Initial Overnight Construction Cost Estimate for Small Modular Reactor

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1. Introduction

This paper was prepared to present the method of initial overnight construction cost estimate for the small modular reactor (hereinafter referred to as "SMR") in case of assuming to be deployed in series of multiple units at the foreign country site. The subject SMR plant has been licensed by standard design, but has no pilot or lead plant, no similar reference plants with its NSSS features and passive safety systems applied and there is a big difference compared to existing plants in its scale of capacity. The method employed here, as top-down method, comprises mainly parametric cost estimating techniques using cost-scaling relationships and related factor applications under the condition that only limited detail information is available. Cost estimate may comprise separate estimates of differing classification. In the view of cost estimate classification defined in RP (Recommended Practice) No. 17R-97, 17R-98 of AACEI (Association for Advancement of Cost Engineering International), this type of cost estimate presented here could be included in Class 3; budget authorization or control with the degree of project definition of 10% to 40% [1,2] when taking into consideration newly designed SMR deployment.

2. Assumptions

Cost estimate for the design, procurement, construction and multiple deployment will exhibit considerable uncertainty, where the magnitude of uncertainty depends on the level of reference design cost estimate and degree of detail engineering definition. To manage the cost-estimating task for newly designed nuclear power plant (NPP) concepts, a number of simplifying assumptions have been made, including the followings: SMR means small modular reactor with the equivalent effective electric power less than 300 MWe as defined by International Atomic Energy Agency (IAEA). Main characteristics of SMR considered will be deployed in land and would be an integral type of pressurized water reactor which contains major components of reactor coolant system such as a pressurizer, steam generators, and reactor coolant pumps within a single reactor pressure vessel. Systems at the deployment stage are assumed to be pre-licensed by its site-specific design in their country of origin. The finance and business model assume that project financing is available for all phases of the final engineering design, site development, plant layout, owner's cost, construction, and commissioning of a plant. No provision is made for force majeure, war, labor strikes, or future changes in regulatory requirements. RD&D (research, development and demonstration) costs are not allocated to any kind of plants (FOAK (First-Of-A-Kind) and/or NOAK(N^{th}-Of-A-Kind)) in this instance.

3. Cost estimate approach

Estimating the cost of newly designed NPP like SMR to be built outside the country of origin is a big challenge because access to cost data may be difficult to find or inconclusive especially in case that the foreign country is at the stage of importing nuclear program. One approach is to complete a cost estimate utilizing the references or comparable plant in the country of origin and then make cost adjustments based on cost differentials between country of origin and countries that want to deploy. More granular location cost factors yield potentially more accurate project cost estimate because differentials will likely vary between capital cost categories (labor rates, equipment, building materials, etc.). As a second approach, country with similar geographic, economic, and infrastructure conditions may be used as a proxy country for estimating location cost factors. Using granular location cost factors requires that cost data in the country of origin be deconstructed into comparable categories [3]. The first approach is adopted in this paper because it is difficult to illustrate a proxy country in this case and requires another daunting work to present relationships between cost categories other than cost estimate process itself.

4. Cost Estimate Steps

The various steps applied in developing cost estimate include as follows:

- Step 1: cost estimate for single unit of FOAK plant in the country of origin.
- Step 2: application of adjustment factors to estimate twin units of FOAK plant cost in the country of origin
- Step 3: adjusting location to estimate twin units of FOAK plant cost in the designated foreign country
- Step 4: application of adjustment factors to estimate series twin units of NOAK plant in the designated foreign country
- Step 5: documentation of cost estimate results and verification

Followings are descriptive processes applied in each step.

Step 1: first of all, it is essential to collect and review the information of the subject project (for example, project definition (% completion of engineering), specific features related with major equipment such as NSSS, adopted passive systems, T/G and any specific systems and/or facilities which are different from those of large NPP) according to the purpose of cost estimate and its intended use. The next is to select reference plant which is most close and comparable to the subject plant. In selecting the reference plant, one important factor is site characteristics i.e., green field or brown field where civil and structural costs can vary greatly because most, if not all, of the support infrastructure may already be in place for a plant expansion project. Another one is the number of unit of the plant. If the reference plant available was built in twin units, and if it is not necessary to estimate cost of subject SMR plant in single unit, step 1 and 2 should be adjusted appropriately to estimate twin units of FOAK plant cost in the manner of one step. Most of significant errors in capital investment are caused by omission of equipment, service, or auxiliary facilities rather than to gross errors in cost estimating. The accuracy of the cost element estimate determines the accuracy of the significant project overnight construction cost. One method enhancing the accuracy and the consistency of estimate is to adapt the notion of WBS, account code, and/or other standardized definition [10]. It is recommended to use the IAEA Account System (Economic Evaluation of Bids for Nuclear Power Plants, 1999 Edition) [5]. A reasonable expectation of a cost estimating process is that it systematically collects cost information in real time rather than being done at the last minute or by trying to collect long after the fact. It is important to realize that any combination of methods may be applied in any given class of estimate. For example, if a stochastic method such as rough order of magnitude is known to be suitably accurate, it may be used in place of a detailed bottom-up estimate even when there is sufficient input information based on the degree of project definition to support a detailed quantity take-off method. On the other hand, the detailed bottom-up estimate should be needed by defining the function as enough as possible even if there is little input information about important cost element. In a newly designed SMR, there should be specific cost drivers for the major cost elements which are different from those of large commercial NPP. So SMR specific cost drivers such as modulated reactor thermal capacity, turbine type, generator electric capacity and function of newly adapted systems should be checked in detail level to the extent possible. These SMR specific cost drivers should be used as input data of cost estimating relationships (CERs). Major cost elements can be estimated using these CERs and the resulting cost should be compared to the quotation prices suggested by the vendors. For example, a CER of dollars per kWe may be applied to the designed electric capacity to figure out the total capital investment cost [10]. In some cases, cost for this SMR specific major element such as modular reactor could be derived in the range estimate rather than point estimate due to the confidence matter because those major elements have never been manufactured and installed before. To facilitate top-down estimate method utilizing parametric estimate technique in which CERs are also used to estimate a particular cost other than SMR specific major element cost by using an established relationship with cost driver, it should need to categorize overnight construction cost into the structured manner to estimate single unit of FOAK plant cost. The overnight construction cost (also known as "fore cost") could be break downed using IAEA accounting system [5] as follows:

Base cost = Direct costs (account nos 21~29) + Indirect costs (account nos 30~41)
Fore cost = Base cost + Supplementary cost (account nos 50~54) + Owner's capital investment and services costs (account no. 70)

To estimate the costs of building and structures at the plant site which are included in IAEA account 21, physical dimension factors are used for the building and structures (for example, site grading or auxiliary building) utilizing available reference historical data based on the volume of that building. Square or cubic meter in this case is CER between subject plant and referent plant. If the cost of a certain building of the previous project was US$ 100 million for the volume of 200,000 M^3 and the new building is to be about 100,000 M^3, the estimated cost of the new building would be US$ 50 million without any adjustment, and capacity factor methods are also used for the building and structures (for example, electrical and water treatment building) when enough historical data are available from similar work based on the capacity of that building. Treatment or production capacity is CER in this instance between subject plant and reference plant. If the cost of a certain building of the previous project was US$ 10 million for the water treatment capacity of 50,000 ton/day and new building is to require water treatment capacity of about 25,000 ton/day, the estimated cost of the new building would be US$ 5.7 million without any adjustment using the following equation:

$$\text{Cost (new)} = \text{Cost (previous)} * (\text{Capacity (new)}/\text{Capacity (previous)})^e$$

Where, e (0.8) is a capacity factor derived from historical data

To estimate the costs of equipment to be installed in the plant which are included in IAEA account 22 through 29, capacity factor methods are used for most equipment by using the well-known standard six-tenths factor rules. The index is a value between 0.3 to 1.2 that depends on the equipment type. In most cases, the index is between 0.4 and 0.8, where 0.6 is used as the default value for non-indexed equipment. Typical cost-scaling indices for equipment cost as function of capacity can be found in most chemical engineering handbooks [3]. To apply this method, equipment list or purchase order list of subject project should be prepared to the extent possible to apply six-tenths factor rules to those of reference plant. If this type of approach is difficult, equipment list may be prepared by using historical data of referent plant or guessing data based on the limited information of subject project itself.

To estimate the indirect costs which are included in IAEA account 30 through 41, specific analogy method is used for engineering, project management, construction and commissioning support services. This method uses the known cost of an item as an estimate for a similar item in SMR project. Adjustments are made to known costs to account for differences in relative complexities of performance, design, construction, and operational characteristics.

To estimate the supplementary costs which are included in IAEA account 50 through 54, specific analogy method is used for transportation and transportation insurance, spare parts, contingencies, insurance. This method also uses the known cost of an item as an estimate for a similar item in SMR project. Transportation and transportation insurance comprise the cost of transportation of equipment and materials, including land, air or marine insurance as appropriate, from the point of origin to the point of delivery as specified. Adjustments are made to known costs to account for differences in relative conditions, limitations, and norms applied.

To estimate the owner's capital investment and services costs which are included in IAEA account 70, deterministic method, if applicable, is used for land and land rights by reflecting the cost presented by the owner and specific analogy method is used for on/off-site infrastructure, administration and general affairs related facilities, plant operation related preparation, insurance, and taxes. This method uses the known cost of an item as an estimate for a similar item in SMR project. Adjustments are made to known costs to account for differences in relative conditions, site characteristics, and provisional scope of the owner.

There should be appropriate additional adjustments to make it more accurate and realistic if the cost estimate methods applied in step 1 do not take into account any economics of scale, or location, or timing of the work. Summing up the above figures according to account codes result in overnight construction cost of single unit of FOAK plant in the country of origin.

Step 2: There are adjustments factors for estimating twin units of NPP construction costs from those of single unit. Based on a study issued by Willium d'Haeseleer (Consideration on Nuclear Projects Organization and Construction Cost, March 11, 2014), construction cost ratio between single unit and twin units of FOAK in large NPP was presented as twins is 0.93 times lower than that of single unit in the capital expenditures. In NEA (Nuclear Energy Agency) report (The Current Status, Technical Feasibility and Economics of Small Nuclear Reactors, June 2011), twin-unit factor is presented as 0.87 ~ 0.93 in total overnight cost.

To estimate twin units of FOAK plant cost in the country of origin from the result of step 1, adjustment factors should be applied cost category by category. For the direct cost of equipment, and building and installation, 0.9 of the average factor presented by NEA is of thinkable choice. For the indirect cost of engineering service, project management, and transportation and transportation insurance, adjustment factors should be prepared and applied based on the reference historical data because more scrutinized evaluation is needed to exclude the non-recurring activities and related work scope.

Step 3: Adjusting location is an important consideration in estimating construction cost. Labor cost, supporting infrastructure, regulations and taxes, and transportation costs can vary greatly between locations and must be included in estimating all cost components. All manufactured equipment except NSSS and initial load fuel, and material which may be procured based on design specification should be estimated at worldwide pricing level and not differ significantly by region. Some bulk commodities such as concrete, lumber, small pipe, miscellaneous steel, embedded metals, and similar locally procured items may differ by region. There are location factors available from various sources such as the Richardson's International Construction Factors and Location Cost Manual [8]. It is general that the survey of the local market situation and government policy should be executed in parallel with source referencing to the extent applicable to generate location factor. The cost of transportation and transportation insurance will vary greatly depending on the point of origin and delivery, the amount of imported equipment and materials considering the level of localization, and customs clearance conditions especially in the case of deploying plant in the foreign country which is at stage of importing nuclear program. At the end of step 3, the final overnight construction cost for twin units of FOAK plant in designated foreign country would be derived.

Step 4: Building reactors in series usually leads to a significant per-unit cost reduction. This is due to better construction work organization, learning effect, larger volumes of orders for plant equipment and other factors. There are applicable adjustment factors for estimating the cost of NOAK plant to be built in series. Based on the report of Small Modular Reactors-Key to Future Nuclear Power Generation in the U.S., Nov. 2011 [13], the economics of series deployment can be derived as follows:

Table1: The Economics of Series Deployment (A)

	Lead1/2	Lead 1	Foak 1	Foak 2	Foak 3	Foak 4
units	1	1	2	3	4	5
reduction rate	1.00	0.74	0.70	0.65	0.62	0.58

* Learning rate is 10%, reduction rate is based on LUEC (Levelized Unit Electricity Cost).

Based on a study issued by Willium d'Haeseleer (Consideration on Nuclear Projects Organization and Construction Cost, March 11, 2014), construction cost decreases in large NPP by ~35% on average between a FOAK and a 5th twin unit as follows:

Table 2: The Economics of Series Deployment (B)

	Foak 1	Foak 2	Noak 1	Noak 2	Noak 3,4	Noak 5
units	2	2	2	2	2,2	2
reduction rate	1.00	0.79	0.74	0.70	0.67	0.65

* Deduction rate of Noak 1 ~ Noak 4 were derived by interpolation.

Based on NEA report (The Current Status, Technical Feasibility and Economics of Small Nuclear Reactors, June 2011 [11]), productivity and program effects of building NPPs in series can be derived as follows:

Table 3: The Economics of Series Deployment (C)

	Foak 1	Noak 1	Noak 2	Noak 3	Noak 4	Noak 5
units	2	2	2	2	2	2
reduction rate	1.00	0.74	0.67	0.61	0.58	0.56

* Deduction rate of Noak 4 and 5 were derived by extrapolation.

According to OECD/NEA report (Cost Estimating Guidelines for Generation IV Nuclear Energy Systems, Sep. 26, 2007), learning experience can be included for the NOAK plant based on learning factors to be developed. Guideline factors for each doubling of construction experience are 0.94 for equipment costs, 0.90 for construction labor, and a 10% reduction in material costs for multi-plant orders [4]. Such information as presented above can be referenced in figuring out the adjustment factors to estimate series twin units of NOAK plant in the designated foreign country. In application of series construction effects, other factors affecting the overnight construction cost such as subsequent factory fabricated units, staggered construction period and design simplification may also be considered, and cost deduction by productivity or program effect including learning will be saturated after 5th-of-a-kind plant according to the reports referenced. The results of this step could be the final estimate cost of series of twin units NOAK plant in designated foreign country.

Step 5: Cost estimate is considered valid only if it is well documented to the point at which it can be easily repeated or updated and can be traced to original sources through review and/or verification. The documentation should explicitly identify the primary methods, calculations, results, rationales, scope of boundary, or assumptions, and sources of the data to generate each cost element according to its purpose and intended use. To assure that the cost estimate is both internally and externally validated, review by the related subject experts and/or third party is the one of the choices, and related literatures and/or reports can be useful in confirming the cost estimate results whether it is in the range of the figure of merits such as OUCC (overnight unit construction cost) which was published in the form of current economic status by credible international nuclear associations.

Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

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