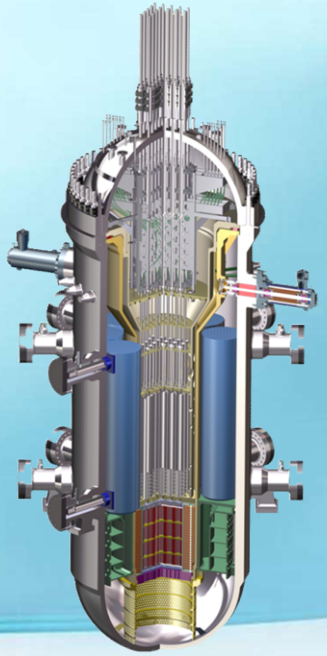
Initial Overnight Construction Cost Estimate

for Small Modular Reactor



2017. 5. 18

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Contents

I. Introduction

❑ Purpose and Application

- To present the estimation method for initial overnight construction cost.
- The estimation method was applied from single unit in the country of origin to multiple units in series at the foreign country site.

❑ Subject plant development status

- SMR (Small Modular Reactor) which has been licensed by standard design
- SMR which has no pilot or lead plant, no similar reference plants in its NSSS features and passive systems applied
- SMR which differs from existing NPP in its scale of capacity
- Degree of project definition is around 20%.

I. Introduction (continued)

❑ Cost estimate method employed

- Top-down method
- Parametric techniques used mainly are follows;
  - End products units method
  - Physical dimension method
  - Capacity factor method
  - Ratio or factor method

❑ Cost estimate classification

- Could be included in Class 3 which is defined by AACEI Recommendation Practice (refer to appendix 1.) ➡

II. Assumptions

❑ Licensing Requirement

- Systems at the deployment stage has been licensed by site-specific design in the country of origin.
- No future changes in regulatory requirements.

❑ Project Financing and Business Model

- Project financing and business model have been completed for all phases of the project.
- No provision is made for force majeure, war, labor strike, etc.
- RD&D (research, development and demonstration) costs are not allocated to any FOAK or NOAK plant.

III. Cost Estimate Approach

❑ International Cost Estimate

- Estimating the cost to build a newly designed SMR outside the country of origin can be challenging.
- It is very difficult to access or to find cost related data.
- It may happen to take long times and needs lots of effort and expenditure.
- It may be inconclusive especially in the case that the designated foreign country is at the stage of importing nuclear program.

III. Cost Estimate Approach (continued)

❑ International Cost Estimate Approach

- Country of origin approach
  - Cost estimate using reference or comparable plant data of the country of origin
  - Apply cost adjustments based on differentials between origin and foreign.
  - Cost estimate accuracy depends on location factors applied.
- Proxy country approach
  - Cost estimate using reference or comparable plant data of a proxy country
  - A proxy country is similar in geographic, economic and infrastructure conditions.
  - Decomposition and comparison of cost data between two countries is needed.
- Country of origin approach is adopted in this case

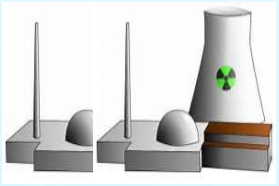
IV. Cost Estimate Steps

- The Steps applied in developing Cost Estimate are as follows;

Step 1.

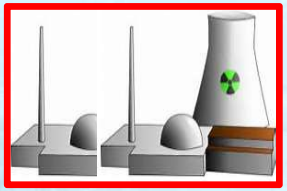
- single units
- in the country of origin

Step 2.



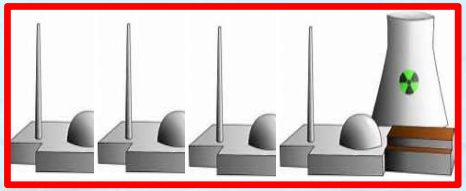
- twin units
- in the country of origin

Step 3.



- twin units
- at the foreign site

Step 4.

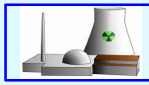


- series of twin units
- at the foreign site

Step 5.

IV. Cost Estimate Step

❑ Step 1.

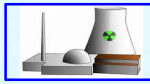


Single unit, country of origin

- Collect and review project information according to the purpose of cost estimate and its intended use
  - Project definition (% complete of engineering)
  - Major equipment characteristics for NI : NSSS, adopted passive systems, etc.
  - T/G, specific system and facilities different from those of large NPP
- Select reference plant
  - Most close and comparable to the subject plant
  - Site characteristics (green field or brown field) should be considered.
  - If reference plant available was built in twin units and the subject plant is supposed to be deployed in twin units from FOAK plant, Step 1 and 2 should be appropriately adjusted in the manner of one step.

IV. Cost Estimate Step (Continued)

❑ Step 1. (continued)



Single unit, country of origin

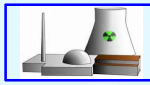
- Prepare code of account
  - WBS, standard account code or other internal account code should be prepared to enhance the accuracy and the consistency of cost estimate.
  - IAEA accounting system is recommended (refer to Economic evaluation of bids for Nuclear Power Plant, 1999 edition).

- Define considerations prior to proceeding cost estimate
  - Freeze reference date for cost estimate in advance.
  - Collect cost information data in real time rather than by trying to collect long after the fact (i.e., constant value application).
  - Any combination of methods may be applied in estimating the cost.

    (i.e., bottom-up by quantity take-off method and/or top-down by parametric method can be used based on the level of cost information)

IV. Cost Estimate Step (Continued)

❑ Step 1. (continued)

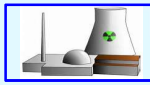


Single unit, country of origin

- Estimate the cost of SMR specific major elements
  - Select SMR specific cost drivers which are major cost estimate elements.
  - Set the CERs (cost estimate relationships) for SMR specific cost drivers.
  - Quote the prices of SMR specific cost drivers from the credible suppliers (e.g., NSSS, Fuel development manufacturers)and compare the figures with those calculated from CERs.
  - The cost of SMR specific cost drivers can be estimated in the range value rathe than in the point value if there are no supporting backup data.

IV. Cost Estimate Step (Continued)

❑ Step 1. (continued)

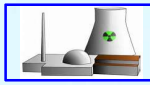


Single unit, country of origin

- Prepare cost estimate table
  - Define the overnight construction cost structure based on the code of account. (i.e., fore cost, base cost, direct cost, indirect cost, supplementary cost, owner's capital investment and service cost)
- Proceed cost estimate according to the code of account
  - Apply appropriate method to cost categories using reference plant data as follows, but not limited to these methods;
  - Physical dimension method : building and structures
  - End products unit or capacity factor method : facilities
  - Capacity factor method using standard six-tenth factor rules : equipment based on p.o list or equipment list

IV. Cost Estimate Step (Continued)

❑ Step 1. (continued)



Single unit, country of origin

- Proceed cost estimate according to the code of account (continued)
  - Specific analogy method

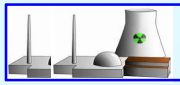
    : indirect cost - engineering, project management, etc.

    : supplementary cost - transportation, spare parts, etc.

    : owner's investment and services cost - general affairs related facilities, provisional scope of owner, etc.
  - Take additional adjustments, if necessary, to make it more accurate and realistic.
  - Summarize the results based on cost estimate table.

IV. Cost Estimate Step (Continued)

❑ Step 2.



Twin units, country of origin

- Survey and review the references for twin unit cost estimate
  - Reference 1. 0.93, 0.79~0.85 : French case in large NPP (refer to appendix 2, 3.) ⇨⇨
  - Reference 2. 0.87~0.93 : NEA report of “the current status, technical feasibility and economics of small modular reactors, June 2011, pp. 172)
- Adjust the result of step 1
  - Application of reference ratio to total figure may be one of the choices.
  - If possible, adjust the result of step 1 into cost category by cost category. (e.g. apply reference ratio to the direct cost, and adjust the indirect cost based on reference ratio and historical data)

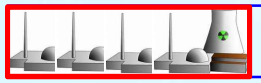
IV. Cost Estimate Step (Continued)

❑ Step 3.  Twin units, foreign country

- Classify cost items into location factor needed or not
  - Cost items <u>needed location adjustment</u> :
    - most of bulk commodities/ labor, supporting structures
    - regulation and taxes related item/ transportation related item
    - site specific or related works/ localized item and works, etc.
  - Cost items <u>not</u> <u>needed location adjustment</u> :
    - equipment/ home office works in the country of origin, etc.
- Prepare and apply location factor
  - Location factor reference : the Richardson's international construction factors and location cost manual
  - Survey <u>the local market and government policy</u>.
  - Apply location factors and adjust the results of step 2.

IV. Cost Estimate Step (Continued)

❑ Step 4.



Series of twin units, foreign country

- Survey and review the references for series construction
  - Reference A : ~35% deduction from FOAK to 5th NOAK (refer to appendix 2.)

	FOAK 1	FOAK 2	NOAK 1	NAOK 2	NOAK 3,4	FAOK 5
Units (no. of plants)	2	2	2	2	2,2	2
Reduction Rate	1.00	0.79	0.74	0.70	0.67	0.65

(source: Willium d'Haeseleer, Consideration on Nuclear Projects Organization and Construction Cost, March 11, 2014)

* Deduction rates of NOAK 1 ~ NOAK 4 were derived by interpolation.

IV. Cost Estimate Step (Continued)

❑ Step 4. (continued)

Series of twin units, foreign country

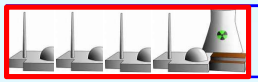
- Survey and review the references for series construction (continued)
  - Reference B : ~42% deduction from LEAD ½ to FOAK 4 (refer to appendix 4.) ➡

	LEAD 1/2	LEAD 1	FOAK 1	FAOK 2	FOAK 3	FAOK 4
Units (no. of plants)	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 total overnight cost and LUCE(Levelized Unit Cost of Electricity). (source: Robert Rosner and Stephen Goldberg, Small Modular Reactors – Key to Future Nuclear Power Generation in the U.S.[1,2], Nov. 2011, Page 15~22)

IV. Cost Estimate Step (Continued)

❑ Step 4. (continued)



Series of twin units, foreign country

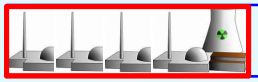
- Survey and review the references for series construction (continued)
  - Reference C : ~44% deduction from FOAK to NOAK 5 (refer to appendix 5.) ➡

	FOAK 1	NOAK 1	NOAK 2	NAOK 3	NOAK 4	NAOK 5
Units (no. of plants)	2	2	2	2	2	2
Reduction Rate	1.00	0.74	0.67	0.61	0.58	0.56

* Deduction rates of NOAK 4 ~ NOAK 5 were derived by extrapolation.
(source: NEA, The Current Status, Technical Feasibility and Economics of Small Modular Reactors, June 2011, page 75~81)

IV. Cost Estimate Step (Continued)

❑ Step 4. (continued)



Series of twin units, foreign country

- Survey and review the references for series construction (continued)
  - Reference D : guideline factors for each doubling construction as follows;
    - 0.94 for equipment costs
    - 0.90 for construction labor
    - 0.90 for material cost

    (source: NEA, Cost Estimating Guidelines for Generation IV Nuclear Energy Systems, Sep. 2007, page 54~55)
  - Cost deduction by series construction is to be saturated after 5th-of-a-kind plant.
- Finalize cost estimate
  - Apply cost deduction rate to the result of step 3.
  - Apply additional adjustments factors, if possible or necessary, such factors as subsequent factory fabricated units, staggered construction intervals and periods, design simplification.

IV. Cost Estimate Step (Continued)

❑ Step 5. 

- Document the cost estimate results
  - Document the results in the form of report which can be traced and reviewed.
  - Include primary estimate methods, calculations, results, rationales, scope of boundary, assumptions, source of the data.

- Verify the cost estimate results
  - Request the internal review by the related subject expert.
  - Confirm the result or consult with third party externally.
  - Compare the result with the figure of merit published by credible international nuclear associations. (e.g. overnight unit construction cost)

V. Conclusion

- Initial Overnight Construction Cost Estimate will exhibit considerable uncertainty.
- Magnitude of Uncertainty depends on the level of Project Definition and Reference Data.
  - The cost estimate results should be well documented especially for assumption, exclusion and risk owners, etc.
  - The cost estimate can be repeated and updated according to its purpose and intended use.
- Any combination of Estimate Methods may be applied in any given class of estimate.
- Initial Overnight Construction Cost Estimate can be the basis or input data to further cost estimate (e.g. for Total Project Cost, Plant Life Cycle Cost) and Initial Project Budget.
- Initial Overnight Construction Cost Estimate from single unit FOAK to series twin unit NOAK is important value in business modeling.
- Final Value may be presented in the figure of merit, e.g. $/kWe.


Thank you!

Cost Estimate Classification Matrix for the Process Industry

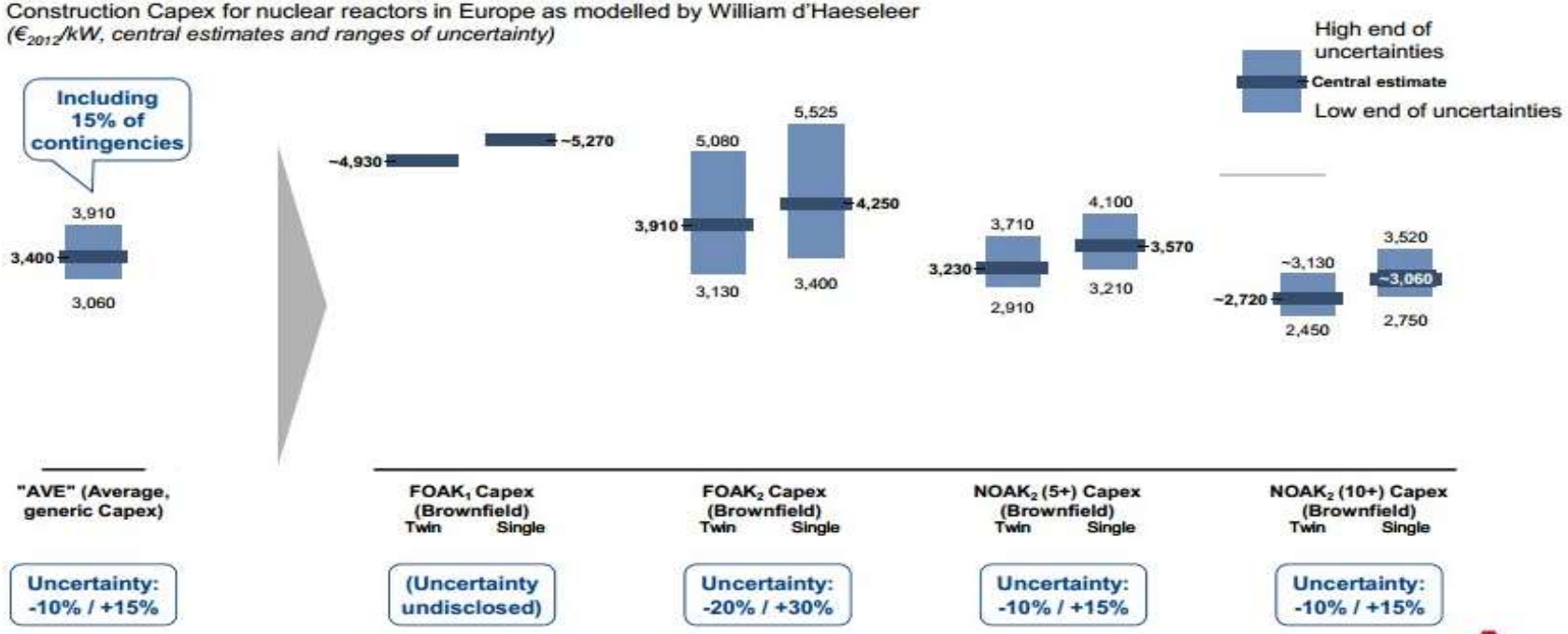
	Primary Characteristic	*Secondary Characteristic*		
ESTIMATE CLASS	**DEGREE OF PROJECT DEFINITION** Expressed as % of complete definition	**END USAGE** Typical purpose of estimate	**METHODOLOGY** Typical estimating method	**EXPECTED ACCURACY RANGE** Typical variation in low and high ranges [a]
Class 5	0% to 2%	Concept screening	Capacity factored, parametric models, judgment, or analogy	L: -20% to -50% H: +30% to +100%
Class 4	1% to 15%	Study or feasibility	Equipment factored or parametric models	L: -15% to -30% H: +20% to +50%
Class 3	10% to 40%	Budget authorization or control	Semi-detailed unit costs with assembly level line items	L: -10% to -20% H: +10% to +30%
Class 2	30% to 70%	Control or bid/tender	Detailed unit cost with forced detailed take-off	L: -5% to -15% H: +5% to +20%
Class 1	70% to 100%	Check estimate or bid/tender	Detailed unit cost with detailed take-off	L: -3% to -10% H: +3% to +15%

Notes: [a] The state of process technology and availability of applicable reference cost data affect the range markedly. The +/- value represents typical percentage variation of actual costs from the cost estimate after application of contingency (typically at a 50% level of confidence) for given scope.

Construction Cost Decrease for Large NPP – French Experience

Based on a study issued by William d'Haeseleer, construction cost decrease by ~35% between a FOAK and a 5th twin-unit

Construction Capex for nuclear reactors in Europe as modelled by William d'Haeseleer
(€2012/kW, central estimates and ranges of uncertainty)



As some Capex values were not explicitly written in the report, AREVA calculated them from W. d'Haeseleer's assumptions, hence the "~" symbol
Source: William d'Haeseleer, 2013 – "Synthesis on the Economics of Nuclear Energy" (public report to the European Commission ENEF)

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Economy of Scale - French Experience

Capital investment decomposition (single unit)

		1 × 300	1 × 650	1 × 1 000	1 × 1 350
20	Land and land rights and site utilities	2.8	2.9	3.0	3.1
21	Buildings and structures	14.8	21.6	26.7	31.0
22	Steam production and discharge processing	23.5	39.4	53.5	66.8
23	Turbines and alternators	10.5	17.7	23.7	29.1
24	Electrical, instrumentation and control	5.6	8.9	11.5	13.8
25	Miscellaneous plant equipment	2.5	3.2	3.7	4.1
26	Water intake and discharge structures	1.9	3.6	5.0	6.4
Sub-total for direct costs		**61.5**	**97.3**	**127.2**	**154.2**
91	Engineering and design	13.3	16.4	18.9	21.1
92	Construction services	6.2	7.1	7.8	8.5
93	Other indirect costs	4.0	4.7	5.4	6.0
Sub-total for indirect costs		**23.4**	**28.2**	**32.1**	**35.6**
Contingencies		2.7	4.1	5.2	6.2
Owner's costs		12.3	15.4	17.5	19.1
Total overnight cost		**100.0**	**145.0**	**182.0**	**215.0**
Specific overnight cost ratio (1 × 300 = 100)		**100**	**67**	**55**	**48**

Source: J. Rouillard and J.L. Rouyer [10].

Capital investment decomposition (two unit)

		2 × 300	2 × 650	2 × 1 000	2 × 1 350
20	Land and land rights and site utilities	2.9	3.1	3.1	3.2
21	Buildings and structures	20.8	30.4	37.6	43.7
22	Steam production and discharge processing	45.8	77.1	105.0	131.1
23	Turbines and alternators	19.5	33.0	44.3	54.3
24	Electrical, instrumentation and control	11.2	17.8	23.0	27.5
25	Miscellaneous plant equipment	4.4	5.6	6.5	7.1
26	Water intake and discharge structures	3.3	6.2	8.8	11.1
Sub-total for direct costs		**107.9**	**173.2**	**228.3**	**278.1**
91	Engineering and design	17.7	23.5	28.4	32.9
92	Construction services	7.5	9.2	10.8	12.2
93	Other indirect costs	5.1	6.7	8.1	9.3
Sub-total for indirect costs		**30.3**	**39.4**	**47.3**	**54.4**
Contingencies		4.7	7.2	9.1	10.8
Owner's costs		15.1	19.1	21.7	23.9
Total overnight cost		**158.0**	**238.9**	**306.4**	**367.1**
Specific overnight cost ratio (1 × 300 = 100)		**79**	**55**	**46**	**41**

Source: J. Rouillard and J. L. Rouyer [10].

* Reduction of Capital costs of NPP, NEA, 2000, page 33-34

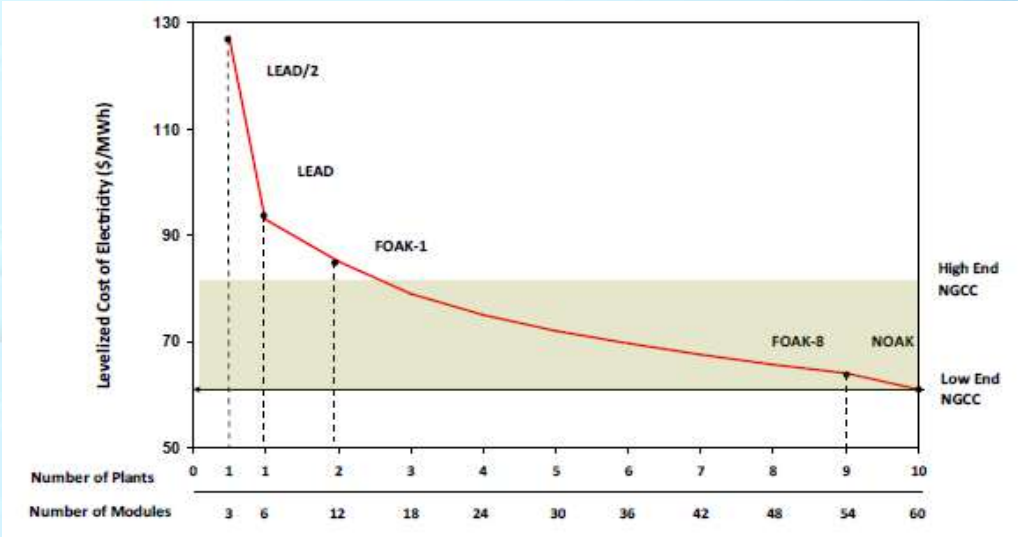
Modeling the SMR Economy

Calculation of Levelized Cost of Electricity for SMRs ($2011, WACC =5.2%)

	Units	NOAK	FOAK-4	LEAD	LEAD/2
Net Electrical Capacity	MWe	600[a]	600[a]	600[a]	300[b]
Direct Costs (see Table 3)	$ M	2,000	2,229	2,837	1,808
Indirect Costs (10% of direct costs)	$ M	200	223	284	181
First Core Costs	$ M	93	93	93	93
DD&E Expenses[c]	$ M	0	50	100	100
Owner's Cost	$ M	200[d]	200[d]	200[d]	200[d]
Overnight Cost	*$ M*	*2,493*	*2,795*	*3,515*	*2,382*
Contingency	%	15	26	35	35
Total Overnight Cost	$ M	2,867	3,529	4,745	3,215
Total Overnight Cost per kW	$/kW	4,778	5,882	7,908	10,717
Interest During Construction Factor	%	8.69	8.69	8.69	8.69
All-in Capital Costs	*$ M*	*3,084*	*3,771*	*5,050*	*3,422*
Levelized Capital Cost + D&D Cost	$/MWh	40.36	49.36	66.09	89.58
Levelized O&M Costs	$/MWh	12.05	13.26	16.54	25.49
Levelized Fuel Cost	$/MWh	8.53	8.53	8.53	8.53
Levelized Cost (real 2011$)	*$/MWh*	*60.95*	*71.15*	*91.17*	*123.60*

a. Six reactors of 100 MWe each. Capacity factor of 90%.
b. Three reactors of 100 MWe each. Capacity factor of 90%.
c. It is assumed that DD&E costs would be 50/50 cost-shared between the federal government and private sector; other scenarios that increase the private sector's share should be considered.
d. Further analysis is required for this cost center.

Levelized costs of learning plants



FOAK Factors and Economy of Subsequent Units on the Site

Productivity and program effects of building NPPs in series

Plant configuration	Productivity effect (multiplicative factor)	Cost of the last unit (in a box)	Total cost of the plant
FOAK	-	$(1+x)T_0$	$(1+x)T_0$
	-	yT_0	$(1+x+y)T_0$
	$\frac{1}{1+k}$	zT_0	$(1+x+y+\frac{z}{1+k})T_0$
	$\frac{1}{(1+k)^2}$	yT_0	$(1+x+y+\frac{z}{1+k}+\frac{y}{(1+k)^2})T_0$

The industrial productivity coefficient k=0%-2%,
FOAK extra cost parameter x=15-55%,
Parameter related to the gain in building a pair of units y=74%-85%,
Parameter related to the gain in building two pairs of units on the same site z=82%-95%

Costs of equipment fabrication and assembly in serial production of nuclear propulsion reactors