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I^2S-LWR Top-Down Differential Economics Evaluation Approach

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ABSTRACT

The Integral Inherently Safe Light Water Reactor (I^2S–LWR) is a design concept of a large (~1000 MWe) light water reactor with integral primary circuit configuration. One of the key design features promoting inherent safety is implementation of an integral primary circuit configuration, which in turn requires a compact design of the core and primary circuit components.

Assessments of the cost of I^2S-LWR is an important aspect of the overall evaluation of the new reactor concept. There are several approaches to cost estimation and economics evaluation of the new nuclear power technologies. Frequently used guidelines rely on the Code of Accounts, originally developed in the U.S. Department of Energy (DOE) Energy Economics Data Base (EEDB) Program Code of Accounts, proposed as evaluation tool by C.R. Hudson, and further popularized in the guidelines for economic evaluation of bids, by The International Atomic Energy Agency (IAEA). The code of accounts allows to break down main costs (Total Capital Investment Cost, Fuel Cycle Cost, Operation and Maintenance) to individual systems and items.

This work aims to implement and apply a top-down differential economics evaluation approach to the Code of Accounts based guidelines, to assess the costs of the I^2S -LWR relative to a representative "standard" PWR. In this methodology, a representative PWR design was taken as a reference and the differential cost was estimated for each individual account based on the design difference (or similarity). Cost estimating techniques were applied to the accounts representing systems that differ from the ones of the reference PWR. In this manner, the cost of the common components cancels out, and the uncertainty in the estimate is reduced.

While this preliminary evaluation yet needs to be completed, the indications so far are that the I^2S-LWR LCOE will be economically competitive with a standard PWR.

Keywords: *PWR, I^2S-LWR, NPP Cost Assessment, Differential Economics, Code of Accounts*

1 INTRODUCTION

The Integral Inherently Safe Light Water Reactor (I^2S–LWR) concept [1,2] is being developed by a multi-disciplinary multi-organization team led by the Georgia Institute of Technology. The reactor concept aims to advance the performance and safety beyond that of current Gen-III+ reactors while maintaining economic competitiveness, through a simplified and low maintenance operation. In particular, the reactor is characterized by an innovative fuel/clad system, passive Decay Heat

Removal System (DHRS), and in-vessel microchannel heat exchangers combined with flashing drums into a Steam Generation System.

Assessments of the cost of I^{2}S-LWR is an important aspect of the overall evaluation of the new reactor concept and its viability for commercialization. There are several approaches to cost estimation and economics evaluation of the new nuclear power technologies. Frequently used guidelines rely on the Code of Accounts, originally developed in the U.S. Department of Energy (DOE) Energy Economics Data Base (EEDB) Program Code of Accounts [3], proposed as evaluation tool by Hudson [4], and further popularized in the guidelines for economic evaluation of bids, by The International Atomic Energy Agency (IAEA) [5]. The code of accounts allows to break down main costs (Total Capital Investment Cost, Fuel Cycle Cost, Operation and Maintenance) to individual systems and items.

In this paper we implemented and applied a top-down differential economics evaluation approach to the Code of Accounts based guidelines, to assess the costs of the I^{2}S -LWR relative to a representative “mainstream” PWR. In this methodology, a representative PWR design was taken as a reference and the differential cost was estimated for each individual account based on the design difference (or similarity). Cost estimating techniques were applied to the accounts representing systems that differ to the ones of the reference PWR. In this manner, the cost of common components cancels out, and the uncertainty in the estimate is reduced. A similar approach was used in [6] to estimate the cost of a Fluoride-salt High-temperature Reactor (FHR).

Cost definitions are summarized in Section 2. Techniques to estimate the Total Capital Investment Cost (TCIC) are discussed in Section 3. The differential economics approach is presented in Section 4. Uncertainties are briefly addressed in Section 5. While this preliminary evaluation yet needs to be completed, the indications so far are that the I^{2}S-LWR LCOE will be economically competitive with a standard PWR.

2 COST DEFINITIONS

The main parameter that is used to compare the cost of electricity produced through different sources, methods and designs is the Levelized Cost of Electricity (LCOE). LCOE represents the cost (in present-value dollars, or other selected currency) per-kWh produced of building and operating a generating plant over an assumed financial life and duty cycle. The factors that affect the LCOE are the following:

- Total capital investment (including interest during construction);
- Operation and Maintenance;
- Fuel;
- Decommissioning.

The predicted LCOE for a given Nuclear Power Plant (NPP) at a time *t* can be evaluated calculating the present value of all the costs items through the following equation [7]:

$$LCOE = \frac{\sum_t \frac{investment_t + OM_t + Fuel_t + Decom_t}{(1+r)^t}}{\sum_t \frac{Electricity_t}{(1+r)^t}} \qquad (1)$$

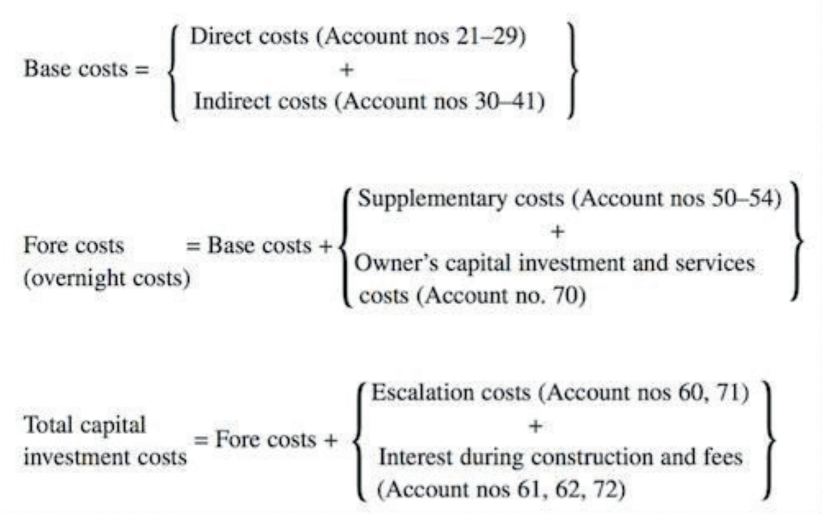
Where r denotes the discount rate, corrected for inflation. This relation is based on two assumptions:

1. The discount rate is stable and does not vary during lifetime of the project under consideration;
2. The price of electricity, P_{el}, is considered to be stable and not to change during the lifetime of the project. All the electricity, once produced, is sold at this price.

To systematically cover these factors for I^{2}S-LWR, the IAEA code of accounts was used. The IAEA account system is in principle capable of describing in detail the cost of a NPP of any size and design, down to individual systems and components. The breakdown of the IAEA accounts system according to the factors that contribute to LCOE is described in this section.

2.1 Total Capital Investment Cost

Total Capital Investment Cost (TCIC) is the parameter that represents the cost of design, construction and testing of the NPP up to commercial operation. TCIC is broken down into the factors shown in Fig. 1. The ‘base costs’ include costs associated with the equipment, structures, installation and materials (direct costs, allocated to accounts 21-29), as well as the engineering, construction and management services (indirect costs, allocated to accounts 30-41). Supplementary costs include spare parts, contingencies and insurance and are allocated to accounts 50-54. Owner’s costs include the owner’s capital investment and services costs, escalation and related financing costs and are described by account 70. The ‘fore costs’ or ‘overnight costs’ consist of the base costs, the supplementary costs and the owner’s capital investment and service costs. Financial costs include escalation (accounts 60, 71), interest during construction (IDC) and fees (accounts 61, 62, 72). Fore costs, escalation costs and IDC and fees define TCIC.



$$\text{Base costs} = \left\{ \begin{array}{c} \text{Direct costs (Account nos 21–29)} \\ + \\ \text{Indirect costs (Account nos 30–41)} \end{array} \right\}$$

$$\begin{array}{l} \text{Fore costs} \\ \text{(overnight costs)} \end{array} = \text{Base costs} + \left\{ \begin{array}{l} \text{Supplementary costs (Account nos 50–54)} \\ \qquad\qquad + \\ \text{Owner's capital investment and services} \\ \text{costs (Account no. 70)} \end{array} \right\}$$

$$\begin{array}{l} \text{Total capital} \\ \text{investment costs} \end{array} = \text{Fore costs} + \left\{ \begin{array}{l} \text{Escalation costs (Account nos 60, 71)} \\ \qquad\qquad + \\ \text{Interest during construction and fees} \\ \text{(Account nos 61, 62, 72)} \end{array} \right\}$$

Figure 1: TCIC breakdown [5]

2.2 Fuel Cycle Cost

Fuel cycle cost is described by the series of accounts presented in Table 1. Fuel cycle cost consists of the cost of the uranium mining, conversion and enrichment; fuel assembly fabrication and transport; spent fuel storage and disposal or reprocessing.

Table 1 – Fuel Cycle code of accounts

100	Fuel assembly, supply, *first core*
101	Uranium supply
102	Conversion
103	Enrichment
104	Fuel assembly fabrication
105	Supply of other fissionable materials
110	Services, *first core*

111	Fuel management (U, Pu, Th)
112	Fuel management schedule
113	Licensing assistance
114	Preparation of computer programs
115	Quality assurance
116	Fuel assembly inspection
117	Fuel assembly intermediate storage
118	Information for the use of third party fuel
120	Fuel assembly, supply, *reloads*
121	Uranium supply
122	Conversion
123	Enrichment
124	Fuel Assembly Fabrication
125	Supply of other fissionable materials
130	Services, *reloads*
131	Fuel management
132	Fuel management schedule
133	Licensing assistance
134	Preparation of computer programs
135	Quality assurance
136	Fuel assembly inspection
137	Fuel assembly intermediate storage
138	Information for the use of third party fuel
140	Reprocessing of irradiated fuel assemblies
141	Credits for uranium, plutonium and other materials
142	Final disposal of fuel assemblies (in the case of no reprocessing)
143	Final waste disposal
170	Financial cost of the nuclear fuel cycle

2.3 O&M

Operation and maintenance costs include all non-fuel related costs needed to operate the plant, as well as maintenance costs. The outline for the IAEA O&M costs account system is presented in Table 2.

Table 2 – O&M code of accounts

800	Wages and salaries for engineering and technical support staff, and O&M and administration staff
810	Consumable operating materials and equipment 820 Repair costs, including interim replacements 830 Charges on working capital
840	Purchased services
850	Insurance and taxes
860	Fees, inspections and review expenses
870	Decommissioning allowances, if not included in capital costs (account 54) 880 Radioactive waste management costs
890	Miscellaneous costs

3 TCIC COST ESTIMATING TECHNIQUES

Total Capital Investment Cost is estimated to contribute about 50-70% to the LCOE for a NPP, followed by O&M and fuel cost [7]. From this consideration arises the importance of studying and analyzing this particular factor above the others. In this section TCIC estimating techniques are presented, with a particular focus on direct cost estimating.

3.1 Bottom-Up Cost Estimating

Bottom-up cost estimating consists of collecting very detailed data on components and activities involved in the NPP construction, such as equipment, materials and labor quantities. Labor-hour rates, installation rates, commodities and unit prices are then applied to calculate costs of activities and components. This approach requires having available a detailed design and construction documents and is applicable to relatively mature designs.

3.2 Top-Down Cost Estimating

For projects early in the development process, bottom-up cost estimates are often not practical (or viable) to use, as information on manufacturing and installation techniques of these systems is not available. For these projects, top-down cost estimating techniques are preferable. The first step consists of identifying a reference design to which estimating techniques can be applied. The estimating part consists of scaling up or down the costs of systems and components used in similar projects.

4 I^{2}S-LWR DIFEFRENTIAL ECONOMICS APPROACH

The I^{2}S-LWR is a reactor at an early stage of development with a small design/development/estimating staff and limited financial resources. The project objective is to assess the difference in TCIC between the I^{2}S-LWR and an idealized representative of current PWRs, to evaluate whether the reactor can be competitive to a standard PWR. For these reasons, a top-down differential approach was used, which consists of evaluating the accounts containing I^{2}S-LWR systems and components that differ from that of the reference design. The approach is illustrated in this section.

4.1 Baseline cost estimate

The reference design was obtained starting from public data [6,7,8], itemized with a great level of detail according to the Code of Accounts. Nuclear Power Plant Cost Data for PWR12BE (best estimate cost for a 1,200 MWe, loop PWR) from [6] were used as the most recent publicly available data. This report provides, for each account, the cost of equipment, site labor and site material. A representative sample of cost data for accounts 22X is shown in Table 3. Summary of costs per high-level accounts is given in Table 4.

The total cost shown in Table 4 is \$3.49B. The costs were reviewed by industry experts, and several corrections and adjustments were made. First, as already shown in Table 4, previously used accounts 91-93 have been replaced with accounts 31-37. Second, detailed review of each subaccount revealed the need to increase the estimates for several items, including the NSSS equipment, reactor I&C, and construction supervision. The combined effect is that the estimated total cost increased to \$3.92B. Moreover, this amount was escalated to 2016\$, giving an updated estimate of \$4.26B. This amount is consistent with the actual current NPP construction costs in the US. For comparison, the cost of the ongoing project constructing two new PWRs is estimated to ~\$16B, or ~\$8B per one PWR.

However, this project cost includes financing costs (interest during construction), grid upgrade costs, and reflects essentially a FOAK construction. The overnight cost of the NOAK NPP alone could then be estimated to be in the $4B-$5B range.

Table 3 – Sample of PWR12BE cost data, per account, in 2011$

220A	Nuclear Steam Supply (NSSS)	Equipment	Site Labor	Site Material	Total
221	Reactor Equipment	174,178,627	9,032,621	14,195,662	197,406,910
222	Main Heat transfer transport system	136,086,550	15,282,276	1,512,180	152,881,006
223	Safeguards systems	79,582,610	13,153,848	1,624,966	94,361,424
224	Radwaste Processing	38,785,262	9,630,929	1,845,586	50,261,777
225	Fuel Handling and storage	26,809,188	2,058,938	253,858	29,121,984
226	Other Reactor Plant Equipment	66,528,996	39,681,605	5,933,026	112,143,627
227	Reactor Instrumentation and Control	53,138,621	18,497,230	1,617,598	73,253,449
228	Reactor Plant Miscellaneous items	-	10,255,392	7,630,068	17,885,460
22	Reactor Plant Equipment	575,109,854	117,592,839	34,612,944	727,315,637

Table 4 – Summary of PWR12BE costs (high-level accounts), in 2011$

Account	**Description**	**Equipment**	**Site Labor**	**Site Material**	**Total**
21	Structures and Improvements Subtotal	$ 54,070,351	$ 272,431,859	$ 155,283,624	$ 481,785,834
22	Reactor Plant Equipment	$ 575,109,854	$ 117,592,839	$ 34,612,944	$ 727,315,637
23	Turbine Plant Equipment	$ 416,437,613	$ 100,710,443	$ 19,920,021	$ 537,068,077
24	Electric Plant equipment	$ 78,512,203	$ 83,340,216	$ 33,322,119	$ 195,174,538
25	Miscellaneous plant equipment subtotal	$ 44,773,942	$ 54,413,727	$ 12,896,887	$ 112,084,556
26	Main Condenser heat rejection system	$ 73,541,933	$ 36,672,240	$ 7,340,144	$ 117,554,317
	Total Direct Costs	$1,242,445,896	$ 665,161,324	$ 263,375,739	$ 2,170,982,959
		Home Office	Site Labor	Site Matl	Total
31	Home Office Design services	$ 482,090,400	$ -	$ -	$ 482,090,400
32	PM/CM at home office	$ 28,490,400	$ -	$ -	$ 28,490,400
33	Design services at site	$ -	$ -	$ -	$ -
34	PM/CM at site	$ -	$ 14,625,600	$ 5,320,800	$ 19,946,400
35	Construction Supervision	$ -	$ 175,005,600	$ 16,281,600	$ 191,287,200
36	Field Indirect	$ 149,260,800	$ 217,833,600	$ 206,587,200	$ 573,681,600
37	Plant Commissioning	$ 27,040,800	$ -	$ -	$ 27,040,800
	Total Indirect Costs	$ 686,882,400	$ 407,464,800	$ 228,189,600	$ 1,322,536,800
	TOTAL	$1,929,328,296	$ 1,072,626,124	$ 491,565,339	$ 3,493,519,759

4.2 Differential Economics

Since the purpose of this work is not to establish the absolute cost of I^{2}S-LWR, but to evaluate the cost of electricity produced by the I^{2}S-LWR as compared to that of current PWRs, a differential approach is used. Under this approach, only the cost of components that differ from the standard design are evaluated, through cost estimating techniques. For example, applying differential economics, it is reasonable to assume that both I^{2}S-LWR and a loop PWR of same power level would use essentially identical switchyards, at essentially identical cost, whatever that cost may be. On the other hand, when the design is different, the cost difference will be estimated. Three examples are given to further illustrate this point:

- Due to its cladding material selection, and other safety features, I^{2}S-LWR does not require hydrogen recombiners. Thus, its equipment cost is reduced by the estimated typical cost of this equipment.

- On the other hand, I^{2}S-LWR will have a larger reactor pressure vessel, due to its integral configuration. Thus, we need to estimate the cost increase of its vessel.
- As a trade-off example, instead of primary loops with steam generators, I^{2}S-LWR will have primary heat exchangers combined with flash drums to generate steam. In this case, cost of both systems needs to be estimated. However, the relevant outcome of our analysis is the difference, not the individual numbers. The uncertainties in some assumptions needed for analyses (e.g., cost of material, needed in both cases) may partly or almost completely cancel out thus reducing the uncertainty in differential economics.

The accounts describing components that are different than that of the PWR12-BE were identified first. For these accounts, the percentage of the total direct investment cost was calculated. A higher priority was assigned to those components with a higher cost percentage of the total cost and the cost estimating process started from the accounts having a higher priority. The accounts cost and their relative weights (percent contributions to the total cost) are shown in Table 5.

Table 5 – Accounts with differing cost basis and their percent contributions to the total cost

Account		**Cost**	**% Cost**
211	Yardwork	59,982,046	2.56%
212	Reactor Containment Building	121,358,642	5.17%
217	Fuel Storage Building	23,709,846	1.01%
218A	Control and Diesel Generator Building	43,436,753	1.85%
218J	Main steam and FW pipe enclosure	18,881,193	0.80%
218T	Ultimate heat sink structure	11,031,771	0.47%
221	Reactor Equipment	197,406,910	8.41%
222	Main Heat transfer transport system	252,881,006	10.78%
223	Safety systems	94,361,424	4.02%
226	Other Reactor Plant Equipment	112,143,627	4.78%
227	Reactor Instrumentation and Control	148,253,449	6.32%
228	Reactor Plant Miscellaneous items	17,885,460	0.76%
231	Turbine Generator	321,562,255	13.71%
233	Condensing Systems	69,556,766	2.96%
234	Feedwater Heating system	56,613,122	2.41%
235	Other turbine plant equipment	53,575,665	2.28%
236	Instrumentation and control	16,450,109	0.70%
237	Turbine plant miscellaneous items	19,310,160	0.82%
241	Switchgear	28,671,080	1.22%
242	Station service equipment	48,392,131	2.06%
243	Switchboards	4,917,355	0.21%
244	Protective equipment	10,227,327	0.44%
245	Electric structure and wiring	53,524,039	2.28%
246	Power and Control wiring	49,442,606	2.11%
251	Transportation and Lifting equipment	14,385,192	0.61%
252	Air, water and steam service systems	68,941,569	2.94%
253	Communication equipment	15,396,111	0.66%
254	Furnishing and Fixtures	6,566,362	0.28%
255	Waste water treatment equipment	6,795,322	0.29%
261	Structures	10,398,528	0.44%
262	Mechanical Equipment	107,155,789	4.57%

The main component contributing to direct cost is the main heat transfer system (Account 222). The system includes main coolant pumps, pressurizer and steam generation system (primary heat exchangers, intermediate piping). The steam generation system is different from that of a standard PWR as it is made of innovative components (microchannel heat exchanger).

The integral configuration has another implication on Account 221, which includes the Reactor Pressure Vessel (RPV), which has a larger diameter and height, control rods and internals. On the cost reduction side, the reactor coolant piping (in Account 222) is not present and the pressurizer is integrated in the hemispherical head of the vessel.

Safety systems are allocated to Account 223. The passive DHRS of the I^2S-LWR consists of a helical coil intermediate heat exchanger placed in the RPV, a water intermediate loop, and a tower water to air heat exchanger. A careful cost analysis of the items included in this account is needed.

Turbine generator equipment (Accounts 23x) is believed to be not much different than that of the reference design. Factors will be applied to scale the cost of these components to the power level of the I^2S-LWR.

I^2S-LWR structures (Accounts 21x) mainly differ from that of a standard LWR in yardwork for the reactor containment vessel, which is partially below grade. The cost associated to this account will depend on the excavation depth that will be chosen. The seismic protection relies on seismic isolators installed on the nuclear building sub-foundation, which are also included in these accounts.

5 TREATMENT OF UNCERTAINTIES

In the cost estimation stage, costs data is collected from historically built plants, manufacturing techniques and expert knowledge on fabrication of innovative components. These costs are then analyzed and manipulated through cost estimating techniques. The cost that will be used for each account is a “most likely” estimate based on industry experts experience and historical data [9]. However, an amount of uncertainty is associated to both the cost analysis process and the cost estimating techniques, with a resulting uncertainty level associated to each account. Uncertainties are inherent to the cost estimating process and are not possible to eliminate, in particular at an early stage of the project. As the development of the I^2S-LWR proceeds and the components sizing, life performance and manufacturing techniques get more well-defined, the level of uncertainty of each account will be reduced. The combination of uncertainties of different accounts might result in a large uncertainty in the value of TCIC and LCOE that needs to be assessed. Therefore, in the cost estimating process, both the best estimate and the appropriate probability distribution function need to be identified for each cost item and account.

In our future work, stochastic methods will be applied to the cost estimating process, associating each cost with a probability distribution. In project management, triangular distributions are often used to describe the stochastic nature of the cost of activities and components [10]. A triangular distribution is defined by three values: the best estimate, the minimum value and the maximum value. Multiple triangular distributed random variables result in a non-triangular distributed combined random variable whose probability distribution can be estimated analytically [11] or through stochastic simulations. The TCIC probability distribution and level of uncertainty, which is a result of the uncertainties of all accounts, can also be assessed through Monte Carlo calculations. Through this method, costs of components and accounts are repetitively sampled according to their probability distribution to estimate the dispersion on the value of TCIC.

6 CONCLUSION

Because of its innovative design, a top-down differential economics methodology was adopted for the evaluation of I^2S-LWR economic. This methodology relies on the Code of Accounts and aims to evaluate the cost difference with respect to a representative conventional reactor. A 1,200 MWe standard PWR was taken as a design reference and cost estimating techniques were applied to assess the cost difference between the reference reactor and the I^{2}S-LWR. The process and methodology are based on an open methodology and on publicly available data, and in principle can be applied to NPPs of any size and design.

While this preliminary evaluation yet needs to be completed, the indications so far are that the I^{2}S-LWR LCOE will be economically competitive with a standard PWR.

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