Advanced Fuel Cycle Cost Basis Report: Supporting Document 4 Considerations on Scaling

Nuclear Fuel Cycle and Supply Chain

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

CONSIDERATIONS ON SCALING

Scaling considerations involve the calculation of "new" facilities' construction and O&M costs starting from available information (from actual facilities and/or studies) on cost of similar facilities of different sizes.

Generally, because of economies of scale, the construction cost C1 of a facility of size S1 is calculated from the known cost C_0 of a facility of known size S_0 with the following equation:

$$C_1=C_0 \cdot (S_1/S_0)^{\alpha}$$

Where α is called the "scaling factor", and assumes a value typically between 0 and 1. Values close to 1 indicate the existence of little economies of scale, so that the cost increase/decrease is close to linear, while values close to zero indicate the presence of large economies of scale, for which an increase in size produces little effect on costs. A typical value of scaling factors for chemical facilities and equipment that is often cited in the literature, e.g. (Peters & Timmerhaus) is 0.6.

The methods for increasing capacity should be considered when developing scaling factors. In some facilities, the individual pieces of equipment may simply be increased in size, while in others, parallel trains of equipment of a constant size may be employed. As equipment is enlarged and/or equipment trains added, buildings will increase in size, either by square footage of floor space or cubic footage of building volume or additional buildings will be added. Scaling also applies to operational costs, where the number of operators may be driven by the number of equipment trains while other labor categories such as security may change little with size.

Construction methods should also be considered as the size of the facility changes. At smaller sizes, it may be possible to fabricate more of the facility in a factory environment, holding down both construction costs and rework. Two types of fabrication should be considered, "equipment" and "modules", where equipment includes pumps, steam generators, and smaller reactor pressure vessels, while "modules" are construction building blocks that include structures, walls, piping, electrical, etc. A modular construction approach may apply at multiple scales, while equipment can only scale to the limit of lifting and transport equipment and at some point must instead be reduced to sub-components that are assembled on site. Referring to the described concept in supplementary document SD2: "Production Based Costing," factory fabrication of nuclear grade equipment such as the reactor vessel may involve a different, more efficient production function (point B in the figure) versus on-site fabrication (points A or C). The scaling equation above assumes a constant production function, so such changes may result in discontinuities (steps) in the otherwise continuous scaling function.

The issue of cost scaling with size has been studied for reactors, especially in light of the recent interest in small modular reactors (SMRs). Results of past studies on this issue produce results that are not fully consistent, and therefore one cannot draw definitive conclusions. For example, the results of the econometric analysis of construction costs between 1971 and 1978 performed in [Komanoff 1981], show that the "*unit size*" variable had virtually no effect on costs (+0.5%), indicating that the beneficial effects of economies of scale were completely counterweighted by other factors that increased the unit costs of larger units. Later econometric analyses with more comprehensive data sets found that larger sizes actually *increased* the cost per MW installed [Zimmerman 1982], [Krautmann 1988], [Cantor 1988] and [McCabe 1996]. Similar results were also found as a result of a statistical analysis conducted by DOE/EIA in 1986, the conclusions of which are quoted here [DOE 1986]:

> *"The analysis indicates that the indirect effect of size on real cost, through the influence of lead-time, outweighs the direct reduction in costs per kWe of capacity that would result from the construction of large power plants if the lead-time and size were not related."*

In particular, the study found that a 25% increase in the power level of the plant would lead to a reduction in cost per kWe of capacity of 12%, *if* the larger power level would not induce an increase in lead time. However, a 25% increase in power level was found to be associated with a 18% increase in lead time, which was in turn found to be associated with an increase of 22% in the real cost of construction. It is cautioned here that "lead-time", being quantitative and readily and precisely available, was used in [DOE, 1986] as a proxy variable for a number of un-quantifiable variables such as design changes, safety and environmental retrofits required by regulatory change, and labor productivity, which were directly responsible for the cost increases.

On the other hand, a more recent econometric analysis performed in [Ganda 2016a], indicated that given a 10% increase in reactor power, costs per kWe of capacity (i.e. the actual cost outcome after construction was completed, normalized for the reactor power) decreased by 17.8% (implying an escalation factor of -1.05) and budget per kWe of capacity (i.e. the pre-construction cost estimate, normalized for the reactor power) decreased by 6.9% (implying a scaling factor of 0.25). Both estimates were found to be significant at the 99% level, and were found when controlling for a number of variables, including size, location, reactor type, time built, etc. When all these variables were not controlled for, the elasticity becomes 0.32, i.e. a 10% increase in reactor power would result in cost per kWe of capacity increase of 3.2%, implying instead diseconomies of scale.

It is noted that most past analyses (one exception is [Ganda 2016a]) simply used "did cost", and did not attempt to include "should cost". By using only "did cost" the combined trends toward larger reactors over time and to more regulation over time may have impacted scaling results. Another factor is the use of data primarily or exclusively from Western countries, which all saw an increase in construction time in the 1970s-80s and not including data from Asian countries that did not experience the same increases. Figure 1shows the historic construction duration trends (from first nuclear concrete to first grid connection) for the three largest Western and three largest Asian reactor fleets. These figures imply that factors other than scaling were driving the historic cost increases. A separate supplementary document (2017-CBR-SD5) to the 2017 AFC-CBR discusses learning.

In summary, it is recommended to use caution when applying cost savings due to economies of scale for reactor facilities, since a definitive consensus on this topic has not been reached yet.

For other fuel cycle facilities, and in particular for reprocessing facilities, the issue of estimating proper escalation factors is especially important, since few cost data points exist, and some of those plants have very different annual throughput. For a meaningful comparison of those costs, it is necessary to have a well-developed approach for escalation that includes understanding how capacity increases would be physically achieved.

Few studies have been performed on the cost of reprocessing, including [Haire 2003] and more recently [Bunn 2016]. An extensive discussion of aqueous reprocessing plant scaling considerations is provided in Module F1 of this 2017 AFC-CBR.

Haire [Haire 2003] points out the following:

> *"In the familiar rule-of-thumb scaling law, capital costs are proportional to the nth powers of capacity; however, n is not a constant. The value of n approaches 0.1 for very small-capacity plants and 0.9 for very large plants. Thus, there is an upper limit to the axiom that states that the larger the plant size, the smaller the unit cost. For example, doubling the throughput rate of a large-capacity plant nearly doubles capital costs".*

The considerations in [Bunn 2016] are based on cost data derived from the construction experience of a 50 MT/y pilot plant at the Jiuquan nuclear complex, and are applied to the derivation of the cost of a hypothetical industrial-size 800 MT/y facility. Chinese experts' estimates mentioned in [Bunn 2016] use a scaling factor of 1.0 for facilities that are between half and double the size of the reference facility, and a scaling factor of 0.6 for facilities larger than twice but smaller than 50 times as large. For this reason, a scaling factor of 0.85 was considered the most realistic for a scaling of a 50 MT/y plant to an 800 MT/y plant in [Bunn 2016]. However, it is also mentioned in (Bunn 2016) that a study of aluminum refineries (which are also expanded primarily by adding production line, rather than by scaling equipment, similarly to reprocessing facilities), found a scaling factor of 0.93 to be appropriate.

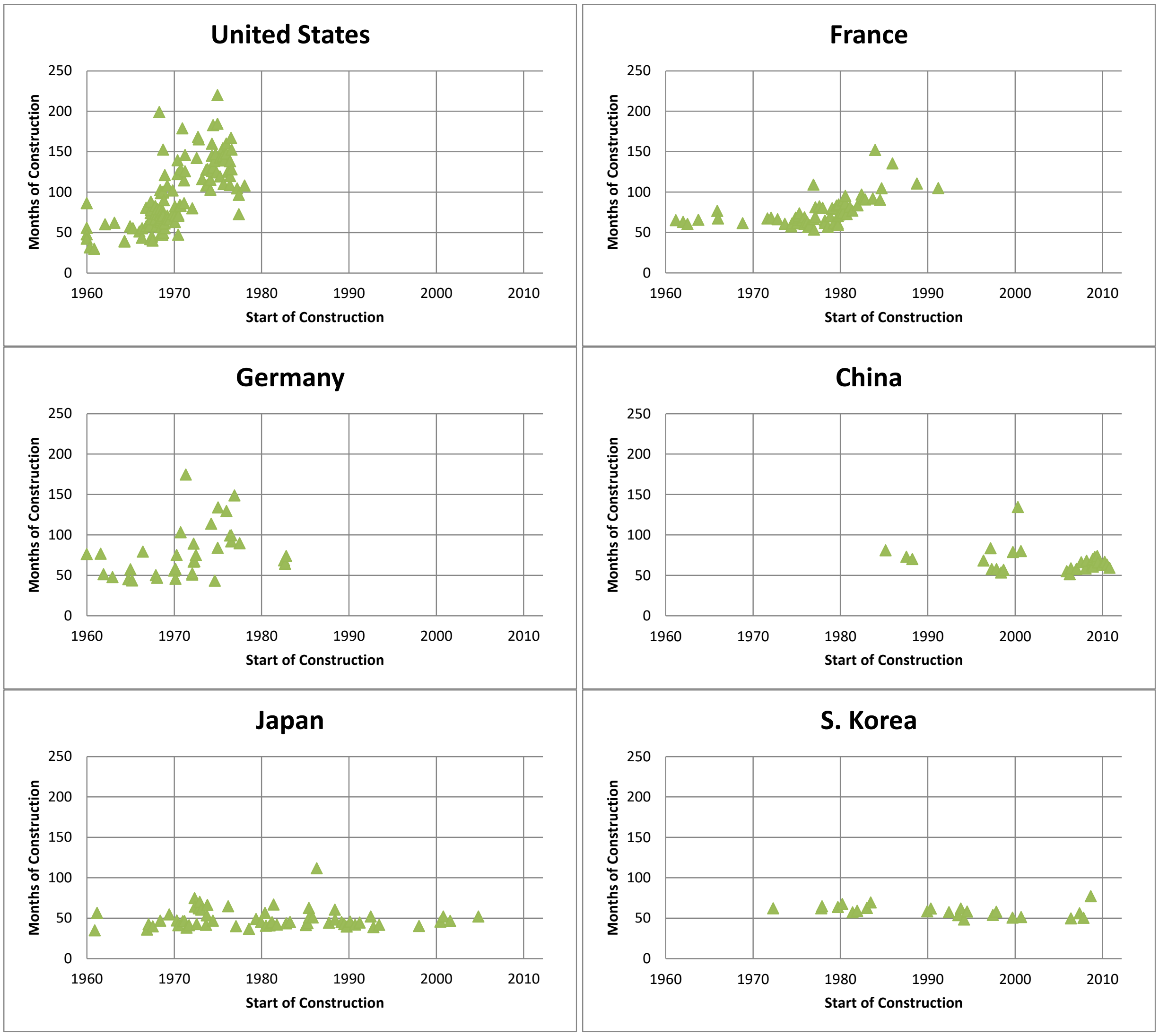

Figure 1. Reactor construction start year versus duration in three Western and three Asian countries.

In a separate study, [Carter 2010] Westinghouse Savannah River Company (WSRC) identified that an electrochemical reprocessing facility that was originally designed for a throughput of 21.3 MT/y, could be modified to a 70 MT/y throughput facility with minimal additional capital spending, because of the suboptimal optimization of equipment that needs a certain minimum size for its required functionality. This consideration is in agreement with that provided by Haire with regards to “very small capacity plants” having a scaling factor close to zero.

In summary, the approach to cost scaling needs to be done differently for different modules, and the exact quantitative approach needs to be carefully addressed separately for individual modules. Where data is available, a discussion on this topic is provided in the CBR to inform the reader on this topic, for example in the F1 Section on aqueous reprocessing. In general, more defensible, high quality data needs to be generated on this important topic.

A1-1.1. References

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