Advanced Fuel Cycle Cost Basis Report: Supporting Document 5 Considerations on Learning

Nuclear Fuel Cycle and Supply Chain

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This latest version of the Supporting Documents 5 Considerations on Learning is the result of the cumulative effort of many authors that have contributed to the Advanced Fuel Cycle Cost Basis Report. It is not possible to identify and acknowledge all those contributions to this module. All the authors, including the four primary authors, fifteen contributing authors, the twelve contributors acknowledged, and the many other unacknowledged contributors in the 2017 version of the report may have contributed various amounts to the development and writing of this module prior to this current revision. Unfortunately, there is no history that allows us to properly acknowledge those that built the foundation that was updated and revised in this latest revision.

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

CONSIDERATIONS ON LEARNING

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

A1-1.1. Learning in Design and Construction

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

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

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

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

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

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

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

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

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

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

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

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

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

A1-1.2. Regulatory Learning and Regulatory Stringency

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

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

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

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

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

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

Learning is also a relevant consideration in the estimation of operation and maintenance (O&M) costs for nuclear facilities. In this case, the historical US experience has shown substantial learning in the efficient operations of nuclear plants, which can be quantified with the increase in availability and capacity factors for existing nuclear plants, as shown in Figure 0-1.

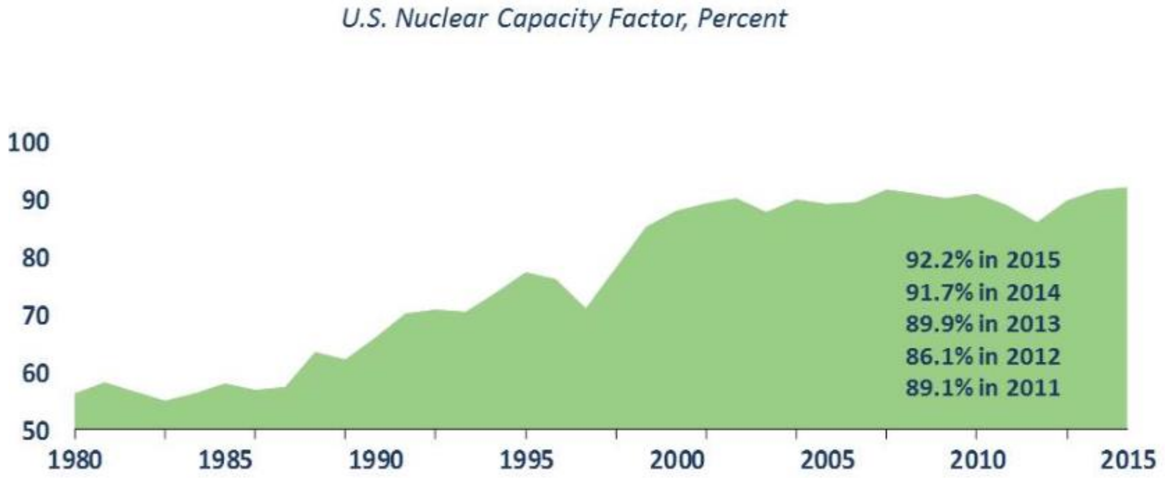

Figure 0-1. Average US nuclear capacity factor [NEI].

A1-1.3. Conclusions

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

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

A1-1.4. References

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