Small Modular Nuclear Reactors:
Parametric Modeling of Integrated Reactor Vessel Manufacturing Within
A Factory Environment
Volume 1

Xuan Chen, Arnold Kotlyarevsky, Andrew Kumiega,
Jeff Terry, and Benxin Wu
Illinois Institute of Technology

Stephen Goldberg and Edward A. Hoffman
Argonne National Laboratory

August 2013

This study continued the work, supported by the Department of Energy's Office of Nuclear Energy, regarding the economic analysis of small modular reactors (SMRs). The study team analyzed, in detail, the costs for the production of factory-built components for an SMR economy for a pressurized-water reactor (PWR) design. The modeling focused on the components that are contained in the Integrated Reactor Vessel (IRV). Due to the maturity of the nuclear industry and significant transfer of knowledge from the gigawatt (GW)-scale reactor production to the small modular reactor economy, the first complete SMR facsimile design would have incorporated a significant amount of learning (averaging about 80% as compared with a prototype unit). In addition, the order book for the SMR factory and the lot size (i.e., the magnitude of IRV units produced per dedicated manufacturing simulation run) remain a key aspect of judging the economic viability of SMRs. Assuming a minimum lot size of five or about 500 MWe, the average production cost of the first-of-the kind IRV units are projected to average about 65% of the cost of the first prototype IRV unit (the Lead unit) that would not have incorporated any learning. This cost efficiency could be a key factor in the competiveness of SMRs for both U.S. and foreign deployments.

DISCLAIMER

Overview:

By Dr. Robert Rosner

The paper is the fourth in a series of papers prepared by the Institute discussing the economic issues pertaining to future nuclear deployments. This paper focuses on the learning process for small modular reactors (SMRs).

In November 2011, we published a technical paper that analyzed the economic and financial aspects of SMRs and suggested policy options regarding incentivizing SMRs ("Small Modular Reactors – Key to Future Nuclear Power Generation in the U.S." (Available at: https://csis.org/files/attachments/111129_SMR_White_Paper.pdf).

Nuclear power continues to offer the potential as a major worldwide, scalable, carbon-free energy source, but only if the challenges of safety, nonproliferation, waste management and economic competitiveness are addressed.

It is believed that small modular nuclear reactors (SMRs) may be able to increase the size of the commercial nuclear reactor market by providing a smaller financial barrier to entry. However, little work on SMRs has focused on the industrial engineering aspects of the SMR industry. The goal of this study is to analyze the learning for the production of factory built components contained within the Integrated Reactor Vessel (IRV) of an SMR, using conventional learning modeling tools. The study participants recognize that new approaches in industrial modeling practices, that incorporates advanced manufacturing operations, would provide further insights into the learning process.

The study developed focused on a 100 megawatt electrical (MWe) model design based on current U.S. SMR designs, using pressurized-water technology. To be economically viable, the U.S. SMR manufacturing industry needs to demonstrate sufficient scale at its facilities as well as significant learning transfer from the existing naval reactor and commercial gigawatt-scale (GW-scale) fabrication operations. The combination of effectively climbing the learning curve and adaptation of modern advanced manufacturing technologies, will be essential in making a potential U.S. nuclear reactor industry cost-competitive in the international marketplace.

Executive Summary

In November 2011, The Energy Policy Institute at the University of Chicago in partnership with Argonne National Laboratory analyzed the economic and financial aspects of SMRs and suggested policy options regarding incentivizing SMRs ("Small Modular Reactors Key to Future Nuclear Power Generation in the U.S." available at: https://csis.org/files/attachments/111129_SMR_White_Paper.pdf).

During this analysis, a learning curve for SMRs was derived based on bounding analysis. The analysis performed at that time concluded that manufacture at scale a series of SMRs is a critical step to achieve commercial viability. However, little work on SMRs has focused on the industrial engineering aspects of the SMR industry[1]. As such, the Argonne study team planned during 2012-2013 to expand the research to analyze further SMR-product architecture, designated as Phase II of the research. The goal of the Phase II study is to analyze in detail the learning for the production of factory- built components contained within the Integrated Reactor Vessel (IRV) of an SMR. The study participants recognize that building upon new approaches in industrial modeling practices could provide further insights into the learning process.

For Phase II of the analysis, Argonne National Laboratory in partnership with the nuclear and industrial engineering expertise at Illinois Institute of Technology performed a detailed analysis. The study team confirmed the bounding analysis that was analyzed in Phase I[2]. The study team also has identified the following key findings:

- The SMR economy is essentially driven by the degree of learning transfer ascribed to the GW-scale industry; in aggregate, if significant learning transfer occurs, approximately 25% cost savings can be achieved in the manufacturing of the first lot of IRVs at a dedicated IRV manufacturing facility. The study team did not have access to the database of the naval reactor program during the course of this study. Because existing spare capacity, that services the naval reactor program, might be utilized to produce SMR IRV subcomponents, additional learning effects could occur; however this additional analysis was beyond the scope of the study.

- Two subcomponents of the IRV unit, the reactor core and the steam generator tubes, are representative of nuclear technology that is the most amenable to learning transfer from the GW-scale design and manufacturing process. The control rod drive mechanisms and the reactor vessel are representative of nuclear technology that is the least amenable to learning transfer.

- Scale economics at the SMR factory remains as a fundamental requirement for a viable SMR industry; due to the scale earned from achieving a lot size of five (based on the modeling assumptions, this represents 500 MWe of SMR capacity), additional cost savings could be achieved[3]. The manufacturing processes of the reactor coolant pumps are good indicators of the importance of lot size.

[1] It is believed that small modular nuclear reactors (SMRs) may be able to increase the size of the commercial nuclear reactor market by providing a smaller financial barrier to entry. The study team understands that the perception financial markets have regarding SMRs are principally driven by the scale economics that SMRs may be able to achieve.
[2] One exception is that the earlier estimates of the LEAD units may be high. The study team found during Phase II that credit for prior learning should be incorporated into the cost estimates for the LEAD IRV units.
[3] For the LEAD IRV unit, approximately 15-20% of additional cost savings are projected when comparing lot size of 5 versus a lot size of 1.

- The analysis considered the learning experience in allied industries such as the as naval shipbuilding, aerospace, and the electronics industries that exhibited 80-90% learning rates[4]. The tooling cost center(s) that measures both the degree of refurbishment and upgrades of the manufacturing process, simulates most closely the learning process of the allied industries.

- The labor and materials cost centers have, in comparison to the tooling center (s), have a significantly less learning rate (i.e., approximately a 95% learning rate), and contribute more significantly (approximately 80-85 percent of the total to the IRV cost than the tooling cost center (s). As a result, the simulated learning behavior for the SMR IRV exhibits a 93 percent learning rate as compared to the 80-90 percent learning rate for the allied industries.

- In sum, the scale economics of SMRs can be achieved if substantive learning transfer occurs from the GW-scale industry and that a significant order book is established.

SMR design, licensing, and detailed engineering activities remain in an early stage. Licensing and design certification documents are expected to be ready for the Nuclear Regulatory Commission (NRC) filing in the 2013-2014 time frame, and detailed engineering is not yet complete. At the time of Phase II analysis, limited cost data were publicly available, and current estimates have a significant amount of uncertainty. It is suggested more detailed industrial engineering work be conducted after more detailed SMR designs are available.

[4] Learning rate is measured as the percentage of the cost that remains after each doubling of production

Table of Contents

Summary

Objective

The goal of small modular reactor (SMR) manufacturing is to move the subcomponent assembly from the reactor site to modular reactor factories. Localizing the manufacturing into a factory environment should result in a core group of employees who learn how to produce components in the most efficient manner. Ideally, the same group of employees will stay together for years, reducing the amount of unlearning or relearning that must occur for each unit.

Methodology

This study focused on the learning process for the factory built components of the Integrated Reactor Vessel (IRV) of a generic 100 MWe SMR using Pressurized Water Reactor (PWR) technology. The project estimation software, SEER–MFG[5] was used to model the manufacturing process for the IRV, including the major subcomponents: integrated reactor pressure vessel, reactor core, control mechanism, coolant pumps, steam generator, and pressurizer. The SEER model was able to simulate expected labor costs, material costs, tooling costs, and fabrication costs for first-of-a-kind subcomponents that make up the complete IRV unit.

Results

The SEER model simulations tested the effects of both prior knowledge and lot size on the rate of learning expected in the manufacturing of the major subcomponents of the SMR IRV units. The simulations were repeated for units produced in lots (i.e., the dedicated manufacturing run) of one through 12 units that would eventually produce a total of 120 units.

All costs were normalized to the production cost of the first factory built unit of lot size one with the assumption of no prior learning (in Phase I of the study, this is labeled as the LEAD unit[6,7]). The learning curves confirm the bounding analysis assumed in Phase I of the study[8]. The subsequent first-of-a-kind (FOAK) units provide the basis for optimizing the supply chain. Phase II of the study provides a spectrum of outcomes for the first and follow-on FOAK units.

---

5 SEER, 2011, http://www.galorath.com/index.php/products/software/C5

6 LEAD refers to the first complete, functional version of some product. The purpose of building a first of a “first-of-a-kind” (FOAK) plant (LEAD) is to show that the design is commercially viable and to facilitate the optimization of the construction of a manufacturing facility dedicated to SMR production. The dedicated manufacturing facility is likely to be built before the completion or near the completion of the LEAD plant.

7 The dedicated manufacturing facility would be amortized over the FOAK units. Therefore, at the time of Phase I of the study, it was assumed that the LEAD plant is likely to cost substantially more than the FOAK plants.

8 https://csis.org/event/small-modular-reactors-key-future-nuclear-power-generation-us

1. Importance of Knowledge Transfer

Figure 1 illustrates curves that were determined in the course of the learning rate simulations[9]. The following three cases were analyzed:

(1) No credit for prior process knowledge

(2) Partial credit for prior knowledge for the components and processes most similar to GW–scale reactor manufacturing

(3) Full process knowledge credit (essentially Nth of a kind production from the start) for the components and processes most similar to GW-scale reactor manufacturing

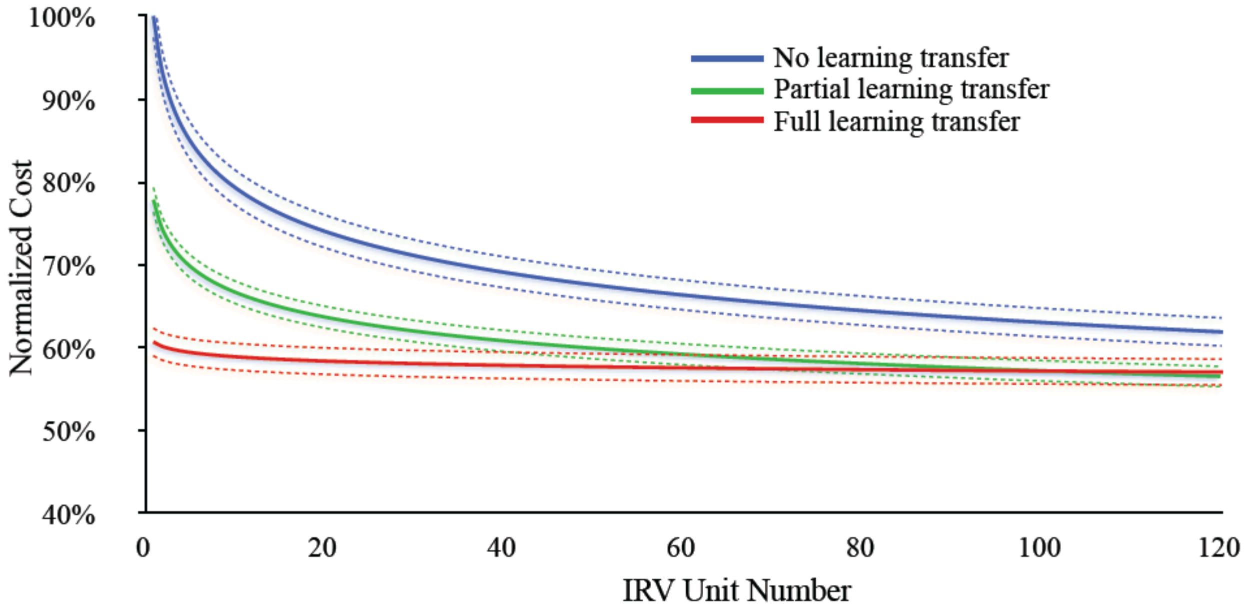

Figure 1: Normalized Cost as a Function of Credited Learning and IRV unit number.

The following observations can be made:

- Based on the simulations, the learning rate of 93% occurs when there is no pre-existing manufacturing knowledge credited. This learning rate represents the highest rate of unit cost reduction or learning rate[10], derived from the SEER modeling simulations. The first IRV unit (i.e., equivalent to the LEAD unit) is assumed to be built in a dedicated factory environment under the assumption that no process knowledge could be transferred from any other manufacturing endeavors.

---

[9] The dotted lines indicate the margin of error in the simulations. They exhibit approximately a 6% margin of error for each of the three learning scenarios.

[10] The learning rate is measured as the percentage of the cost that remains after each doubling of production.

- For the partial- and full-learning credit simulations, the first IRV unit (i.e., equivalent to the first FOAK unit) represents an initial significant unit cost reduction (about 20-40%). However, the subsequent cost reduction for future IRV units is less and the equivalent learning is less than the simulation for no prior knowledge transfer case. The learning credit simulations represent the likely situation of the manufacturing technology for the SMR manufacturing process, "piggybacking" on the *prior knowledge* of processes and components that the nuclear industry has used to build up the GW-scale reactors over the last several decades[11]. To transition from the LEAD to the first–of–a–kind (FOAK) production unit, the learning model implemented the concept of crediting knowledge. Crediting knowledge is the based on the hypothesis that, unless a technology is (from the ground up) completely novel, then that technology stands on the shoulders of the industries that precede it[12,13] Stated in terms of the model developed thus far, each of the IRV units stands to benefit from knowledge credited to existing industries[14].

2. Importance of Lot Size

Using partial-knowledge-transfer scenario as the reference case, the study team analyzed the cost reductions that could be gained by lot size[15]. Based on the relative cost reductions of proceeding from lot to lot, there are large cost efficiencies in establishing a five-lot size campaign; however, after a lot size of five, the degree of efficiency gain is significantly smaller. Figure 2 represents the average cost variance (i.e., the ratio of the normalized cost change when increasing the lot size by one unit by the normalized cost for producing the IRV unit). Figure 3 represents the expected learning curve for IRVs assuming partial-transfer-of-knowledge scenario and production in lot sizes of one and of five units. Based on the results indicated in Figure 2, the study team found that the inflection point in the simulated production runs -indicating a change in the behavior of the production cost reduction occurs just below an order size of five units. Between lots of one unit and lots of five units, there is a steep drop in the difference between lot average costs. Lot sizes of greater than five units see a much slower drop in the difference between lot average costs. In fact, the differences approach the limits of the accuracy of the model. Figure 3 represents the normalized costs for a partial transfer of learning based on size of lot and lot number (the number represents the series of lot runs that produce IRV units). Based on the results indicated in Figure 3, a lot size of five and lot number of one (i.e., the first five IRV units produced) will exhibit about the same percentage of reduction as a lot number of approximately ten combined with the assumption of a lot size of one (i.e., about ten IRV units produced).

---

[11] https://csis.org/event/small-modular-reactors-key-future-nuclear-power-generation-us

[12] http://econpapers.repec.org/article/eeeiepoli/v_3a12_3ay_3a2000_3ai_3a1_3ap_3a47-68.htm
[13] http://www.quora.com/Technology/What-Are-the-Most-Promising-Post-IT-Industries#
[14] Pre-existing knowledge was incorporated into the SEER-MFG model by imputing the number of similar components (like fuel assemblies) previously produced.
[15] Lot size for the purposes of this study represents the magnitude of IRV units produced per dedicated manufacturing simulation run

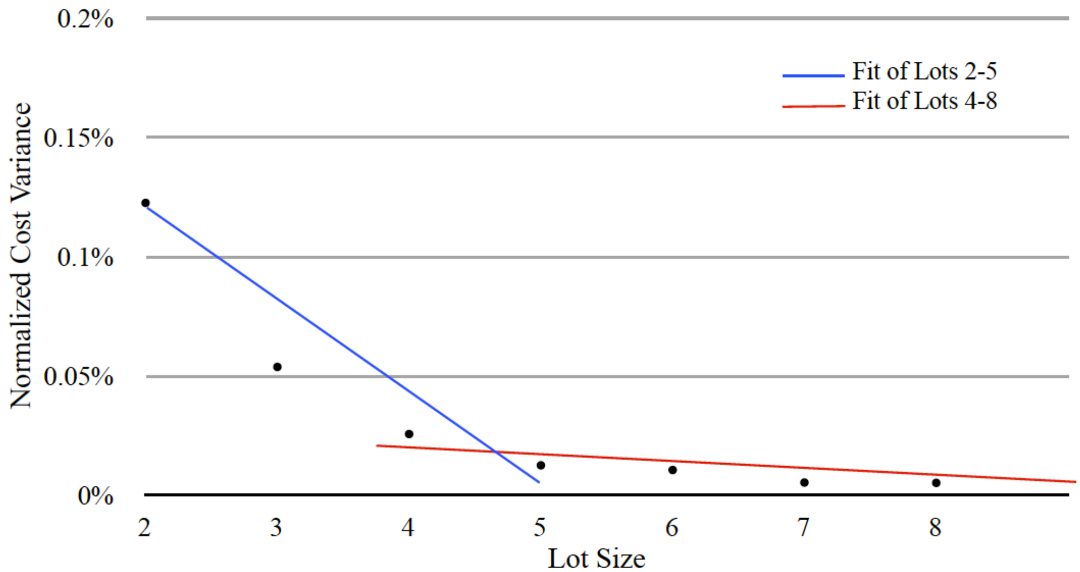

Figure 2: Sensitivity of Normalized Cost Variance by Lot Size.

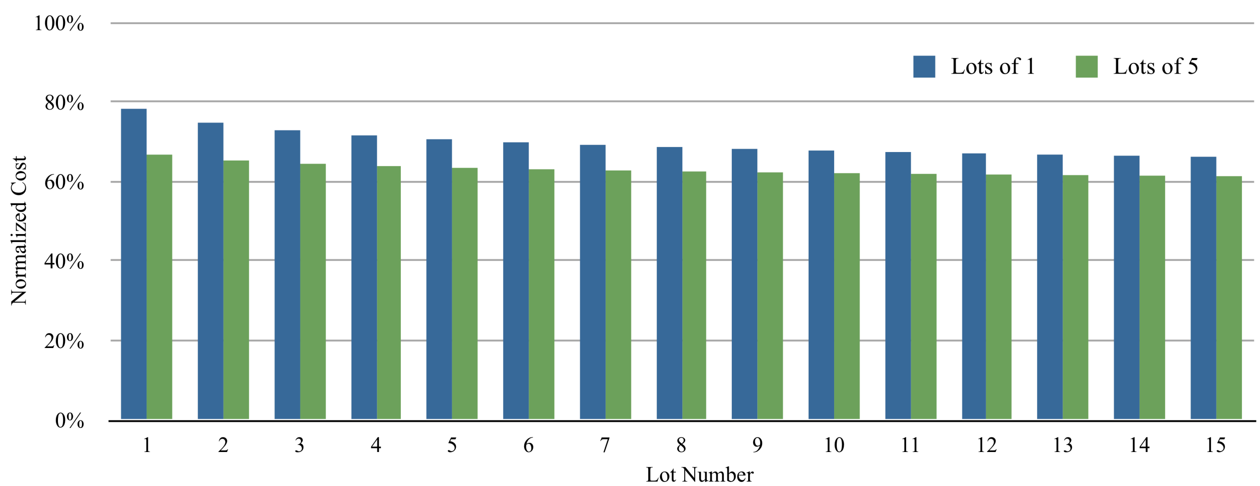

Figure 3: Normalized Cost for Partial Transfer of Knowledge for Lot Sizes 1 & 5.

3. *Crediting Knowledge by Subcomponents of the IRV*

- Full Knowledge Transfer

The study team found that crediting knowledge (tending to maximum transfer of knowledge) is most likely to be prevalent in the production of fuel assemblies and steam generator tubes. In the case of the fuel assemblies, records indicated that the AP1000 reactor fuel assemblies, a design similar to that that is used in the generalized IRV, have been in production. Over 14,000 Westinghouse-fabricated fuel assemblies have operated in 252 fuel cycles at 50 plants worldwide since 1997[16]. The large number of assemblies produced indicated that prior knowledge would have a large effect on the production cost of the reactor core. Similarly, steam generators used in PWR reactors have been a commercial product for decades. At least, 297 steam generators have been produced by Babcock & Wilcox[17]. With over 10,000 steam tubes in each steam generator, it would be unrealistic to neglect the learning that will be transferred to SMR manufacturing from this component. Figure 4 represents the learning simulations of these two IRV subcomponents (calculated in terms of normalized cost contributions of the steam generator and the reactor core to the overall IRV unit normalized cost) by lot number and lot size. The cost contribution represents the percentage that these subcomponents contribute to the total LEAD and subsequent IRV units. The study team found that the cost of the first set of steam generators and reactor cores is reduced by about 40%, because of the full transfer of learning (i.e., the approximately 30% total normalized cost estimate would be about 40%, if there were no transfer of knowledge). The capital cost component of the reactor core and steam generator remains constant and is not reduced significantly by lot number and lot size (i.e., by the production of IRV units).

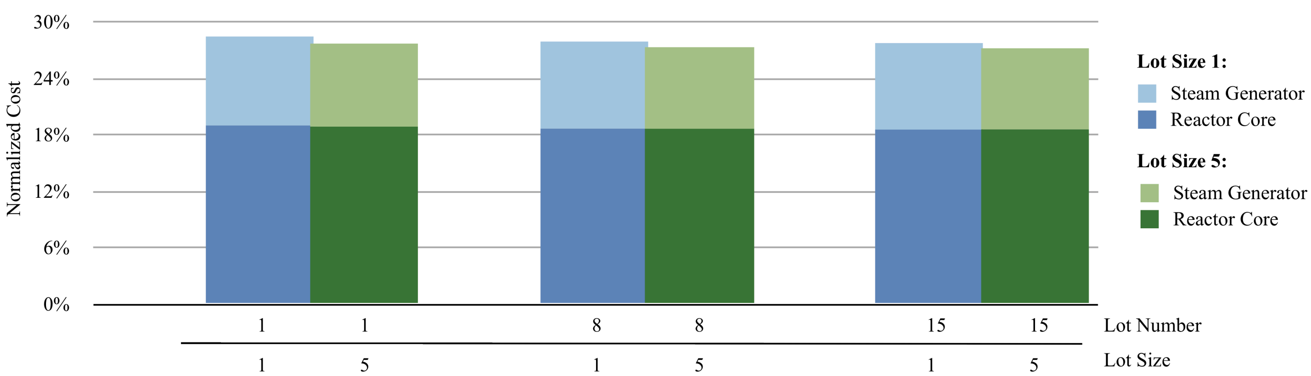

Figure 4: Normalized Cost Contributions – Reactor Core and Steam Generator Subcomponents.

- Limited Transfer of Knowledge

The study team found that transfer of knowledge is not as clear-cut with two other IRV subcomponents (tending to minimal transfer of knowledge), the pressure vessel and the (control rod) drive mechanism. For the pressure vessel, despite the emphasis on replicating the production process used in manufacturing the AP1000 reactor vessel in the SEER simulation[18], the IRV pressure vessel was not identical. Also, the number of pressure vessels manufactured did not approach the number of steam generator tubes or fuel assemblies produced. Therefore, the pressure vessel was taken to be a novel subcomponent in the estimate of the

[16] http://www.neimagazine.com/features/featurethe-westinghouse-smr
[17] http://www.babcock.com/bwc/ and http://www. Babcock.com/products/modular-nuclear/
[18] http://www.jsw.co.jp/en/product/material/vessel/fabsequence.html

normalized cost contribution of the first unit(s) produced (representing closely to the cost contribution of a LEAD subcomponent). Regarding the drive mechanism subcomponent, as compared with the traditional light-water reactor design at the GW- scale, the model the study team used was the drive mechanism that is internal to the pressure vessel and therefore is subject to the extremes of temperature and pressure typical of nuclear power generation. Even though the drive mechanism includes the control rods, that are likely to be very similar to the traditional design used in existing PWRs, the specifics of how they integrate with the new drive mechanism are unknown. In recognition of the uncertain nature of the design elements, similar to the IRV pressure vessel, no prior transfer of knowledge was credited to the production of the control mechanism.

The learning for the coolant pumps and pressurizer exhibit partial transfer of knowledge. The study team assumed that the model IRV included eight coolant pumps that are benefitted by larger lot sizes. For each production configuration, the cost of the coolant pumps converges to an nth state in fewer IRV units than does the total IRV. It is possible that this early convergence is partly responsible for the inflection indicating the minimum order size, as exhibited in Figures 2 and 3.

Figure 5 represents the learning simulation of these two subcomponents as well as the pressurizer and coolant pumps by lot size and lot number. The normalized costs represent the percentage that these subcomponents contribute to the total IRV unit (s). For these classes of sub-components, the learning is more significant when comparing lot size and lot numbers (normalized cost reductions by factor of two) than for the steam generator and reactor core subcomponents.

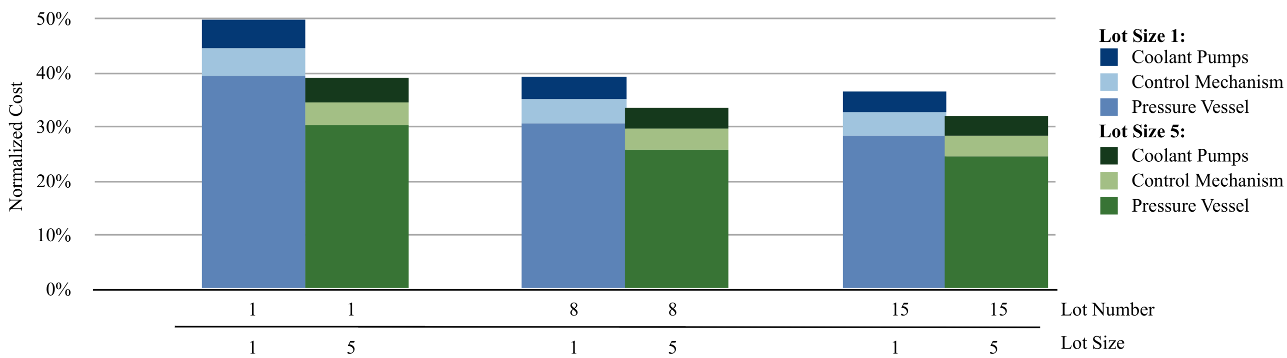

Figure 5: Normalized Cost Contributions – Other Subcomponents of the IRV.

4. *Learning By Cost Categories*

The results of the simulation of IRV production as a function of the number of lots produced details the learning process. The decrease in cost due to learning in labor, materials, tooling, cost centers (labor tooling and tooling replacement) and miscellaneous items (other) as a function of lot number is shown for production in lots sizes of one and five in Figure 6. The cost contribution represents the percentage that these subcomponents contribute to the total LEAD and subsequent IRV units. Materials and labor (84%) dominate the total cost of the simulated SMR IRV unit exhibiting the least rate of unit cost reductions. Figure 7 represents the simulation learning process for the tooling labor (representing the setup costs for each lot run) and replacement tooling cost centers for the SMR IRV unit. While learning is observed to reduce the cost in all of the cost centers, the largest learning effect is evident in the tooling labor tooling cost category. In a factory environment, improvements in tooling, software, and factory arrangement occur during the time period between the productions of different lots. Therefore, the tooling replacement category demonstrates significantly less cost reductions between lots than does tooling labor. Within the production of a given lot, only replacement of worn tools occurs. When the lot size is increased, the normalized tooling labor cost category demonstrates significantly more learning effects as compared to tooling replacement cost category as well. The larger the lot size, the more units over which the tooling and setup costs that occur at the start of each lot cycle can be amortized. The lot size of five does not maximize this effect but is a reasonable target for a lot size for the IRV of the SMR.

Figure 6: Normalized Cost by Cost Categories for Two Lot Sizes.

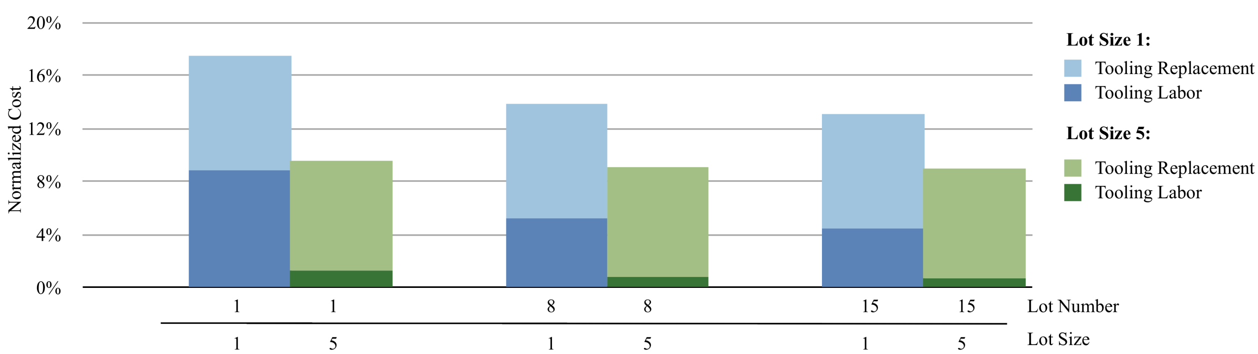

Figure 7: Normalized Cost Contributions By Tooling Labor and Tooling Replacement Cost Categories for Two Lot Sizes.

5. Other Findings

A detailed review of manufacturing within industries with similar technical and regulatory requirements (aerospace, shipbuilding, and electronics) was undertaken to both populate the parameter space of the model and to compare the results of modeling the IRV/SMR. The learning rates were found to be significantly higher for these industries due to the following two key cost drivers: (1) the early stages of these antecedents industries had no antecedents, similar to the GW-scale units and (2) the first-of-a-kind units for these allied industries were constantly being retooled.