EEDB Convention)	Account Description	Old Cost (Same as Table 1) Million of 2017 USD. Source: (EEDB 1987) (Holcomb 2011)	Updated Cost Million of 2017 USD. Source: (EEDB 1987) (Ganda 2018) & This Report	Updated% of total costs
231	Turbine Generator	384.53	**384.53**	14.81%
212	Reactor Containment Building	186.08	**186.08**	7.17%
220A.223	Steam Generators (NSSS)	61.76	**149.80**	5.77%
262	Condensing Systems Mechanical Equip	128.14	**128.14**	4.94%
220A.221	Main Coolant Pumps (NSSS)	46.32	**125.24**	4.82%
233	Condensing Systems	83.18	**83.18**	3.20%
252	Air Water & Service System	82.44	**82.44**	3.18%
211	Yardwork	71.73	**71.73**	2.76%
220A.211	Vessel Structure (NSSS)	82.35	**70.00**	2.70%
234	Feed Heating System	67.70	**67.70**	2.61%
213	Turbine Room & Heater Bay	66.45	**66.45**	2.56%
235	Other Turbine Plant Equipment	64.07	**64.07**	2.47%
245	Elect. Structures +Wiring Containers	64.01	**64.01**	2.47%
227	Rx Instrumentation + Control	61.86	**61.86**	2.38%
224	Rad-waste Processing	60.10	**60.10**	2.32%
246	Power & Control Wiring	59.13	**59.13**	2.28%
242	Station Service Equipment	57.87	**57.87**	2.23%

226.7	**Aux Cool Sys (Broken Down Further)**	55.60	**55.60**	2.14%
215	**Prim Aux Building + Tunnels**	53.02	**53.02**	2.04%
218A	**Control Rm/D-G Building**	51.94	**51.94**	2.00%
216	**Waste Process Building**	41.23	**41.23**	1.59%
226.4	**Coolant Treatment & Recycle**	41.07	**41.07**	1.58%
220A.2132	**Control Rod Drives (NSSS)**	30.88	**34.90**	1.34%
241	**Switchgear**	34.29	**34.29**	1.32%
220A.2121	**Lower Internals (NSSS)**	30.88	**31.78**	1.22%
220A.2122	**Upper Internals (NSSS)**	30.88	**31.78**	1.22%
217	**Fuel Storage Building**	28.35	**28.35**	1.09%
237	**Turbine Plant Misc. Items**	23.09	**23.09**	0.89%
218J	**Main Steam + Feedwater Pipe Enc.**	22.58	**22.58**	0.87%
228	**Reactor Plant Miscellaneous Items**	21.39	**21.39**	0.82%
236	**Turbine Instrumentation + Control**	19.67	**19.67**	0.76%
218B	**Administration + Services Building**	19.08	**19.08**	0.73%
253	**Communications Equipment**	18.41	**18.41**	0.71%
251	**Transportation & Lift Equipment**	17.20	**17.20**	0.66%
222.12	**Reactor Coolant Piping System (Field Cost 222)**	17.02	**17.02**	0.66%
221.14	**Transport To Site (Field Cost 221)**	15.90	**15.90**	0.61%
220A.2322	**Accumulator Tank (NSSS)**	7.72	**15.30**	0.59%
223.4	**Containment Spray System (Field Cost 223)**	15.21	**15.21**	0.59%
218T	**Ultimate Heat Sink Structures**	13.19	**13.19**	0.51%
261	**Condensing Systems Structures**	12.43	**12.43**	0.48%
244	**Protective Equipment**	12.23	**12.23**	0.47%
220A.222	**Reactor Coolant Piping (NSSS)**	23.16	**11.40**	0.44%
223.3	**Safety Injection System (Field Cost 223)**	10.46	**10.46**	0.40%
220A.262	**Maintenance Equipment (NSSS)**[d]	2.57	**9.19**	0.35%
225	**Fuel Handling & Storage**	9.09	**9.09**	0.35%
222.11	**Fluid Circulation Drive System (Field Cost 222)**	8.65	**8.65**	0.33%
220A.224	**Pressurizer (NSSS)**	15.44	**8.30**	0.32%
255	**Waste Water Treatment Equipment**	8.13	**8.13**	0.31%
254	**Furnishing + Fixtures**	7.85	**7.85**	0.30%
218E	**Emergency Feed Pump Building**	7.17	**7.17**	0.28%
221.12	**Vessel Structure (Field Cost 221)**	7.09	**7.09**	0.27%
223.1	**Residual Heat Removal Sys (Field Cost 223)**	6.86	**6.86**	0.26%
220A.2312	**Residual Heat Removal Heat Exchanger (NSSS)**	15.44	**6.26**	0.24%
243	**Switchboards**	5.88	**5.88**	0.23%

[d] Account 220A.262, "Maintenance Equipment" is supplied as part of the NSSS. This account is so heterogeneous and complex that it was not possible to develop any cost model, even preliminary: this issue is discussed in Section 3.18. Nevertheless, a cost for this account is provided in this Table (primarily as a placeholder), using the difference between the known total cost of the NSSS components from EEDB (1987) and the aggregated costs of all the NSSS components evaluated in Ganda (2018) and in the current report. Vendor quotes will be necessary to obtain defensible cost estimates for this account in the future.

226.3	**Reactor Makeup Water Sys**	4.28	**4.28**	0.17%
221.11	**Reactor Support (Field Cost 221)**	3.94	**3.94**	0.15%
214	**Security Building**	3.91	**3.91**	0.15%
226.1	**Inert Gas Sys**	3.56	**3.56**	0.14%
223.5	**Combustible Gas Control System (Field Cost 223)**	3.10	**3.10**	0.12%
220A.2131	**Control Rods (NSSS)**	30.88	**3.10**	0.12%
220A.254	**Fuel Storage Racks (NSSS)**	12.87	**2.51**	0.10%
220A.2612	**Heat Transfer Equipment (NSSS)**	6.43	**2.45**	0.09%
220A.2614	**Purification And Filtration Equipment (NSSS)**	6.43	**2.45**	0.09%
222.13	**Steam Generator Equipment (Field Cost 222)**	2.41	**2.41**	0.09%
218L	**Technical Support Center**	2.27	**2.27**	0.09%
220A.2611	**Rotating Machinery (Pumps And Motors) (NSSS)**	6.43	**2.22**	0.09%
218S	**Waste Water Treatment**	2.20	**2.20**	0.08%
218F	**Manway Tnls. (Radiological Ctrl Access Tunnels)**	2.19	**2.19**	0.08%
220A.2311	**Residual Heat Removal Pumps & Drives (NSSS)**	15.44	**1.94**	0.07%
220A.225	**Pressurizer Relief Tank (NSSS)**	7.72	**1.85**	0.07%
226.9	**Sampling Equip**	1.84	**1.84**	0.07%
220A.2321	**Safety Injection Pumps And Drives (NSSS)**	15.44	**1.72**	0.07%
221.13	**Vessel Internals (Field Cost 221)**	1.72	**1.72**	0.07%
221.21	**Control Rod System (Field Cost 221)**	1.55	**1.55**	0.06%
218H	**Non- Essen. Switchgear Bldg.**	1.54	**1.54**	0.06%
226.8	**Maintenance Equipment**	1.52	**1.52**	0.06%
218D	**Fire Pump House, Including Foundations**	1.22	**1.22**	0.05%
220A.2613	**Tanks And Pressure Vessels (NSSS)**	3.86	**1.14**	0.04%
218K	**Pipe Tunnels**	0.91	**0.91**	0.04%
220A.2323	**Boron Injection Tank (NSSS)**	7.72	**0.90**	0.03%
218P	**Containment Equipment Hatch Missile Shield**	0.63	**0.63**	0.02%
226.6	**Fluid Leak Detection Sys**	0.50	**0.50**	0.02%
220A.251	**Fuel Handling Tools (NSSS)**	12.87	**0.40**	0.02%
222.14	**Pressurizing System (Field Cost 222)**	0.33	**0.33**	0.01%
218V	**Control Rm Emergency Air Intake Building**	0.26	**0.26**	0.01%
218G	**Elec. Tunnels**	0.19	**0.19**	0.01%
220A.2324	**Boron Injection Surge Tank (NSSS)**	7.72	**0.05**	0.00%
220A.2325	**Boron Injection Recirc. Pump & Drives (NSSS)**	7.72	**0.04**	0.00%
220A.27	**Instrumentation And Control (NSSS)**	12.87	**0.00**	0.00%
220A.28	**Standard NSSS Valve Package (NSSS)**	12.87	**0.00**	0.00%
	TOTAL (Million of 2017 USD)	**2,596.13**[e]	**2,596.13**	

[e] It is noted that the total cost of the 3rd and 4th columns are identical because the cost of Account 220A.262 "Maintenance Equipment" in column 4, being unknown as discussed in Section 3.18, was calculated (as a placeholder) as the difference between the total cost of $2,596.13 (known from EEDB (1987)) and the sum of all the other costs without Account 220A.262.

6. CONCLUSIONS AND RECOMMENDED FUTURE WORK

This report presents the work, performed in FY19, dedicated to the improvement of the Algorithm for the Capital Cost Estimation of Reactor Technologies (ACCERT).

The overall objective of this work was to increase the fidelity of the ACCERT algorithm, and consequently the usefulness and credibility of the evaluations performed with this tool. For this objective, the following has been accomplished in FY19:

- Cost models of *all* the NSSS-supplied components were developed, for which costs were not provided in the reference cost databases (EEDB 1987), as discussed in Ganda (2018). This work was initiated and substantially advanced in FY18, with the development of detailed cost models for the eight largest and most expensive parts of the NSSS. The work in FY19 completed that task, with an inclusion of all the remaining NSSS-supplied components that were not analyzed in FY18. These include relatively minor, but numerous components, including rotating machinery, heat exchangers, demineralizers, tanks etc. for several important functions of nuclear power plants.
- The reasonableness of the NSSS cost models was checked, by summing the calculated costs derived from the models of this work and of Ganda (2018), and comparing the sum to the total aggregated NSSS costs, known from EEDB (1987). The agreement between the two was found to be excellent: the entire set of the NSSS components was calculated at $505.52 million in 2017 USD, versus the known aggregated cost of the total set of NSSS-supplied components from EEDB (1987), of $514.71 million in 2017 USD. In fact, this agreement exceeds the most optimistic expectations about this result before this work was initiated. Each of the cost models for the NSSS components was developed independently, regardless of the influence of each particular model on the total NSSS aggregated cost. This agreement should substantiate confidence in the cost models developed for the NSSS systems, at least at an aggregated level. This work offers, for the first time in the public domain, a complete set of models to evaluate the NSSS cost of advanced reactors systems.
- The number of cost models was substantially extended, in order to include all the costs that, in the preliminary list presented in Section 2, contribute at least 0.5% of the total direct costs of the reference PWR12-BE. In order to accomplish this, a total of 29 cost models were newly developed in FY19, including some of the NSSS-supplied components that contribute less than 0.5% to the total direct costs of the reference PWR12-BE. These, combined with the 31 cost models developed in FY17 and FY18, reach a total of 60 cost models, with a cumulative contribution to the total direct cost of the reference PWR12-BE of more than 95%. With only less than 5% of the direct cost of the reference design not directly quantified, the estimates performed with ACCERT have now a high degree of robustness and defensibility.
- New work was performed on the quantification of uncertainties of the cost estimates produced with the ACCERT algorithm, in Chapter 4. The cost models of the ACCERT algorithm produce deterministic estimates, which can be considered the "expected values" of cost estimates that are, in reality, uncertain. The shape and magnitude of the uncertainties were, however, unknown until the work performed here allowed their quantification, in a defensible and robust way. The standard deviation, and the functional form of the uncertainty distributions, are the new information that could be derived in this work for the first time, for well-executed construction projects, based on actual historical data on input cost uncertainty, such as labor, steel, concrete etc. As an example, it was possible to calculate that the standard deviation of the reference PWR containment's cost is 8.3% of the expected value. Therefore, in order to have a 95% confidence that the actual realized cost of a containment construction will be within the allocated budget, it is necessary to allocate a contingency of two standard deviations, or of 16.6%. This contingency would be sufficient to cover most of the uncertainty in input costs, which are outside of the control of the constructors. The

uncertainty quantification methodology developed here is now an integral part of the ACCERT methodology.

In summary, substantial improvements have been made to the ACCERT methodology in this work. However, it is also noted that the work on this tool is not complete, and that further efforts can improve the quality and robustness of the cost evaluations performed with the ACCERT tool, as well as expand its applicability beyond reactor systems, to other fuel cycle facilities.

Importantly, future work should also include the comparison of the algorithm's cost predictions with available cost estimates for an advanced reactor design, in order to verify the credibility of the cost models that have already been developed, and that will continue to be developed and improved in the future.

Additionally, the code capabilities should be further improved in order to increase the range of applicability of the tools to advanced reactor designs, to non-reactor fuel cycle facilities, and in general to further increase the robustness, quality and defensibility of the estimates performed with this tool.

The development of additional cost models, beyond the 60 developed so far, can further increase the fidelity of the estimates. However, these efforts will be compensated with progressively lower payoffs, as the development focuses on components with progressively lower cost contributions. Therefore, it is not recommended to prioritize this area of work, and to focus instead on work with a higher payoff, as suggested below.

The robustness, quality and defensibility of some of the most important cost models developed so far should be further improved, especially for the components that contribute a high fractional costs for most advanced designs. For example, several of the large mechanical components, such as the reactor vessels, frequently generate a relatively large fraction on the total direct costs for advanced designs, as was shown in the case of the ABR1000 in Ganda (2018). However, the current costs models for those components are approximate and top-down: i.e. they are primarily based on the weight of the components, and are differentiated only by fabrication materials (e.g. stainless versus carbon steel). This does not allow an adjustment of the fabrication costs with slight changes in component design, for example with modification of the geometry or other parameters. Therefore, the current cost models are insufficient to provide a full set of information to designers and to R&D policy makers, on how to optimize the design of advanced concepts with the objective of minimizing costs. The improvement of the cost models for large mechanical components should be considered a high priority for future work in this area. It is therefore recommended to engage fabricators of large mechanical components, as well as experts in the area of cost of large mechanical parts from other industries, national laboratories and academia, and to utilize their aggregated expertise to develop *bottom-up cost estimates* for large mechanical parts. This development should include all the fabrication steps, and ideally should be detailed enough to be sensitive to changes in design and other relevant parameters. On top of the benefits already discussed, such complete and detailed models would allow a robust application of the uncertainty models developed in this work. This would allow a further improvement of the uncertainty evaluation of the entire, aggregated plants.

An additional benefit of the development of detailed models as described above, is the capability to develop robust estimates for components of advanced reactor designs that have never been fabricated, or that have only been fabricated as prototypes, possibly at different scales or with different materials. This would allow a robust cost estimates, for example, of components which are missing in PWRs, but may be present in other advanced reactor designs, and the extension of the cost approach developed in this work to other nuclear fuel cycle facilities, such as for example reprocessing plants, or remote fabrication facilities. Nevertheless, the work contained in this report allows now complete bottom-up estimates of the cost of non-reactor fuel cycle facilities, including uncertainties in the estimates. Future work may further improve the quality and robustness of such estimates.

Additionally, further work could be performed specifically to adapt the ACCERT algorithm to the unique features of modular plants, and especially small modular plants, for which a high degree of standardization and possibly factory fabrication may reduce the need for indirect costs as compared to standard plants. An approach to estimate indirect costs have not been developed yet in the ACCERT methodology. Additionally, small modular reactors may be fabricated with a higher level of productivity as compared to conventional site-built plants, through the use of more efficient factory settings and modular construction, thus resulting in potentially lower costs. Future work could quantify the productivity enhancement factors that are possible through factory and modular fabrication, and apply those to the cost algorithm, thus enhancing its fidelity for factory-fabricated and modular plants.

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APPENDIX A: COST MODELS FOR SMALL AND MEDIUM-SIZED PUMPS

The cost and technical information of a range of pumps with different designs, materials, and operating parameters was extracted from EEDB (1987) and EEDB (1987b) (shown in Table 35), with the objective of developing a costing approach for small and medium-sized pumps. Cost models for very large primary pumps were previously developed in Section 3.16 of Ganda (2018), where a number of scaling approaches were identified. Among those, scaling with an exponent of 0.52 using the C/H factor (where the C/H factor is the product of the flow rate and of the head), as proposed in Phung (1987), was recommended as the reference costing model for large pumps.

From the data in Table 35, it is observed that the pumps' operating parameters such as pressure, speed, and head, vary over a wide range. Also, the pumps vary in material types (SS – stainless steel, CS - carbon steel), and safety class (NNS – non-nuclear safety; and safety grade).

It is also observed that the pumps featuring the highest unit costs, both in terms of [$/kW] and of [$/(C/H)], are not necessarily made of stainless steel nor featuring a high safety grade. For example, the largest normalized cost is observed for the pumps of account 233.213, which is a non-nuclear safety (NNS) pump and made of mix steels, and for the pump of account 218B.22124, which is also NNS and made of carbon steel. However, both pumps are small in size, which generally is associated with larger unit costs. In fact, the pump of account 218B.22124 is the smallest (at 100 W of power) and has the smallest factory cost of all the pumps in the table.

Table 35 – Pump specifications and cost information from EEDB (1987) for costs and of EEDB (1987b) for the technical specifications.

Account	Mat. [a]	Safety Grade [b]	Flow rate (gal / min)	Feet of head (ft)	C/H (gal-ft/min)	Power (kW)	Actual cost		
							$/kW	$/(C/H) x 1000	Factory cost (in 2017 USD)
226.311	SS	NNS	150	360	54,000	10.2	576	108	5,855
226.4212	SS	NNS	200	210	42,000	7.9	2461	463	19,461
224.1511	SS	NNS	140	330	46,200	8.7	3348	631	29,131
226.7111	SS	C3	13000	170	2,210,000	416	3026	570	1,259,119
226.7211	CS	C3	11000	200	2,200,000	414	1026	193	424,972
218A,23121	CS	NNS	14	85	1,190	0.2	6404	1206	1,435
218B.22123	CS	NNS	230	30	6,900	1.3	3865	728	5,023
218B.22124	CS	NNS	43	15	645	0.1	7798	1468	947
224.1113	SS	NNS	100	300	30,000	5.6	5168	973	29,194
224.1113	SS	NNS	140	250	35,000	6.6	4429	834	29,194
226.4211	SS	NNS	30	320	9,600	1.8	5787	1090	10,461
226.4211	SS	NNS	100	250	25,000	4.7	2222	418	10,461
233.211	Mix	NNS	11100	1100	12,210,000	2299	373	70	858,606
233.213	Mix	NNS	600	40	24,000	4.5	15518	2922	70,131
235.311	Mix	NNS	1600	120	192,000	36.2	1447	272	52,304

[a] SS – Stainless Steel; CS – Carbon Steel; Mix – multiple steel types;
[b] NNS – Non-Nuclear Safety; C3 – Class 3.

Figure 21 shows a plot of the factory costs, normalized to the C/H factor, for the small and medium pumps of Table 35. A general down-ward sloping trend is observed in the normalized costs as the C/H factors increase, even though several points are substantially off the trend-line. For those points, a simple interpolation of the data would obviously yield substantially different values than what is reported in EEDB (1987), even though (as can be observed from the color-coding) the points off the trend-line share similar characteristics as other points that are instead on the trend-line. Therefore, the fact that some points are off the trend-lines cannot be explained simply by differences in material or safety class.

Similar results were obtained when plotting pump costs, or normalized pump costs, as a function of the pump power levels instead of the C/H factors.

Fitting curves are shown in Figure 22 and in Figure 23 for, respectively, the "factory total" and "normalized" costs as a function of the C/H, for the entire set of pumps of Table 35.

One fitting is performed using the 0.52 scaling law proposed by Phung (1987), while a second fitting is an interpolation through all the data. From the second fitting, an exponent of 0.74 is derived for the scaling, which is substantially higher than the 0.52 value proposed by Phung (1987). However, is it also noted that the sample in Table 35 presents a wide range of performance parameters in terms of flow rates, heads, construction materials and nuclear safety classes, for a relatively small numbers of data points: consequently it is difficult to disregard one approach as compared to the other. Additionally, it is not excluded that there could be errors or approximations in the cost values of EEDB (1987) for some of the small and medium pumps of Table 35: for example, a number of smaller pumps over a significant range of operating conditions had identical costs down to the last dollar, which is not expected.

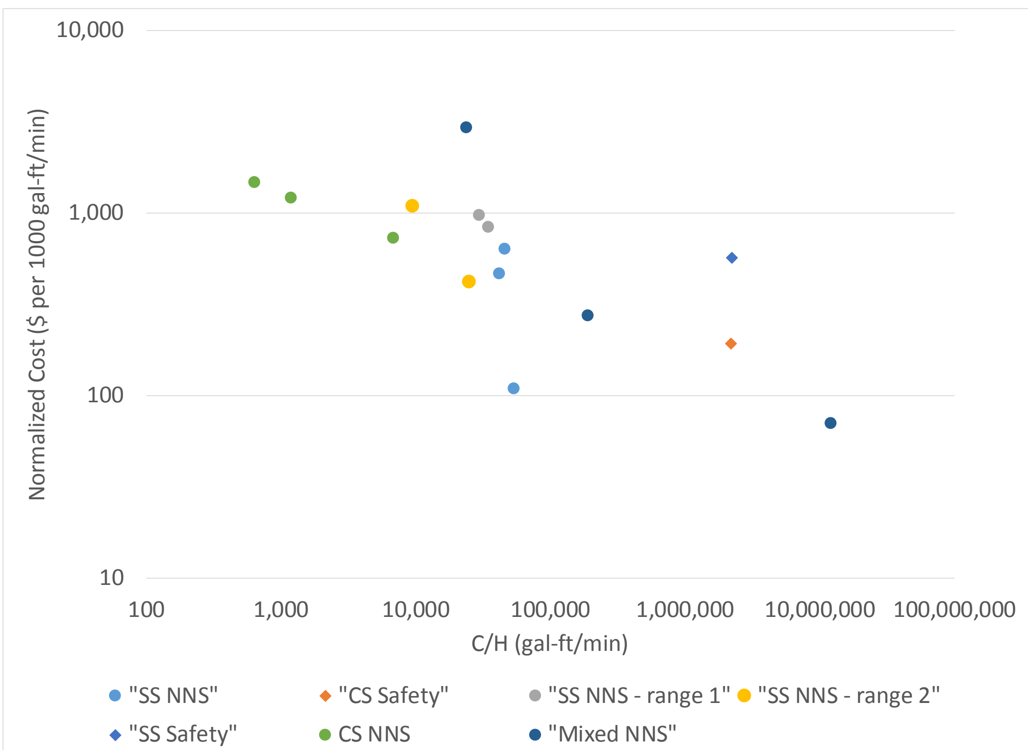

Figure 21 – Normalized pump cost information extracted from the EEDB.

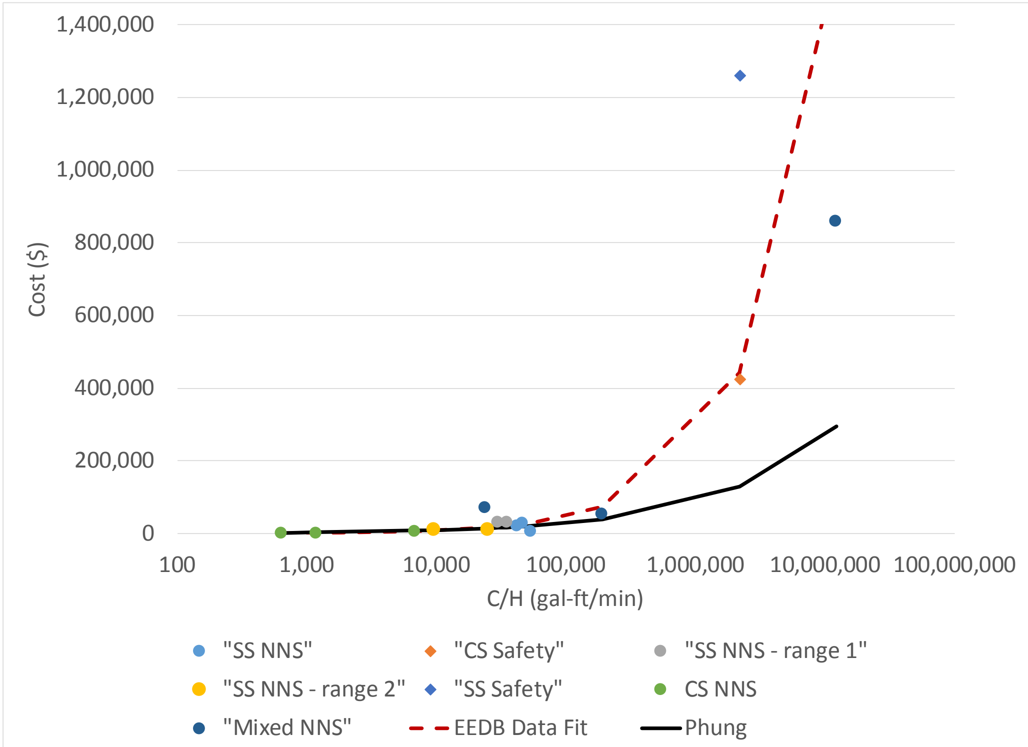

Figure 22 –Pump cost information extracted from the EEDB with curve fits.

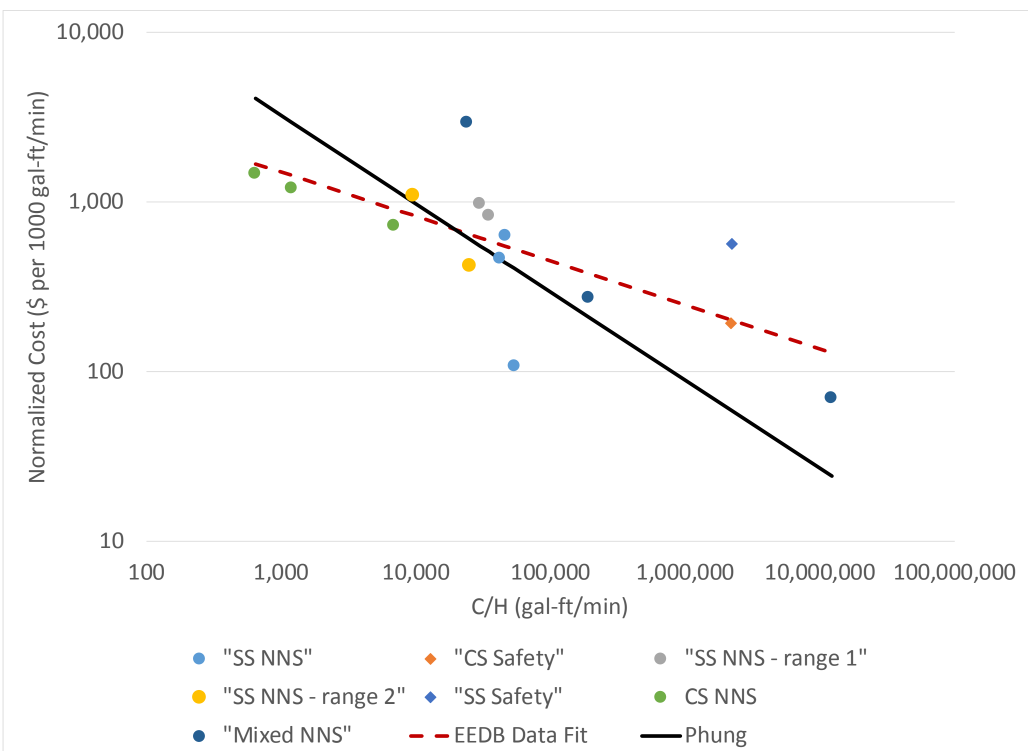

Figure 23 – Normalized pump cost information extracted from the EEDB with curve fits.

In summary, it was realized that the data does not support a simple scaling law or correlation for the cost of pumps.

Therefore, as a preliminary approach, and until more is understood about an effective approach to determine the factory cost of small and medium/sized pumps, it is recommended to select a pump that is closest in terms of C/H, safety class and design to the one for which the cost needs to be estimated, and for which the factory cost is known (for example from EEDB (1987)), and scale this cost with the C/H factor, using an exponent of 0.52, as recommended by Phung (1987), according to the following Equation:

$$C_{pump} = C_{pump,ref}\left(\frac{C/H_{pump}}{C/H_{pump,ref}}\right)^{0.52}$$

Work was initiated in this report on developing cost models for other fuel cycle facilities, with specific focus on fuel fabrication and reprocessing facilities.

APPENDIX B: Time Series Data

Table 36 Average Weekly Wage in Power and Communication System Construction, Current Dollars Not Seasonally Adjusted[f] (BLS 2019)

Year	Qtr1	Qtr2	Qtr3	Qtr4
2001	752	765	769	853
2002	783	806	815	900
2003	816	848	829	915
2004	820	863	899	984
2005	864	896	975	1030
2006	993	973	969	1068
2007	1037	1029	1020	1146
2008	1082	1074	1108	1214
2009	1116	1075	1095	1257
2010	1120	1117	1138	1262
2011	1177	1193	1229	1273
2012	1233	1203	1224	1413
2013	1269	1260	1219	1379
2014	1298	1292	1267	1464
2015	1272	1311	1307	1493
2016	1314	1327	1375	1475
2017	1464	1397	1445	1539
2018	1526	1461	1462	

Table 37 Producer Price Index by Commodity for Construction: New Industrial Building Construction, Base year 2007, not seasonally adjusted (BLS 2019)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2007						100.0	100.7	100.8	100.7	102.5	102.5	102.4
2008	102.8	102.8	102.8	103.2	103.1	103.1	105.7	105.7	105.8	110.5	110.4	110.4
2009	111.8	111.8	110.9	109.4	109.4	108.5	105.5	105.2	105.1	105.7	105.5	105.2
2010	105.3	105.2	105.0	105.2	105.2	105.0	105.4	105.4	105.3	105.7	105.7	105.7
2011	105.9	105.5	105.5	106.4	106.4	106.4	107.9	107.8	107.7	109.3	109.2	109.0
2012	109.7	109.7	109.9	110.4	110.2	110.2	110.1	110.2	109.9	110.4	110.5	110.5
2013	111.2	111.2	111.2	111.9	111.9	112.0	112.6	112.7	112.9	114.9	114.9	115.0
2014	115.6	115.6	115.6	115.8	115.9	116.0	116.6	116.6	116.6	117.2	117.3	117.1
2015	117.8	117.9	117.9	117.8	118.1	118.0	119.0	118.9	118.7	119.5	119.6	119.7
2016	119.3	119.3	119.3	120.0	119.6	119.4	118.5	118.5	118.6	119.7	119.7	119.7
2017	120.2	120.2	120.3	121.1	121.1	121.1	123.7	123.5	123.5	124.3	124.3	124.5
2018	125.6	125.6	125.6	127.0	127.0	127.2	128.0	128.0	128.1	131.5	132.0	131.8
2019	132.9	133.0	133.0									

[f] Seasonality can be observed directly in this series by comparing the index across quarters. Weekly wages rise steadily from Quarter 1 through Quarter 4, and then in the following year Quarter 1 begins the year lower than the previous quarter. A consistent pattern like this is exactly why adjusting data for seasonality is necessary, which was conducted in analysis and described in the text. Notice that the raw data provided by BLS for this series are not seasonally adjusted. In this case Quarter 4 is consistently greater than the previous quarters of the same year. While the BLS does not directly explain this, one could postulate that the reason for this may have something to do with year-end or holiday bonuses. This supposition can be supported by the fact that if one where to remove Quarter 4 from the series, the increase in the index from Quarter 3 to Quarter 1 of the following year appears consistent

Table 38 Industrial Production: Durable Goods: Cement, Index 2012=100, Seasonally Adjusted (FRED 2019)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1972	156.0	149.8	148.8	150.3	147.8	146.9	147.4	150.8	150.1	148.2	138.4	138.1
1973	151.4	156.3	155.2	150.1	153.9	151.7	155.8	155.7	151.4	153.5	159.3	159.9
1974	156.3	163.8	165.1	167.6	162.8	162.4	154.0	151.8	155.6	155.8	143.5	145.9
1975	145.1	129.2	118.7	120.1	127.0	130.3	135.4	135.5	137.4	138.1	134.3	133.2
1976	132.5	139.3	136.2	137.4	132.4	131.1	133.0	135.0	132.9	127.1	131.0	128.6
1977	110.5	132.2	143.1	147.9	147.9	146.2	144.2	141.7	141.4	143.9	143.8	144.2
1978	119.9	122.1	140.4	154.9	159.8	162.5	158.5	158.6	156.4	159.8	157.5	161.7
1979	126.7	124.2	142.8	149.5	157.5	160.8	160.8	161.4	160.2	161.6	161.1	165.1
1980	160.4	152.4	134.7	135.5	135.0	137.0	136.4	135.9	138.3	139.7	139.3	142.1
1981	141.9	138.9	139.3	137.9	126.7	118.9	119.8	118.1	118.1	113.9	118.5	115.9
1982	106.7	113.1	114.4	113.0	114.7	114.9	114.8	115.4	116.1	115.5	110.0	111.5
1983	124.3	115.9	110.3	107.8	112.0	117.4	119.0	119.1	119.4	121.3	120.4	108.2
1984	119.3	139.8	126.9	126.2	127.5	128.1	127.4	129.0	126.7	124.4	129.1	126.0
1985	123.7	124.1	130.2	133.4	133.0	129.3	128.7	127.6	127.7	124.9	116.4	117.2
1986	142.9	131.3	128.1	126.3	122.8	122.4	123.0	125.0	124.6	126.7	124.1	128.1
1987	133.4	132.9	132.2	133.2	133.6	133.0	137.3	132.3	135.2	137.4	137.3	134.4
1988	120.5	128.9	134.7	133.0	135.8	136.8	130.5	129.3	130.8	130.5	130.9	137.0
1989	143.2	124.0	124.9	128.8	127.4	126.7	127.2	133.5	130.3	133.8	135.4	124.0
1990	148.9	145.6	143.0	137.2	133.6	132.7	131.9	129.0	128.0	122.6	125.7	117.1
1991	109.5	117.1	113.6	112.3	112.3	114.3	116.5	115.6	116.9	117.3	112.1	116.7
1992	120.2	119.1	119.1	122.2	122.5	121.6	120.9	120.6	121.5	123.3	112.8	113.1
1993	112.8	112.6	111.1	112.5	116.4	116.7	118.2	119.0	117.8	118.5	120.8	121.5
1994	114.4	113.2	126.0	126.1	129.2	128.1	126.7	128.5	131.0	128.2	133.5	139.0
1995	136.6	134.7	137.5	132.4	129.1	134.0	134.8	135.5	136.2	138.1	138.0	136.2
1996	133.5	133.9	132.8	140.3	140.6	139.4	138.3	140.4	136.8	138.9	136.0	133.8
1997	134.9	142.7	147.8	147.2	144.7	146.1	149.1	149.3	154.8	154.3	151.4	151.9
1998	154.7	150.1	148.1	148.8	150.0	149.7	152.9	150.2	152.5	149.9	154.5	161.8
1999	154.5	158.5	151.2	146.4	144.3	144.4	142.1	143.7	141.7	147.4	160.4	160.2
2000	156.1	155.3	163.6	153.4	155.0	152.1	151.5	155.3	153.4	154.7	148.2	140.7
2001	150.5	155.3	159.2	164.7	161.5	158.6	159.4	156.8	154.5	158.0	163.2	161.3
2002	166.3	165.5	156.2	153.9	153.0	156.2	154.4	153.7	155.3	151.6	152.8	146.9
2003	157.1	141.0	150.7	154.7	155.0	158.0	163.7	164.5	167.2	174.9	169.2	172.8
2004	164.8	161.6	182.4	184.5	180.1	173.8	178.4	178.4	177.6	172.3	168.2	178.2
2005	175.2	179.7	177.6	173.1	177.5	177.5	169.9	171.4	172.8	174.5	180.0	183.5
2006	207.2	202.0	188.8	178.9	173.2	173.9	164.8	165.7	161.7	162.9	165.3	180.9
2007	172.8	165.2	166.4	164.6	166.7	161.8	162.3	160.8	161.5	159.4	163.4	156.4
2008	160.2	156.6	152.8	152.8	148.4	145.3	145.6	136.4	132.2	127.8	119.2	111.9
2009	102.7	105.3	93.8	88.4	85.1	85.0	86.0	83.3	82.4	73.1	80.1	75.3
2010	73.8	71.5	80.1	90.2	87.5	86.2	84.2	87.2	87.0	89.4	89.2	86.6
2011	85.2	89.3	86.6	86.5	89.6	92.3	93.5	95.4	94.4	95.3	94.6	99.6
2012	103.4	102.9	101.0	102.3	100.1	98.6	97.1	97.2	96.8	98.6	103.4	103.7
2013	106.7	108.7	108.7	103.2	107.4	109.2	110.0	111.2	113.4	111.4	107.8	106.6
2014	104.0	103.9	105.7	107.5	111.1	109.9	113.0	111.7	114.9	116.2	108.2	116.7
2015	117.1	106.9	106.6	111.9	113.7	116.6	122.2	123.3	123.0	121.0	119.7	127.0
2016	123.5	126.0	126.0	116.3	114.2	117.8	113.5	113.5	114.7	116.7	119.1	117.0
2017	119.2	127.7	123.5	119.2	118.6	119.1	117.7	117.6	117.5	119.0	122.7	123.5
2018	122.4	121.9	121.6	124.0	126.6	121.9	122.5	122.5	118.9	118.2	114.1	116.7
2019	120.3											

Table 39 Industrial Production: Durable Goods: Raw steel, Index 2012=100, Monthly, Seasonally Adjusted (FRED 2019)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1972	115.72	122.16	133.30	136.77	138.63	135.61	130.19	137.07	137.72	139.31	143.72	152.49
1973	151.20	154.72	153.06	155.36	157.54	160.14	160.41	162.13	165.58	166.29	173.74	182.96
1974	174.90	172.72	172.22	172.92	176.90	177.71	182.79	177.06	178.86	180.26	172.47	163.33
1975	161.50	160.95	155.16	136.92	125.93	113.99	113.23	114.77	121.90	116.47	116.02	118.43
1976	124.35	127.82	130.73	134.95	137.36	138.93	141.56	139.22	134.82	126.48	126.17	124.72
1977	118.48	123.57	135.01	137.85	145.48	142.91	134.85	136.26	135.44	135.02	134.55	137.09
1978	135.52	133.30	131.99	138.49	146.15	145.57	147.17	150.23	153.47	155.46	160.08	158.31
1979	144.92	145.96	148.82	149.97	155.15	159.62	161.50	156.69	151.38	148.14	145.50	141.11
1980	147.44	146.39	143.96	141.98	120.64	106.47	99.76	103.06	117.61	134.04	150.55	143.95
1981	143.25	142.94	140.77	142.05	142.77	137.70	139.53	137.59	137.10	123.43	120.75	112.20
1982	109.14	104.58	98.99	90.92	83.42	79.61	76.04	72.61	70.44	65.63	62.09	56.48
1983	66.34	69.02	73.76	75.29	78.70	79.02	79.65	82.37	83.64	87.23	89.98	92.13
1984	89.09	91.89	91.87	94.68	99.22	92.37	88.09	83.43	80.10	80.03	78.58	71.34
1985	78.26	79.37	81.78	78.71	79.20	78.36	77.57	79.06	78.95	79.11	79.36	74.80
1986	82.92	81.74	79.96	79.25	76.48	74.82	73.81	67.29	67.29	70.41	71.15	70.38
1987	71.52	73.21	77.82	81.91	83.72	86.90	88.07	91.57	96.63	96.83	99.91	101.34
1988	98.31	98.21	99.07	97.63	102.63	99.36	104.59	102.46	104.89	98.79	98.72	99.43
1989	101.17	100.21	99.98	97.68	94.94	95.50	91.65	90.47	88.25	90.17	86.87	85.88
1990	89.42	90.73	91.60	91.93	94.21	95.19	93.40	98.73	94.81	94.93	94.50	88.68
1991	86.07	82.33	80.28	80.42	79.54	81.47	85.61	86.76	87.39	86.67	86.65	87.12
1992	86.61	87.44	88.81	90.58	89.20	88.40	87.84	86.07	85.86	86.32	87.24	87.42
1993	88.02	89.08	87.47	88.05	90.06	90.88	92.01	91.14	90.58	92.50	90.78	93.66
1994	88.48	91.46	91.82	92.35	93.29	93.47	93.24	94.32	96.05	96.20	98.66	102.67
1995	99.08	100.12	99.57	97.98	96.47	96.18	96.12	97.22	100.70	96.40	99.88	99.43
1996	97.94	97.06	98.58	97.52	98.14	100.76	99.43	98.99	98.23	98.30	96.19	99.01
1997	97.24	97.22	98.63	98.54	97.94	98.47	98.83	98.71	101.73	102.48	106.24	106.13
1998	107.98	108.75	106.32	107.74	106.76	102.92	104.00	106.06	100.33	98.66	92.80	94.66
1999	97.01	96.25	98.71	98.13	99.21	97.24	96.81	99.63	96.75	104.57	108.62	109.09
2000	105.27	99.86	102.85	103.38	102.98	101.44	99.73	96.91	93.93	93.72	89.58	89.23
2001	91.04	91.46	92.22	85.99	93.74	93.16	94.52	92.16	91.85	87.34	83.87	76.06
2002	87.96	88.47	87.58	87.86	88.79	91.73	92.21	95.35	94.68	93.52	93.17	92.46
2003	90.49	90.67	89.72	91.59	85.68	89.42	85.79	85.24	86.23	90.45	93.63	97.65
2004	94.45	95.09	98.72	98.28	99.91	101.58	104.44	105.93	103.55	105.64	105.77	107.92
2005	105.08	102.01	99.42	97.84	96.20	91.12	89.01	93.39	98.12	98.63	101.53	100.68
2006	100.57	101.41	104.84	104.43	107.01	105.99	103.62	104.10	103.92	98.42	95.59	89.11
2007	94.95	99.61	98.59	100.64	102.02	103.84	103.28	103.66	100.24	108.28	113.05	117.21
2008	118.57	117.63	117.62	118.97	121.97	120.23	125.63	126.16	116.89	102.84	77.33	64.37
2009	65.06	69.51	57.84	56.43	62.34	65.04	77.03	84.08	88.31	85.93	88.87	86.12
2010	91.91	96.30	100.99	101.25	100.35	99.57	95.47	94.14	95.82	95.15	96.10	97.58
2011	101.97	104.73	102.28	102.17	100.37	102.25	103.73	103.33	103.57	102.13	103.17	107.95
2012	103.53	104.57	102.58	106.01	102.69	97.92	97.16	100.09	94.36	92.50	96.04	100.89
2013	98.69	98.89	98.23	98.19	99.81	99.24	102.62	101.77	104.00	103.47	102.54	99.81
2014	98.43	98.55	99.06	99.80	99.53	101.00	102.16	101.26	101.94	103.29	103.65	103.42
2015	100.64	93.47	87.42	90.80	91.82	94.37	95.75	93.01	91.38	91.02	83.78	84.37
2016	86.68	87.96	88.79	89.73	90.24	90.62	88.03	87.62	87.69	86.54	88.75	90.05
2017	93.41	93.25	92.16	93.63	92.18	91.93	92.89	93.56	93.62	94.25	95.59	96.49
2018	96.10	97.91	99.66	98.61	100.12	97.36	101.43	101.42	104.04	106.41	105.92	106.45
2019	101.88											

Table 40 Producer Price Index by Industry: Welding and Soldering Equipment Manufacturing: Arc Welding Electrodes, Metal, Index Dec 1984=100, Monthly, Not Seasonally Adjusted (FRED 2019)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1972	115.72	122.16	133.30	136.77	138.63	135.61	130.19	137.07	137.72	139.31	143.72	152.49
1973	151.20	154.72	153.06	155.36	157.54	160.14	160.41	162.13	165.58	166.29	173.74	182.96
1974	174.90	172.72	172.22	172.92	176.90	177.71	182.79	177.06	178.86	180.26	172.47	163.33
1975	161.50	160.95	155.16	136.92	125.93	113.99	113.23	114.77	121.90	116.47	116.02	118.43
1976	124.35	127.82	130.73	134.95	137.36	138.93	141.56	139.22	134.82	126.48	126.17	124.72
1977	118.48	123.57	135.01	137.85	145.48	142.91	134.85	136.26	135.44	135.02	134.55	137.09
1978	135.52	133.30	131.99	138.49	146.15	145.57	147.17	150.23	153.47	155.46	160.08	158.31
1979	144.92	145.96	148.82	149.97	155.15	159.62	161.50	156.69	151.38	148.14	145.50	141.11
1980	147.44	146.39	143.96	141.98	120.64	106.47	99.76	103.06	117.61	134.04	150.55	143.95
1981	143.25	142.94	140.77	142.05	142.77	137.70	139.53	137.59	137.10	123.43	120.75	112.20
1982	109.14	104.58	98.99	90.92	83.42	79.61	76.04	72.61	70.44	65.63	62.09	56.48
1983	66.34	69.02	73.76	75.29	78.70	79.02	79.65	82.37	83.64	87.23	89.98	92.13
1984	89.09	91.89	91.87	94.68	99.22	92.37	88.09	83.43	80.10	80.03	78.58	71.34
1985	78.26	79.37	81.78	78.71	79.20	78.36	77.57	79.06	78.95	79.11	79.36	74.80
1986	82.92	81.74	79.96	79.25	76.48	74.82	73.81	67.29	67.29	70.41	71.15	70.38
1987	71.52	73.21	77.82	81.91	83.72	86.90	88.07	91.57	96.63	96.83	99.91	101.34
1988	98.31	98.21	99.07	97.63	102.63	99.36	104.59	102.46	104.89	98.79	98.72	99.43
1989	101.17	100.21	99.98	97.68	94.94	95.50	91.65	90.47	88.25	90.17	86.87	85.88
1990	89.42	90.73	91.60	91.93	94.21	95.19	93.40	98.73	94.81	94.93	94.50	88.68
1991	86.07	82.33	80.28	80.42	79.54	81.47	85.61	86.76	87.39	86.67	86.65	87.12
1992	86.61	87.44	88.81	90.58	89.20	88.40	87.84	86.07	85.86	86.32	87.24	87.42
1993	88.02	89.08	87.47	88.05	90.06	90.88	92.01	91.14	90.58	92.50	90.78	93.66
1994	88.48	91.46	91.82	92.35	93.29	93.47	93.24	94.32	96.05	96.20	98.66	102.67
1995	99.08	100.12	99.57	97.98	96.47	96.18	96.12	97.22	100.70	96.40	99.88	99.43
1996	97.94	97.06	98.58	97.52	98.14	100.76	99.43	98.99	98.23	98.30	96.19	99.01
1997	97.24	97.22	98.63	98.54	97.94	98.47	98.83	98.71	101.73	102.48	106.24	106.13
1998	107.98	108.75	106.32	107.74	106.76	102.92	104.00	106.06	100.33	98.66	92.80	94.66
1999	97.01	96.25	98.71	98.13	99.21	97.24	96.81	99.63	96.75	104.57	108.62	109.09
2000	105.27	99.86	102.85	103.38	102.98	101.44	99.73	96.91	93.93	93.72	89.58	89.23
2001	91.04	91.46	92.22	85.99	93.74	93.16	94.52	92.16	91.85	87.34	83.87	76.06
2002	87.96	88.47	87.58	87.86	88.79	91.73	92.21	95.35	94.68	93.52	93.17	92.46
2003	90.49	90.67	89.72	91.59	85.68	89.42	85.79	85.24	86.23	90.45	93.63	97.65
2004	94.45	95.09	98.72	98.28	99.91	101.58	104.44	105.93	103.55	105.64	105.77	107.92
2005	105.08	102.01	99.42	97.84	96.20	91.12	89.01	93.39	98.12	98.63	101.53	100.68
2006	100.57	101.41	104.84	104.43	107.01	105.99	103.62	104.10	103.92	98.42	95.59	89.11
2007	94.95	99.61	98.59	100.64	102.02	103.84	103.28	103.66	100.24	108.28	113.05	117.21
2008	118.57	117.63	117.62	118.97	121.97	120.23	125.63	126.16	116.89	102.84	77.33	64.37
2009	65.06	69.51	57.84	56.43	62.34	65.04	77.03	84.08	88.31	85.93	88.87	86.12
2010	91.91	96.30	100.99	101.25	100.35	99.57	95.47	94.14	95.82	95.15	96.10	97.58
2011	101.97	104.73	102.28	102.17	100.37	102.25	103.73	103.33	103.57	102.13	103.17	107.95
2012	103.53	104.57	102.58	106.01	102.69	97.92	97.16	100.09	94.36	92.50	96.04	100.89
2013	98.69	98.89	98.23	98.19	99.81	99.24	102.62	101.77	104.00	103.47	102.54	99.81
2014	98.43	98.55	99.06	99.80	99.53	101.00	102.16	101.26	101.94	103.29	103.65	103.42
2015	100.64	93.47	87.42	90.80	91.82	94.37	95.75	93.01	91.38	91.02	83.78	84.37
2016	86.68	87.96	88.79	89.73	90.24	90.62	88.03	87.62	87.69	86.54	88.75	90.05
2017	93.41	93.25	92.16	93.63	92.18	91.93	92.89	93.56	93.62	94.25	95.59	96.49
2018	96.10	97.91	99.66	98.61	100.12	97.36	101.43	101.42	104.04	106.41	105.92	106.45
2019	101.88											

APPENDIX C: Correlation Scatterplots

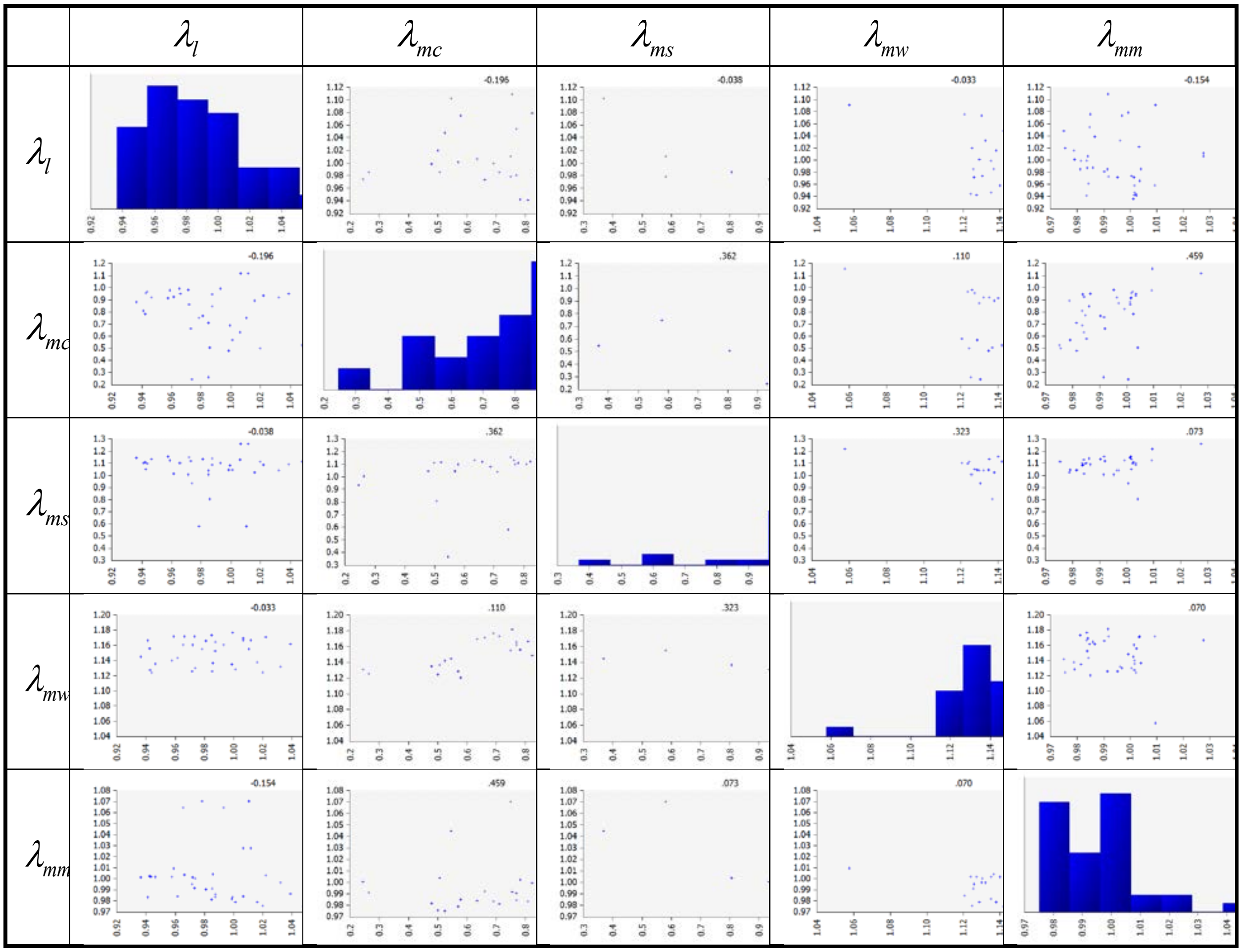

Figure 24 Correlation scatterplots of modeled input cost uncertainty distributions

APPENDIX D: Matlab code to perform the correlated sampling of the containment costs

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% Auth. Francesco Ganda
% Iman Conover rank correlation approach
% Updated by Francesco Ganda ANL - 5/14/2019

clear all; close all;

Cost_Labor     = 101.95; % million USD
Cost_Materials = 7.58;   % million USD
Cost_Concrete  =  4.53;  % million USD
Cost_Steel     = 68.03;  % million USD
Cost_Welding   =  3.79;  % million USD

Total_cost= Cost_Labor + Cost_Materials + Cost_Concrete + Cost_Steel + Cost_Welding;

N=5e5;
k=zeros(N,5); % Un-correlated samples
K=zeros(N,5); % Correlated samples

% How to automatically generate a correlation matrix with 5 elements and 0.7 on all non-diagonal
elements
% C = ones(5)*0.7 + eye(5)*(1-0.7);
% Un-correlated matrix
% C=eye(5);

% Correlation Matrix from Table 30
%   labor     concrete   steel     welding  materials
C=[   1        -0.196     -0.038  -0.033    -0.154;...     % labor
    -0.196       1          0.362   0.110     0.459;...     % concrete
    -0.038      0.362       1       0.323     0.073;...     % steel
    -0.033      0.110      0.323     1        0.070;...     % welding
    -0.154      0.459      0.073    0.070      1  ];        %  materials

% Create and sort, randomly, vectors of integers
% sort by rows according to the 2nd columns, which are the random numbers
R_unsorted=[1:N]';
pos1=rand(N,1);       ip1=[R_unsorted,pos1];      Rc1=sortrows(ip1,2);
pos2=rand(N,1);       ip2=[R_unsorted,pos2];      Rc2=sortrows(ip2,2);
pos3=rand(N,1);       ip3=[R_unsorted,pos3];      Rc3=sortrows(ip3,2);
pos4=rand(N,1);       ip4=[R_unsorted,pos4];      Rc4=sortrows(ip4,2);
pos5=rand(N,1);       ip5=[R_unsorted,pos5];      Rc5=sortrows(ip5,2);

R_i=[Rc1(:,1),Rc2(:,1),Rc3(:,1),Rc4(:,1),Rc5(:,1)];
disp('Correlation matrix of the sampled rank correlation matrix R; desired to have non-diagonal
elements = 0');
T=corrcoef(R_i);  disp(T);    % Should be close to I, T used for the variance reduction method

R=sqrt(2)*erfinv(2*(R_i./(N+1))-1);

% Cholesky decomposition
P=chol(C,'lower');

% ------------------ approximate matrix
R_ast_a=R*P';
disp('Correlation matrix of the sampled rank correlation matrix R*; before variance reduction');
T_ast_a=corrcoef(R_ast_a);  disp(T_ast_a);      % just for checking
% ------------------

% ------------------ Variance reduction technique
Q=chol(T,'lower');
S=P/Q;
R_ast=R*S';
disp('Correlation matrix of the sampled rank correlation matrix R*; after variance reduction');
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T_ast=corrcoef(R_ast);  disp(T_ast);


% ------------------ generate the samplings (uncorrelated) ----------------------
% % Distribution 1: Labor
mean_lognorm = Cost_Labor * 1.0;
std_lognorm = mean_lognorm * 0.04679; % from Table 30
 sigma = sqrt (log(std_lognorm^2/exp(2*log(mean_lognorm))+1) );
 mu    = log(mean_lognorm)- sigma^2/2;
for i=1:N,
    U=randn;
    X= exp(mu+sigma*U);
    k(i,1)=X;
end


% % Distribution 2: Concrete (Materials)
mean_lognorm = Cost_Concrete * 1.0;
std_lognorm = mean_lognorm * 0.18014; % from Table 30
 sigma = sqrt (log(std_lognorm^2/exp(2*log(mean_lognorm))+1) );
 mu    = log(mean_lognorm)- sigma^2/2;
for i=1:N,
    U=randn;
    X= exp(mu+sigma*U);
    k(i,2)=X;
end


% % Distribution 3: Steel (Materials)
mean_lognorm = Cost_Steel * 1.0;
std_lognorm = mean_lognorm * 0.2086; % from % from Table 30
 sigma = sqrt (log(std_lognorm^2/exp(2*log(mean_lognorm))+1) );
 mu    = log(mean_lognorm)- sigma^2/2;
for i=1:N,
    U=randn;
    X= exp(mu+sigma*U);
    k(i,3)=X;
end


% % Distribution 4: Welding (Materials)
mean_lognorm = Cost_Welding * 1.0;
std_lognorm = mean_lognorm * 0.3079; % from % from Table 30
 sigma = sqrt (log(std_lognorm^2/exp(2*log(mean_lognorm))+1) );
 mu    = log(mean_lognorm)- sigma^2/2;
for i=1:N,
    U=randn;
    X= exp(mu+sigma*U);
    k(i,4)=X;
end

% % Distribution 5: Materials (Materials)
mean_lognorm = Cost_Materials * 1.0;
std_lognorm = mean_lognorm * 0.02236; % from % from Table 30
 sigma = sqrt (log(std_lognorm^2/exp(2*log(mean_lognorm))+1) );
 mu    = log(mean_lognorm)- sigma^2/2;
for i=1:N,
    U=randn;
    X= exp(mu+sigma*U);
    k(i,5)=X;
end

% --------------- end of sampling ----------------------


% ---- sorting to match correlation matrix -----------------

k_sorted = sort(k); % each element sorted in ascending order
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disp('Correlation matrix of the final (un-sorted) sampled data:');
T_k=corrcoef(k);  disp (T_k);    % just for checking

% creates a Kx matrix the first columns of which are "correctly" sorted
R_pos1 = [R_ast(:,1),R_unsorted]; R_pos_sorted1 = sortrows(R_pos1,1);
R_pos2 = [R_ast(:,2),R_unsorted]; R_pos_sorted2 = sortrows(R_pos2,1);
R_pos3 = [R_ast(:,3),R_unsorted]; R_pos_sorted3 = sortrows(R_pos3,1);
R_pos4 = [R_ast(:,4),R_unsorted]; R_pos_sorted4 = sortrows(R_pos4,1);
R_pos5 = [R_ast(:,5),R_unsorted]; R_pos_sorted5 = sortrows(R_pos5,1);
for i=1:N,
    K(R_pos_sorted1(i,2),1)=k_sorted(i,1);
    K(R_pos_sorted2(i,2),2)=k_sorted(i,2);
    K(R_pos_sorted3(i,2),3)=k_sorted(i,3);
    K(R_pos_sorted4(i,2),4)=k_sorted(i,4);
    K(R_pos_sorted5(i,2),5)=k_sorted(i,5);
end

disp('Correlation matrix of the final (sorted) sampled data:');
T_K=corrcoef(K); disp (T_K);
figure; plot(K(:,2),K(:,3),'.'); title('Scatter plot of the cost of concrete and steel materials
(Rho=0.36)'); xlabel('Cost of concrete (millions of 2017 USD)'); ylabel('Cost of steel (millions
of 2017 USD)')
figure; plot(K(:,1),K(:,2),'.'); title('Scatter plot of the cost of labor and concrete materials
(Rho=-0.19)'); xlabel('Cost of labor (millions of 2017 USD)'); ylabel('Cost of concrete (millions
of 2017 USD)')

%   labor  materials   concrete steel welding
figure; hist(K(:,1),100); xlabel('Total Labor Cost [Million of USD]');
ylabel('Frequency');
set(gca,'XScale','lin','YScale','lin','Box','on','Xlim',[0.7*Cost_Labor,Cost_Labor*1.3]);%,'YTick
Label',[],'YTick',[]);
figure; hist(K(:,2),100); xlabel('Total Concrete Materials Cost [Million of USD]');
ylabel('Frequency');
set(gca,'XScale','lin','YScale','lin','Box','on','Xlim',[0.01*Cost_Concrete,Cost_Concrete*2.0]);%
,'YTickLabel',[],'YTick',[]);
figure; hist(K(:,3),100); xlabel('Total Steel Materials Cost [Million of USD]');
ylabel('Frequency');
set(gca,'XScale','lin','YScale','lin','Box','on','Xlim',[0.01*Cost_Steel,Cost_Steel*2.0]);%,'YTic
kLabel',[],'YTick',[]);
figure; hist(K(:,4),100); xlabel('Total Welding Materials Cost [Million of USD]');
ylabel('Frequency');
set(gca,'XScale','lin','YScale','lin','Box','on','Xlim',[0.01*Cost_Welding,Cost_Welding*2.0]);%,'
YTickLabel',[],'YTick',[]);
figure; hist(K(:,5),100); xlabel('Total Other Materials Cost [Million of USD]');
ylabel('Frequency');
set(gca,'XScale','lin','YScale','lin','Box','on','Xlim',[0.7*Cost_Materials,Cost_Materials*1.3]);
%,'YTickLabel',[],'YTick',[]);
K_save=K';
eval(['save Corr_5distrib.prt K_save -ASCII']);


Containment_cost=sum(K_save);
figure; hist(Containment_cost,100); title('Total Containment cost frequency distribution');
set(gca,'XScale','lin','YScale','lin','Box','on','Xlim',[Total_cost*0.7,Total_cost*1.3]);%,'YTick
Label',[],'YTick',[]);
disp(['Mean Containment Cost: ',num2str(mean(Containment_cost))]);
disp(['Standard Deviation of the Containment Cost: ',num2str(std(Containment_cost))]);
xlabel('Total Containment Cost [Million of USD]'); ylabel('Frequency');
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