

Assessing I²S-LWR Economic Competitiveness Using Systematic Differential Capital Cost Evaluation Methodology

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Highlights

- Developed a methodology for systematic evaluation of differential nuclear power plants capital cost, based on the code of accounts;
- The methodology has been applied to evaluate the Integral Inherently Safe Light Water Reactor (I²S-LWR);
- The analysis indicates the economic competitiveness of the I²S-LWR as compared to a traditional loop PWR design.

List of abbreviations

CPI: consumer price index

CV: containment vessel

DHRS: decay heat removal system

DOE: Department of Energy

EEDB: Energy Economics Data Base

FHR: Fluoride-salt High-temperature Reactor

HICP: Harmonised Index of Consumer Prices

I²S-LWR: Integral Inherently Safe Light Water Reactor

IAEA: International Atomic Energy Agency

IHX: intermediate heat exchanger

IRIS: International Reactor Innovative and Secure

MCHX: microchannel heat exchanger

MSBR: Molten Salt Breeder Reactor

NPP: nuclear power plant

NSSS: nuclear steam supply system

PCCS: passive cooling containment system

PCHE: printed circuit heat exchanger

PGA: peak ground acceleration

RPV: reactor pressure vessel

SMR: small modular reactor

Abstract

One of the main factors impeding nuclear power plant (NPP) construction is their economics. In this study, a systematic differential economics evaluation approach was developed through the use of the Code of Accounts guidelines to assess the costs of nuclear power plants. The methodology, entirely based on publicly available data, may serve as a template to evaluate direct costs for reactors of any size and design at any stage of developments. In particular, this approach was used to assess the costs of the Integral Inherently Safe Light Water Reactor (I²S-LWR).

The I²S-LWR is a design concept of a large (~1000 MWe) light water reactor. One of its key design features promoting inherent safety is implementation of an integral primary circuit configuration, which however necessitates a compact design of the core and primary circuit components.

Through the methodology here presented, a representative loop 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 scaling techniques were applied to the accounts representing systems that differ from the ones of the reference PWR. Cost estimating techniques were used to evaluate cost of innovative components that are not part of standard PWR designs. By evaluating the cost difference of the I²S-LWR from the standard PWR, rather than the absolute cost, the uncertainty in the estimate is reduced. A similar approach was used by ORNL to estimate the cost of a Fluoride-salt High-temperature Reactor (FHR).

A traditional four-loop PWR plant with a core thermal power of 3417 MWth (1144 MWe) was selected as the reference. Costs for that plant were prepared in 1978 by the Department of Energy (DOE) Energy Economics Data Base (EEDB), averaging actual cost incurred in the construction of several nuclear power plants (NPP), itemized with a great level of detail according to the Code of Accounts. This best estimate costs are denoted PWR12-BE. For each account, the cost of equipment, site labor and site material is provided. Industry experts at Westinghouse Electric Company performed a “sanity check” of the cost items, adjusting the cost of several items to match the current market and supply chain data.

The detailed cost assessment of I²S-LWR was performed, systematically analyzing cost for each account, and applying the differential economics approach. First, Relative importance of each account, i.e., its contribution to the total cost was established, to help focus analysis on the most significant contributors. Moreover, the accounts describing components that are different than that of the PWR12-BE were identified.

The integral configuration of the reactor has important implications on the cost of the reactor plant equipment (accounts 22x). Turbine generator equipment (Accounts 23x) is not believed to be much different than that of the reference design. I²S-LWR structures (Accounts 21x) mainly differ from that of a standard LWR as several buildings (containment building, shield building, annex building, waste processing building, fuel storage building) are integrated into a single building (nuclear island). Yardwork has a higher cost for the I²S-LWR, as the NI is partially below grade. On the other hand, due to its compact Nuclear Island footprint, I²S-LWR facilitates (and includes in its reference version) the use of seismic isolators, which contribute to reducing

the direct cost. The total capital investment cost (TCIC), on the \$/kW basis, of I²S-LWR is 5.84% lower than that of PWR12-BE, in spite of the lower power output of I²S-LWR. However, for the Western US (0.7g), benefits of the seismic isolation are more pronounced, and the I²S-LWR total capital investment cost is 13.02% lower than that of PWR12-BE. If the I²S-LWR is compared to a PWR10-BE (traditional loop design, but scaled to the same power level as I²S-LWR), the savings are even higher, in the range 11.12%-17.89%.

The analysis indicates that I²S-LWR has potential to offer an economically attractive design, with TCIC lower than that of a nuclear power plant based on a traditional loop PWR design. In other words, I²S-LWR design offers significantly enhanced safety, while at the same time improving economics.

The differential economics approach developed in this paper can be used in identifying changes in cost of key components in order to improve the economics of a nuclear reactor design. The method can also help compare the economics of advanced Generation IV reactors and innovative water-cooled SMR (Small Modular Reactors) with respect to standard LWR technologies. In summary, the differential economics approach and can be used as a tool capable of helping stakeholder decisions.

1. Introduction

Assessment of the cost of a nuclear reactor design is an important aspect of the overall evaluation of any new reactor concept and its viability for commercialization. There are several approaches to cost estimation and economics evaluation of 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 (US Department of Energy, 1988), proposed as evaluation tool by Hudson (Hudson, 1986), and then published in the guidelines for economic evaluation of bids, by The International Atomic Energy Agency (IAEA) (1999). 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. A systematic differential economics evaluation approach was developed through the use of the Code of Accounts guidelines to assess the costs of the NPP under consideration relative to a representative “mainstream” PWR.

In this methodology, a representative loop PWR design is taken as a reference and the differential cost was estimated for each individual account based on the design difference, or similarity. Cost scaling techniques are applied to the accounts representing systems that differ from the ones of the reference PWR. Cost estimating techniques are used to evaluate cost of innovative components that are not part of standard PWR designs. By evaluating the cost difference of the NPP from the standard PWR, rather than the absolute cost, the uncertainty in the estimate is reduced. A similar (even though less detailed) approach was used to estimate the

cost of a Fluoride-salt High-temperature Reactor (FHR) (Holcomb et al., 2011) and of integral small PWRs (Carelli et al., 2007b).

This methodology was used to assess the direct cost of the Integral Inherently Safe Light Water Reactor (I²S-LWR) (Petrovic, 2014a, 2014b; Petrovic et al., 2017). The I²S-LWR is an innovative light water reactor that was developed by a multi-disciplinary multi-organization team led by the Georgia Institute of Technology, as a U.S. DOE NEUP integrated research project (IRP) (Petrovic, 2017). 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. A schematic of the I²S-LWR integral reactor pressure vessel (RPV) concept is shown in Figure 1, while a schematic of the I²S-LWR site is shown in Figure 2.

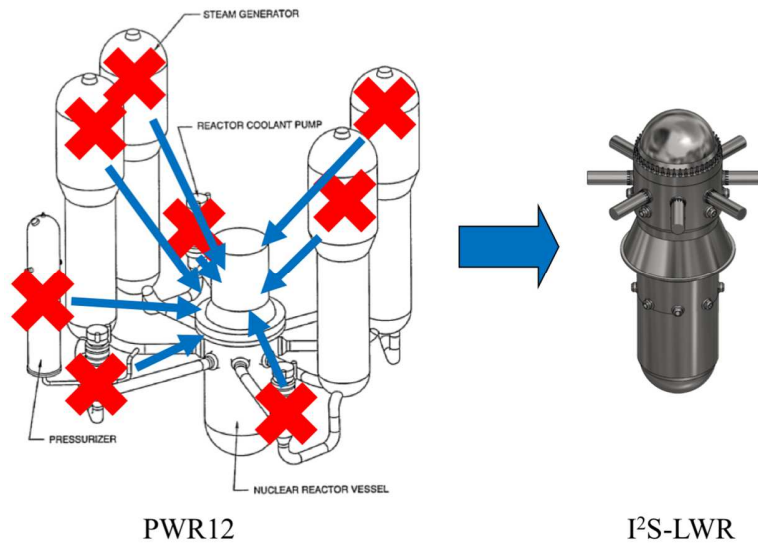


Figure 1 – PWR steam generator, primary loop and piping (US Nuclear Regulatory Commission, 2012) as compared to I²S-LWR integral RPV concept

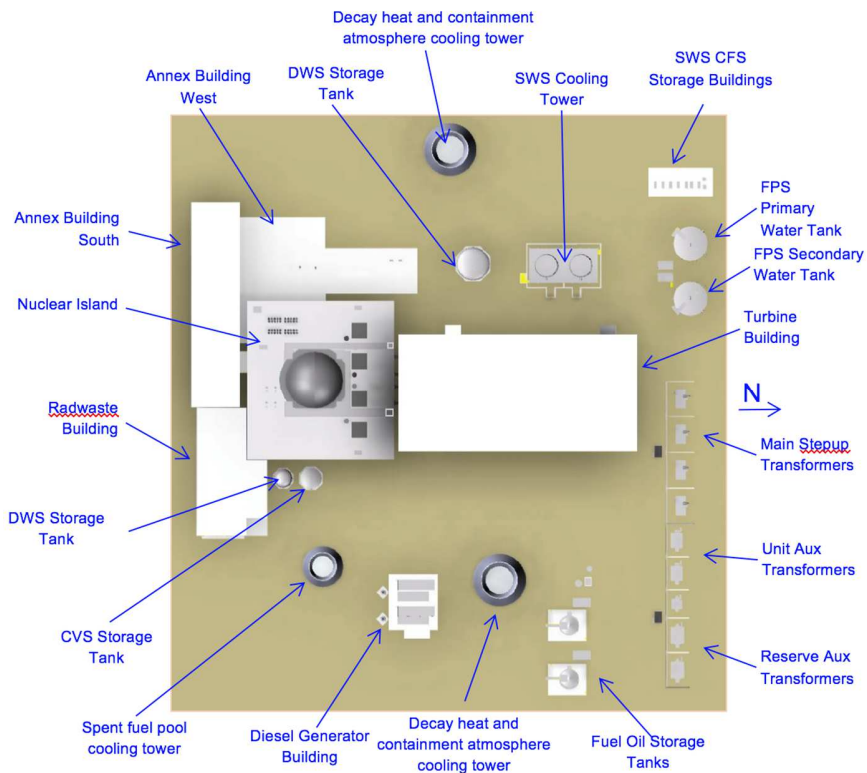


Figure 2 – I²S-LWR site layout (Ammerman et al., 2017)

The design differences between the I²S-LWR and a traditional four loop PWR (PWR12) are shown in Table 1, in particular those that lead to different systems and components.

Table 1 – Design differences between PWR12 and I²S-LWR

	PWR12 (US Department of Energy, 1987c)	I ² S-LWR (Petrovic, 2017)
Power [MWe]	1144	985
Primary circuit	Loop	Integral
Steam generation system	Steam generators	Primary heat exchangers and flash drums
Main coolant pumps	Primary loop inline	Attached to RPV
Pressurizer	Primary loop inline	Integrated in RPV head
Emergency decay heat removal system	Active	Fully passive
CRDM	External	Internal
Ultimate heat sink	Pool/tank (limited)	Ambient air (unlimited)
Grace period	Hours	Practically indefinite under most scenarios
Large break LOCA (LB-LOCA)	Possible	Not possible
LOCA mitigation	High pressure system injection	Equalization of pressure in vessel and containment
Containment cooling	Active	Passive
Spent fuel cooling	Active	Passive
Primary seismic design approach	Reinforced components	Seismic isolators
Nuclear island	Traditional	Compact

The rest of this article is organized as follows. Section 2. summarizes this approach and relates it to the Code of Accounts. In Section 3. the basic cost definitions that were used in the cost evaluation are summarized, and cost scaling techniques are described. Section 4. contains the I²S-LWR direct cost estimation. Section 5 describes the indirect capital cost, capitalized preconstruction cost, capitalized owner's costs and overnight capital cost estimation. The impact of seismic isolators on overnight capital cost is assessed in Section 6.

2. Objective and approach

The objective of this study was to develop a methodology to compare the capital cost of the I²S-LWR plant and a standard PWR plant. Under this methodology, only the cost of components, systems and labor that differ from the standard design are evaluated, through cost estimating techniques. Costs of similar components were scaled using cost scaling techniques.

For this purpose, a systematic differential approach was used. First, a reference PWR design was identified. Nuclear Power Plant Cost Data for PWR12-BE (best estimate cost for a 1,144 MWe, loop PWR) from Holcomb et al. (2011) was used as this is the most recent publicly available data. The PWR12-BE represents a traditional four-loop PWR plant, with a core thermal power of 3417 MWth (US Department of Energy, 1987c). Costs for the plant were prepared in 1978 by EEDB, averaging actual cost incurred in the construction of several nuclear power plants (NPPs), itemized with a great level of detail according to the Code of Accounts. For each account, the cost of equipment, site labor and site material is provided. The latest version of the account cost items were released in 1988 (US Department of Energy, 1987a, 1987b, 1987c), and are summarized in Holcomb et al. (2011) along with the amounts converted to January 2011 US dollars. Industry experts at Westinghouse Electric Company performed a “sanity check” of the cost items (Mack, 2016). The equipment cost of account 222 (Main heat transfer transport system) was increased by \$100 M (in 2011 USD) to match the current market and supply chain data. Similarly, the equipment cost of account 227 (Reactor instrumentation and control) was increased by \$75 M (in 2011 USD) and construction supervision on site (from (US Department of Energy, 1987a, 1987b, 1987c)) was increased by \$250 M (in 2011 USD).

The accounts describing components that are different than that of the PWR12-BE were then identified. For these accounts, the percentage of the total direct investment cost was calculated. The accounts having a higher cost percentage of the total cost were given a higher priority and were estimated first. The accounts cost and their percent contributions to the total cost are shown in Table 2.

Table 2 – Accounts with differing cost basis and their percent contributions to the direct costs (Holcomb et al., 2011)

Account	Cost	% Cost
211 Yardwork	59,982,046	2.56%
212 Reactor Containment Building	155,606,497	6.63%
213 Turbine Room and Heater Bay	55,565,592	2.37%
214 Security Building	3,268,692	0.14%
215 Primary Auxiliary Building and Tunnels	44,333,149	1.89%
216 Waste Processing Building	34,481,564	1.47%
217 Fuel Storage Building	23,709,846	1.01%
218 Other Structures	104,838,447	4.47%
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%
224 Radwaste Processing	50,261,777	2.14%
225 Fuel Handling and storage	29,121,984	1.24%
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	107,155,789	4.57%
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	68,941,569	2.94%
	TOTAL	2,345,982,958	100.0%

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 exchangers, flash drums).

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

Safety systems are allocated to Account 223. The passive DHRS of the I²S-LWR consists of a helical coil intermediate heat exchanger placed in the RPV, a water intermediate loop, and a cooling tower with a water-to-air heat exchanger. A careful cost analysis of the items included in this account was performed.

Turbine generator equipment (Accounts 23x) is not believed to be much different than that of the reference design. Factors were applied to scale the cost of these components to the power level of the I²S-LWR.

I²S-LWR structures (Accounts 21x) mainly differ from that of a standard LWR as several buildings (containment building, shield building, annex building, waste processing building, fuel storage building) are integrated into a single building (nuclear island). Yardwork has a higher cost for the I²S-LWR, as the NI is partially below grade. The cost associated with this account will depend on the excavation depth that will be chosen. On the other hand, due to its compact Nuclear Island footprint, I²S-LWR facilitates—and includes in its reference version—the use of seismic isolators, which contribute to reducing the direct cost. The seismic isolators are installed on the nuclear building sub-foundation, and are also included in these accounts.

3. Cost definitions and methodology

3.1 Factory equipment cost and sizing

Cost of components can be broken down into few categories. The cost of a complete component (C) is made of the equipment cost (C_{eq}) and installation cost (C_{inst}).

$$C = C_{eq} + C_{inst} \quad (1)$$

The equipment cost reflects the cost of material and labor associated with the manufacturing stage. As an example, the equipment cost for a shell and tube heat exchanger not only consists of

the cost of material (steel) but also the machining and labor costs to transform the raw material into tubes, bend the tubes, and assemble them into a final heat exchanger.

$$C_{eq} = C_{mat} + C_{lab} \quad (2)$$

Similarly, the installation cost consists of the material ($C_{mat,inst}$) and labor ($C_{lab,inst}$) needed to install and make the component able to operate in the plant.

$$C_{inst} = C_{mat,inst} + C_{lab,inst} \quad (3)$$

For a component, equipment cost can be estimated through a bottom-up approach calculating the quantity of material, the man-hours and machine-hours needed for the component fabrication. However, calculating labor cost can be quite difficult in absence of specific estimates and quotes from manufacturers. Equipment cost can also be estimated through scaling techniques from the cost of a component taken as a reference based on a particular size or capacity involved. Special care must be taken to make certain that the two pieces of equipment are characterized by similar type of construction, materials of construction, operating ranges, and other variables. (Peters et al., 2003). As an example, the cost of a heat exchanger of a certain size (heat exchange area) can be estimated from the cost of a tube and shell heat exchanger of the same design, with known cost and size. Predictions for the unknown cost of equipment A can be scaled using the power relationship known as the six-tenths factor rule, from a similar component B having different capacity (Peters et al., 2003). The scaling law can be expressed as:

$$C_A = C_B \cdot \left(\frac{S_A}{S_B}\right)^n \quad (4)$$

Where C_A and C_B represent the cost of components A and B and S_A and S_B the correspondent capacities under consideration. Peters et al. (2003) (Chapter 6) suggests scaling exponents (n) and capacities to use for scaling the cost of various mechanical and chemical equipment, such as pumps, tanks, pipes and pressurized vessels. The author warns that the cost capacity concept should not be used beyond a 10-fold range capacity. In case of the absence of other information, the author suggests using an exponent equal to 0.6. Economic Modeling Working Group (2007) shows typical scaling exponents and capacities of components and equipment used in the nuclear industry, and are reported in Table 3. Phung (1987) presents scaling factors for direct and indirect cost items, for nuclear and coal power plants (Table 4).

Table 3 – Sample size/rating cost exponent factors (Economic Modeling Working Group, 2007)

Plant	Rating (unit of measure)	Cost exponent
Generation Plant		
Steam turbine	kWe	0.50
Diesel generators to 500Ton/min	kWe	0.62
Diesel generators to 120Ton/min	kWe	
Gas turbines	kWe	
Combined cycle gas turbines	kWe	
Equipment		
Centrifugal pump and motor	HP	0.41
Compressors and motors	HP	0.83
Electric motors > 50kW	kW	0.77
Heat exchangers (over 100m ²)	m ³	0.62
Tanks	m ³	0.63
River pumps and filtration plant	LPM	0.81
River pumps, filters and treatment plant	LPM	0.44
Refrigeration plant	Ton	0.72
Gas compressor and motor	HP	0.82

Piston pumps	HP	0.71
Horizontal vessel	m ³	0.60
Vertical vessel	m ³	0.65
Air receiver	m ³	0.73
Heat exchanger	m ²	0.65

Table 4 – Nuclear and coal cost-size scaling exponents (Phung, 1987)

	Scaling exponents	
	Nuclear	Coal
Direct costs		
Land and land rights	0	0
Structures and improvements	0.50	0.55
Reactor/boiler plant equipment	0.60	0.60
Turbine plant equipment	0.80	0.75
Electric plant equipment	0.40	0.50
Miscellaneous plant equipment	0.30	0.25
Main condenser heat rejection system	0.80	0.95
Indirect costs		
Construction services	0.45	0.60
Ham office engineering and services	0.20	0.60
Field office engineering and services	0.40	0.70
Owner's costs	0.50	0.60

For special materials, high pressures and special designs involving different capacities and costs, equipment cost can be corrected through a “material and pressure factor”, *MPF*, as (Guthrie, 1969):

$$C_{eq,corrected} = C_{eq} \cdot MPF \quad (5)$$

Fuente (2013) shows different factors that affect *MPF* for a broad variety of components (Table 5).

Table 5 – MPF for different components

EQUIPMENT	MPF
Pressure vessels	$F_m \cdot F_p$
Heat exchangers	$F_m \cdot (F_p + F_d)$
Centrifugal pumps	$F_m \cdot F_o$

The *MPF* factor is made of the following factors:

- *F_d*: design variation
- *F_m*: construction material variation
- *F_p*: pressure variation
- *F_o*: operating limits (as a function of Temperature and Pressure)

Final cost of the installed equipment can be calculated from the basic cost, taking into account labor, piping instruments and accessories through an empirical “Module factor”, *MF*:

$$C = C_{eq,corrected} \cdot MF \quad (6)$$

The module factor expresses the ratio between the total cost (equipment and installation) and the equipment cost. Therefore, the module factor includes the installation cost, which can be calculated from the equipment cost as:

$$C_{inst} = C_{eq} \cdot (MF - 1) \quad (7)$$

Peters et al. (2003) (in Chapter 6, page 244) shows values of $(MF-1)$ for different types of process equipment. Typical values are in the range 0.2-0.9. The range of the installation cost as a fraction of the equipment cost varies broadly for different component types. Therefore, a conservative assumption has been made for the I²S-LWR cost of components estimation and the upper bound of the parameter $(MF-1)$ is taken. A more detailed evaluation with specific $(MF-1)$ factors would somewhat reduce the I²S-LWR cost estimate. Moreover, the value of the $(MF-1)$ factor depends on the location where the installation activity is performed. If a component is modularized, the installation activity can be shifted to a location where it can be performed more efficiently, with a subsequent lower labor time. The 1-3-8 rule describes the reduction in labor time obtained as activities are performed in more efficient locations, as 1, 3 and 8 represent the required labor time to perform the same task in an off-site factory, in the on-site assembly area and in the on-site hole (Barry, 2009; US Government Accountability Office, 2010). I²S-LWR is designed to allow and maximize modular construction. This can provide additional savings, on the order of 10-15% (Maronati et al., 2016a; Maronati et al., 2017; Maronati et al., 2016b). However, since the modular construction has not been widely demonstrated for nuclear power plants, this potential saving was also not credited to I²S-LWR in this study.

3.2 Structural components cost and sizing

In a stick-built Nuclear Power Plant, the structural materials are transported to the site where the structures are built. In the construction of structural components, often the manufacturing stage is not present and the cost of the component (Eq.(1)), simplifies to:

$$C = C_{inst} = C_{mat,site} + C_{lab.site} \quad (8)$$

3.3 Escalation and Cost Indices

In the cost estimation described in this report, costs of different components are scaled based on the component costing data from different sources. In these sources, costs refer to specific years and are affected by the market value of the materials, the power value of the currency and the base currency to dollar exchange rate in the reference year. Since the price of materials, the purchasing power of the currency and exchange rates change considerably over time, it is necessary to refer all costs to the same year. Holcomb et al. (2011) escalated the PWR12-BE costs from 1987 to 2011 using an escalation factor of 2.4 (results previously shown in Table 2). The value of this factor was chosen to reflect the escalation shown both by the Civil Works Construction Cost Index and the Handy-Whitman index. For the purpose of this report, January 2016 is chosen as the time reference, and costs from all references were escalated to the value of January 2016 USD using the Consumer Price Index (CPI) prepared by the US Department of Labor (2017). The PWR12-BE account costs, escalated to 2016 USD, are shown in Table 6. Costs estimated based on several novel components that were available in euros were first escalated to the value of 2016 euros using the Harmonised Index of Consumer Prices (HICP) for the euro area (European Central Bank, 2017), and the converted to 2016 USD using the monthly euro-dollar exchange rate for January 2016 (X-Rates).

Table 6 – Accounts with differing cost basis and their percent contributions to the direct costs (2016 USD, escalated from Holcomb et al. (2011))

Account	Cost	% Cost
211 Yardwork	66,434,915	2.56%
212 Reactor Containment Building	172,346,644	6.63%
213 Turbine Room and Heater Bay	61,543,338	2.37%
214 Security Building	3,620,338	0.14%

215	Primary Auxiliary Building and Tunnels	49,102,509	1.89%
216	Waste Processing Building	38,191,091	1.47%
217	Fuel Storage Building	26,260,551	1.01%
218	Other Structures	116,116,967	4.47%
221	Reactor Equipment	218,643,945	8.41%
222	Main Heat transfer transport system	280,085,945	10.78%
223	Safety systems	104,512,826	4.02%
224	Radwaste Processing	55,668,939	2.14%
225	Fuel Handling and storage	32,254,927	1.24%
226	Other Reactor Plant Equipment	124,208,038	4.78%
227	Reactor Instrumentation and Control	164,202,555	6.32%
228	Reactor Plant Miscellaneous items	19,809,578	0.76%
231	Turbine Generator	356,155,922	13.71%
233	Condensing Systems	77,039,683	2.96%
234	Feedwater Heating system	62,703,562	2.41%
235	Other turbine plant equipment	59,339,335	2.28%
236	Instrumentation and control	18,219,812	0.70%
237	Turbine plant miscellaneous items	21,387,547	0.82%
241	Switchgear	31,755,515	1.22%
242	Station service equipment	53,598,156	2.06%
243	Switchboards	5,446,364	0.21%
244	Protective equipment	11,327,583	0.44%
245	Electric structure and wiring	59,282,155	2.28%
246	Power and Control wiring	54,761,642	2.11%
251	Transportation and Lifting equipment	15,932,751	0.61%
252	Air, water and steam service systems	118,683,609	4.57%
253	Communication equipment	17,052,425	0.66%
254	Furnishing and Fixtures	7,272,771	0.28%
255	Waste water treatment equipment	7,526,363	0.29%
261	Structures	11,517,202	0.44%
262	Mechanical Equipment	76,358,303	2.94%
	TOTAL	2,598,363,806	100.0%

3.4 Steel physical parameters and costs

A density of 7,860 and 7,970 kg/m³ was used for carbon steel and stainless steel, respectively. A representative carbon steel cost of 1,000 dollars per ton was used. Peters et al. (2003) shows that the cost of stainless steel SS-316 ranges between 2.3-4.3 the cost of carbon steel. A conservative

value of 4.3 was used to calculate the cost of SS-316 from the reference costs of carbon steel. Since some equipment costs are expressed in other reference year dollars, the steel unit costs were escalated using the CPI (US Department of Labor, 2017).

4. Direct capital cost evaluation

This section compares, account by account, cost of I²S-LWR against the representative traditional loop PWR, PWR12.

4.1 Structures and improvements – account 21

The I²S-LWR relies on a more compact site layout than that of the PWR12, as shown in Figure 3 (Ammerman et al., 2017). The I²S-LWR nuclear island performs the function of the PWR12 containment building, fuel storage building, administration and service building, and part of the radioactive waste (radwaste) building. Furthermore, as the I²S-LWR relies on fully passive safety systems, the diesel generators are not present.

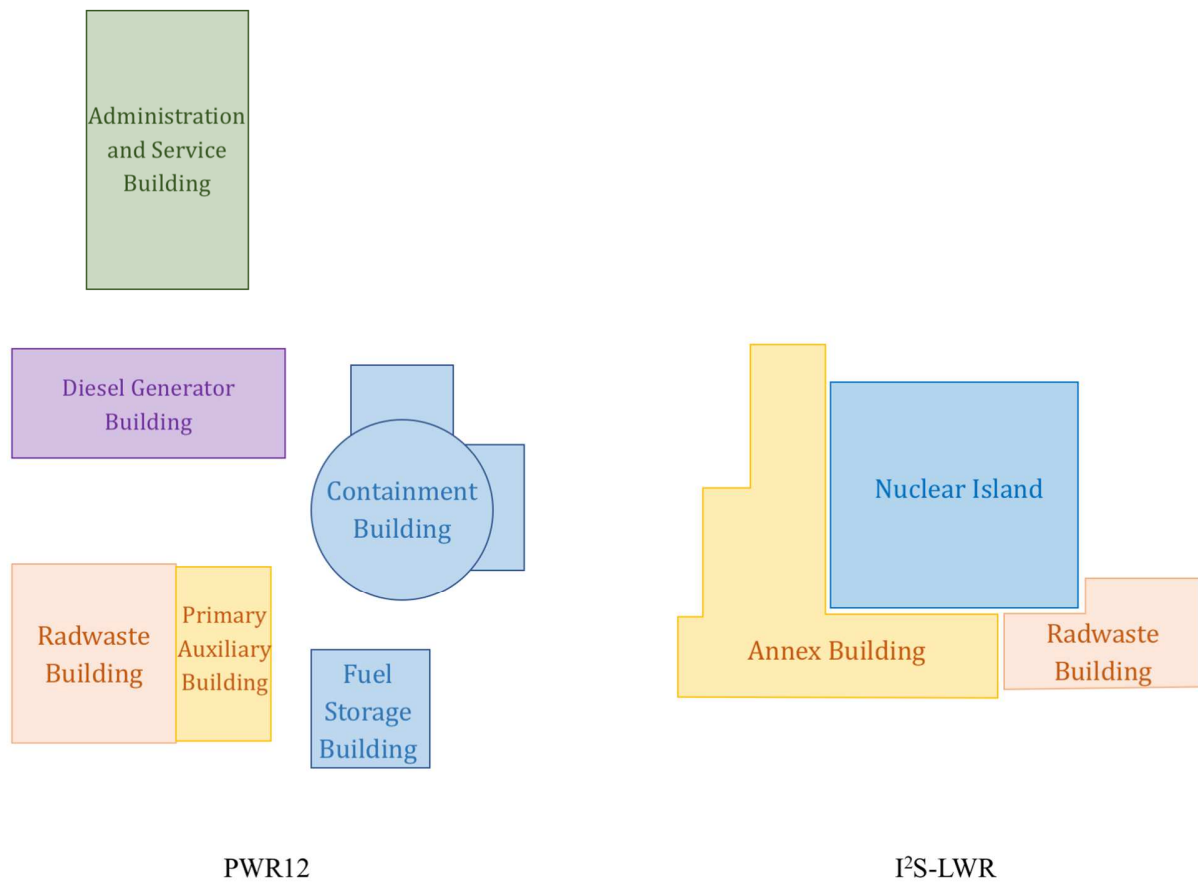


Figure 3 – PWR12 and I²S-LWR site layout comparison (Ammerman et al., 2017)

4.1.a Account 211 – site preparation/yardwork

Site preparation/yardwork cost depends on the size of the construction site. However, a conservative approach was used to estimate the cost of this account, as it was scaled based on the reactor electric power, with an exponent equal to 0.5 (Phung, 1987). As the I²S-LWR is designed to increase compactness, this approach is conservative, i.e., it does not give full credit to I²S-LWR for its compact nuclear island. Costs of account 211, for the PWR12-BE and the I²S-LWR are shown in Table 7.

Table 7 – Yardwork - account 211 (2016 USD)

		<i>PWR12-BE</i>		<i>P²S-LWR</i>		
		<i>Total</i>	<i>Equipment</i>	<i>Site Labor</i>	<i>Site Material</i>	<i>Total</i>
<i>211</i>	<i>Yardwork</i>	<i>66,434,915</i>	<i>700,558</i>	<i>35,744,058</i>	<i>25,146,113</i>	<i>61,590,729</i>
	General cut and fill	2,994,292	-	1,871,267	904,692	2,775,959
	Roads, walks and parking areas	4,111,314	-	1,808,123	2,003,409	3,811,532
	Fencing and gates	572,726	-	257,223	273,742	530,965
	Sanitary sewer facility	3,657,143	700,558	2,301,294	388,625	3,390,478
	Yard drainage storm sewers	3,836,268	-	1,110,121	2,446,421	3,556,542
	Roadway and yard lighting	1,924,717	-	987,398	796,976	1,784,374
	Settling basins	637,915	-	209,725	381,676	591,401
	Railroads	7,801,429	-	3,750,891	3,481,687	7,232,578
	Structure-associated open cut	17,292,148	-	11,911,085	4,120,185	16,031,269
	Structure-associated fill/backfill	23,606,962	-	11,536,930	10,348,701	21,885,631

4.1.b Account 212 -Reactor Containment Building

The P²S-LWR containment building consists of a metal cylindrical vessel with an upper hemispherical dome. It is designed to resist the pressure in case of LOCA. Unlike the Westinghouse AP-1000, it is not surrounded by a shield building. Instead, similar to the Westinghouse-SMR, the containment vessel is incorporated into a single building (Nuclear Island) (Ammerman et al., 2017). Together with the adjoining annex building and the radwaste building, this configuration allows a lesser use of structural materials and labor during the construction. A complete 3D-CAD model of the nuclear island is shown in Figure 4. Figure 5 illustrates a section of the nuclear island, which shows the Containment Vessel (CV) with conceptual designs of the internal components (Yehl et al., 2017).

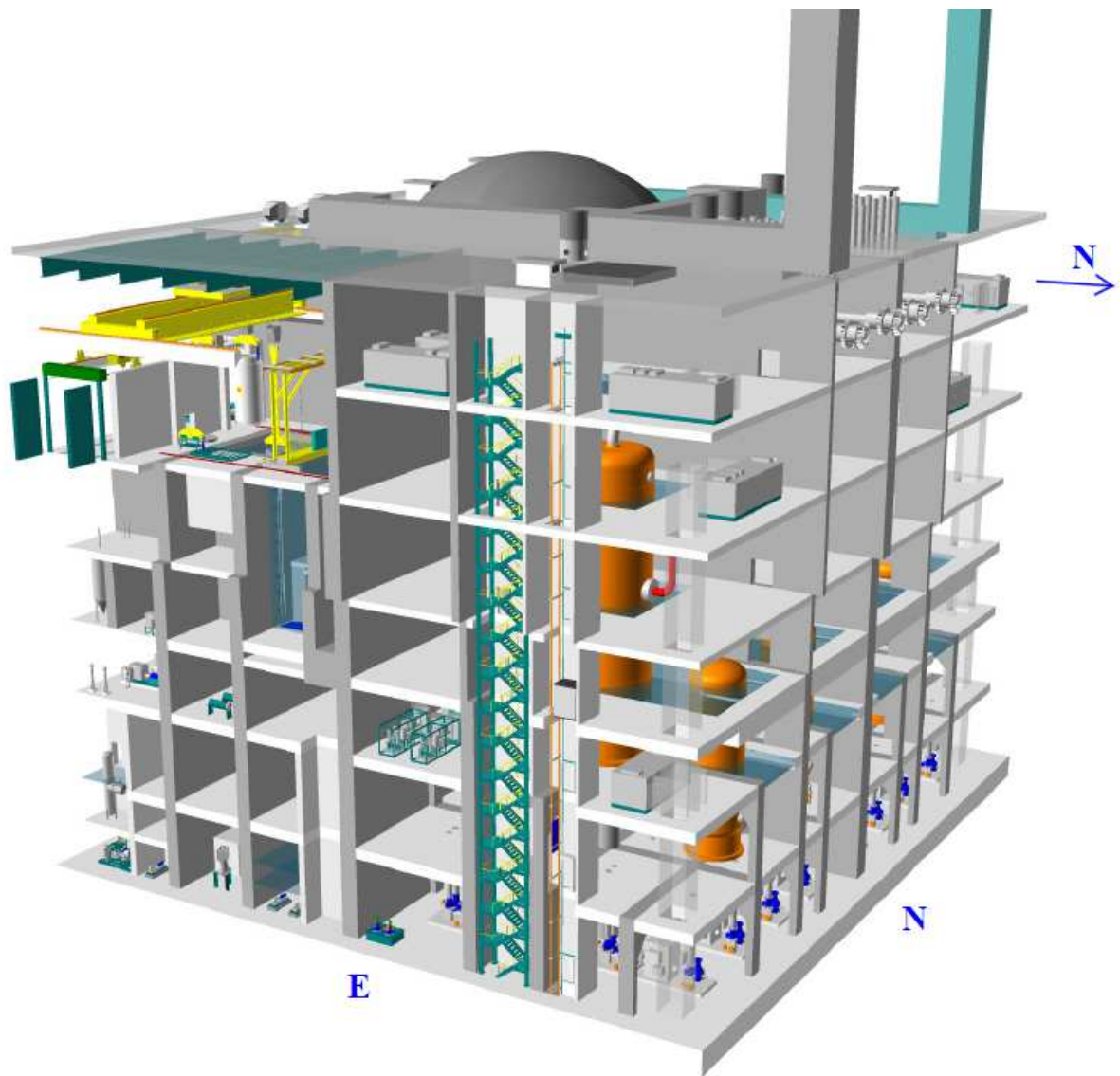


Figure 4 – Nuclear Island: Isometric View Looking Southwest (Ammerman et al., 2017)

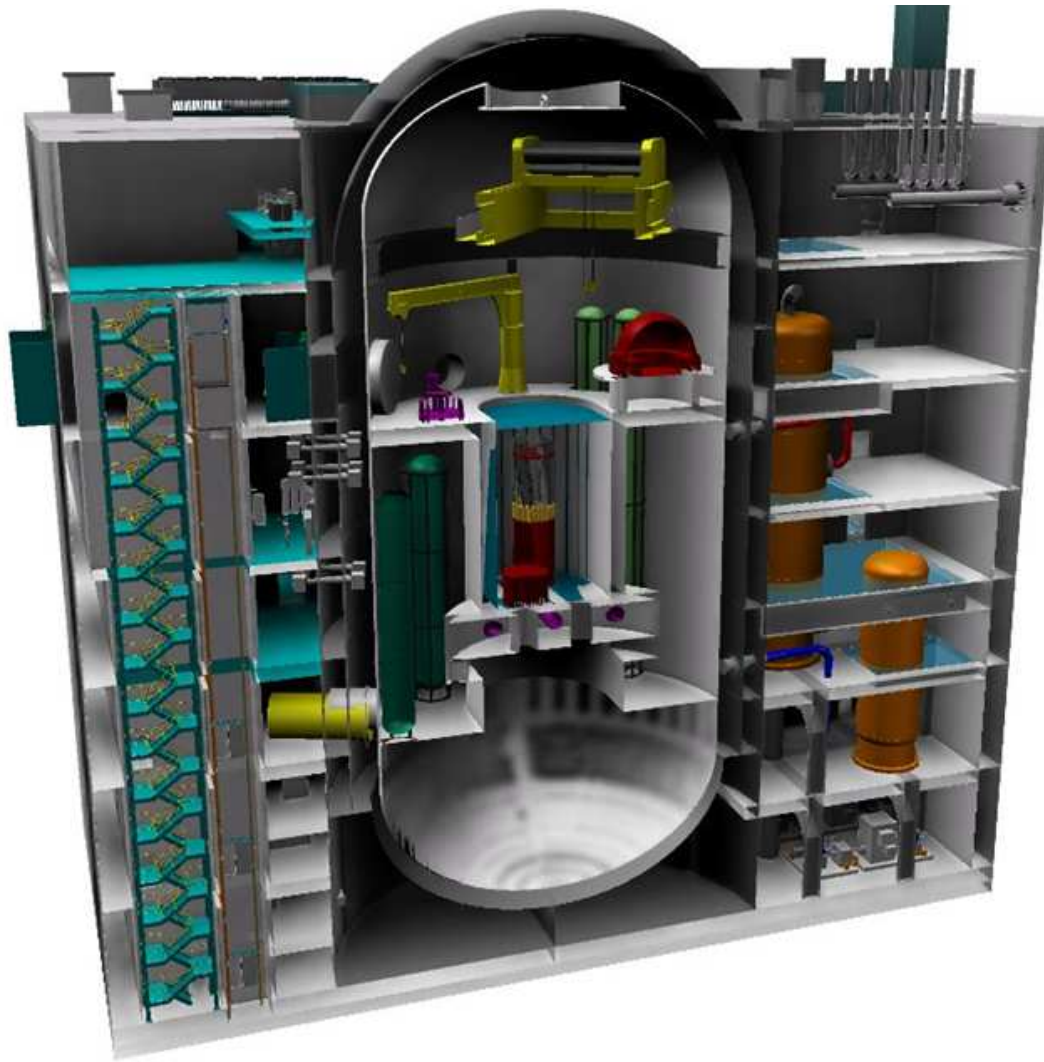


Figure 5 – Nuclear Island with encapsulated Containment Vessel (Yehl et al., 2017)

Figure 6 depicts relative sizes of the PWR12 and I²S-LWR containment vessels, clearly illustrating the compact size of the latter. The dimensions of the two reactor containment vessels are listed in Table 8.

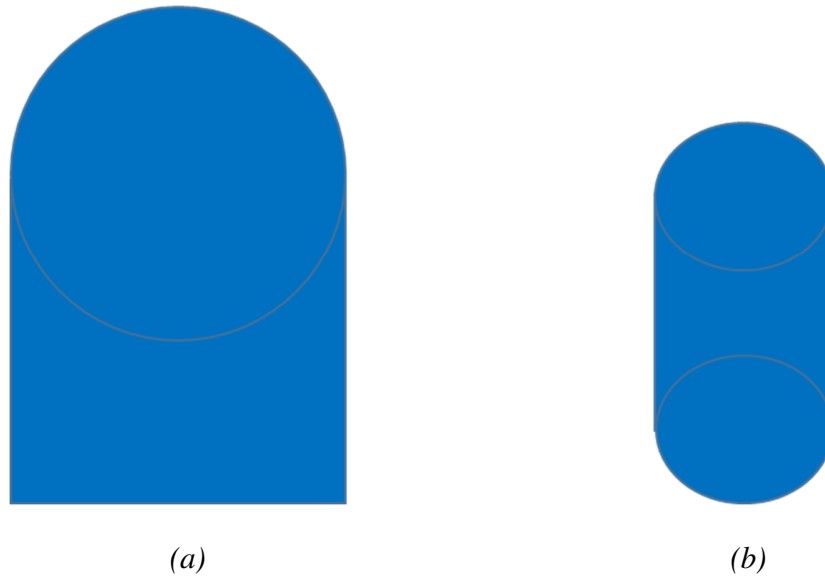


Figure 6 – Comparison between PWR12 (a) and I²S-LWR (b) containment vessel

Table 8 – PWR12 and I²S-LWR containment vessel dimensions

	Outer Diameter (m)	Height (m)
PWR12	45.5	66.6
I ² S-LWR	23	52

The PWR12-BE accounts complete printout prepared by EEDB (1987a) was analyzed in detail and, labor cost and material costs, the bulk commodity pricing and installation rates were extracted for the containment building. These values were assumed the same to calculate the construction cost of the whole I²S-LWR nuclear island. PWR12-BE bulk commodity pricing, installation unit-hour rates, and installation unit-hour costs (escalated to 2016 USD) and are shown in Table 9.

Superstructure formwork commodity pricing is the only item that differs in the nuclear and non-nuclear cases. Different installation rates were found for the substructure and for each component of the superstructure (shell, dome, interior).

Table 9 – Bulk commodity pricing and unit hour installation rates (extracted from US Department of Energy (1987a), escalated to 2016 USD)

Commodity	Unit	Commodity price (\$/unit)	Inst. rate (h/unit)	Inst. cost (\$/h)
Formwork - substructure	m ²	45.87	7.53	42.86
Formwork - superstructure, shell	m ²	57.33	10.76	42.86
Formwork - superstructure, dome	m ²	57.33	10.23	42.86
Formwork - superstructure, interior	m ²	56.47	13.95	42.90
Reinforcing steel - substructure	t	1,608.75	28.66	49.64
Reinforcing steel - superstructure, shell, dome	t	1,651.02	41.89	49.64
Reinforcing steel - superstructure, interior	t	1,651.02	49.60	49.64
Embedded metal – substructure, superstructure	t	7,480.09	336.20	46.96
Concrete - substructure	m ³	133.06	3.14	38.86
Concrete - superstructure, shell, dome	m ³	133.06	5.49	38.86
Concrete - superstructure, interior	m ³	133.06	6.28	38.86
Structural steel	t	3,776.45	38.58	49.94
Miscellaneous steel	t	6,235.36	74.96	49.94

The I²S-LWR reactor containment building cost was estimated from the amount of concrete in the nuclear island. The amounts of rebar and miscellaneous steel for the I²S-LWR were calculated using the same ratios relative to concrete amount of the PWR12-BE. Material costs, installation unit-hour rates and installation rates shown in Table 9 were used. Considering only concrete and metal, a containment building cost (in 2016 USD) of \$128,425,672 was obtained (Table 10).

Table 10 – I²S-LWR nuclear Island building quantities and costs of concrete, reinforcement steel, and miscellaneous steel calculated from (Peterson et al., 2005) (2016 US dollars)

	Concrete	Rebar	Miscellaneous steel
Volume (m ³)	74,900	-	-

Mass (t)	-	19,062	3,143
Material unit cost	133.06	1,651.02	6,235.36
Material cost (\$)	9,966,426	31,471,205	19,597,586
Installation unit-hour rate (h)	5.49	41.89	74.96
Installation rate (\$)	38.86	49.64	49.94
Installation cost (\$)	15,990,156	39,635,350	11,764,949
Total cost (\$)	25,956,581	71,106,555	31,362,536
Total concrete and metal cost (\$)		128,425,672	

For the PWR12-BE, the sum of concrete and metal costs items is the 69.30% of the total reactor containment building cost, which contains other items, such as painting, waterproofing, etc. Using the same percentage between total concrete and metal cost and the total reactor containment building cost, the nuclear island cost is \$185,339,446.

A sub account was added to account 212 to account for the cost related to placing the containment vessel partly below grade. Vertical excavation for different digging depths was evaluated through the methodology described in this section. A general location with representative soil characteristics was chosen. It was assumed that the location is characterized by only soil for depth between 0 to 40 feet. After 40 feet deep, only rock is present.

Vertical excavation has a \$40 cost per cubic yard of soil removed and \$50 per cubic yard of rock removed. A \$50,000 dewatering for deep interior wells is also needed (costhelper.com, 2015) . The excavation well has to be supported by Diaphragm Walls panels, each having a width between 0.5 and 1.5 meters. The cost per square meter of Diaphragm Walls is \$1,300. 1.5 meters wide panels were assumed. The excavation area was assumed to be equal to the containment cross sectional area plus the Diaphragm Walls width and a 1.5 meter additional gap, which is

then backfilled. Backfilling cost is \$20 per cubic foot of flowable fill or earth fill (Dewberry, 2009).

Through this method, the cost of placing half of the NI underground is \$ 20,504,954. The cost of digging the NI completely underground is \$ 35,706,283. The cost of placing half of the Nuclear Island underground was accounted. Cost items of the PWR12-BE and the I²S-LWR reactor containment buildings are shown in Table 11.

Table 11 – Reactor containment building - account 212 (2016 USD)

		<i>PWR12-BE</i>	<i>I²S-LWR</i>
		<i>Total</i>	<i>Total</i>
212	<i>Reactor Containment Building</i>	172,346,644	205,844,400
	Excavating work	-	20,504,954
	Containment structure	119,422,681.40	128,425,672
	Other	52,923,962.60	56,913,774

4.1.c Account 213 – Turbine-room and heater bay Building

Turbine building size is relatively independent on plant type and power level. All costs were scaled through the power law expressed by Eq. (4) based on the electric power using an exponent equal to 0.5 (2007; Phung, 1987). Costs of account 213, for the PWR12-BE and the I²S-LWR are shown in Table 12.

Table 12 – Turbine room and heater bay building - account 213 (2016 USD)

		<i>PWR12-BE</i>		<i>I²S-LWR</i>		
		<i>Total</i>	<i>Equipment</i>	<i>Site Labor</i>	<i>Site Material</i>	<i>Total</i>
213	<i>Turbine Room and Heater Bay</i>	61,543,338	1,531,394	27,533,276	27,991,158	57,055,828
	Excavation work	-	-	-	-	-

Substructure concrete	13,879,497	0	8,459,271	4,408,185	12,867,456
Superstructure	39,766,589	0	14,619,154	22,247,804	36,866,958
Plumbing and drains	3,399,378	29,245	2,425,856	696,407	3,151,508
Heating, ventilation, air conditioning	2,767,986	1,285,285	1,071,381	209,489	2,566,155
Fire protection	-	0	0	0	0
Lighting and service power	1,424,799	0	897,633	423,274	1,320,908
Elevator	305,090	216,864	59,981	5,999	282,844

4.1.d Account 214 -215– Miscellaneous buildings and structures

Regarding the Security Building and the waste processing building, no changes are considered at this time. The I²S-LWR has an auxiliary building that is integrated together with the waste processing building and the containment vessel in the nuclear island. This configuration allows important reductions in the quantity of material required by the structures. As the auxiliary building and the waste processing building are not part of the I²S-LWR layout, the cost of these items was set to zero. Costs of other buildings are shown in Table 13.

Table 13 – Other Buildings—accounts 214-215 (2016 USD)

		<i>PWR12-BE</i>		<i>I²S-LWR</i>		
		<i>Total</i>	<i>Equipment</i>	<i>Site Labor</i>	<i>Site Material</i>	<i>Total</i>
<i>214</i>	<i>Security Building</i>	<i>3,620,338</i>	<i>138,015.54</i>	<i>2,505,890.89</i>	<i>976,430.34</i>	<i>3,620,336.78</i>
	Excavation work	-	-	-	-	-
	Substructure concrete	235,617	-	148,518.72	87,097.88	235,616.60
	Superstructure	2,237,427	-	1,581,005.10	656,421.69	2,237,426.79
	Building services	1,147,293	138,015.54	776,367.06	232,910.78	1,147,293.39
<i>215</i>	<i>Primary Auxiliary Building and Tunnels</i>	<i>49,102,508</i>	<i>-</i>	<i>-</i>	<i>-</i>	<i>-</i>
	Excavation work	-	-	-	-	-
	Substructure concrete	1,916,982	-	-	-	-
	Superstructure	30,216,901	-	-	-	-
	Plumbing and drains	1,448,804	-	-	-	-
	Heating, ventilation, air conditioning	12,314,261	-	-	-	-
	Special HVAC	1,335,157	-	-	-	-
	Lighting and service power	1,367,727	-	-	-	-

Elevator	502,675	-	-	-	-
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4.1.a Account 216– Waste processing buildings

Waste processing building is relatively independent on plant type and power level, and includes equipment for liquid, gaseous and solid radioactive waste. However, for the I²S-LWR the liquid and gaseous waste processing systems are included in the nuclear island (account 212), and this building only contains minimal equipment related to processing and storage of low-level waste. For the PWR12-BE, it was assumed the cost of this account is equally distributed between the liquid, solid and gaseous systems. Therefore, since for the I²S-LWR this building contains solid waste-related equipment, for the I²S-LWR the costs of this account was estimated as a third of those of the PWR12-BE. Costs of account 216 are summarized in Table 14.

Table 14 – Waste processing building—account 216 (2016 USD)

		<i>PWR12-BE</i>		<i>I²S-LWR</i>		
		<i>Total</i>	<i>Equipment</i>	<i>Site Labor</i>	<i>Site Material</i>	<i>Total</i>
<i>216</i>	<i>Waste Processing Building</i>	<i>38,191,091</i>	<i>1,604,542</i>	<i>22,237,543</i>	<i>11,564,255</i>	<i>12,730,364</i>
	Excavation work	-	-	-	-	-
	Substructure concrete	3,819,604	-	2,005,211	1,535,882	1,273,201
	Superstructure	28,064,168	-	16,990,260	9,027,573	9,354,723
	Plumbing and drains	1,139,224	-	858,790	197,366	379,741
	Heating, ventilation, air conditioning	3,727,495	1,257,313	1,670,897	527,490	1,242,498
	Lighting and service power	930,843	-	598,422	264,548	310,281
	Elevator	509,757	347,229	113,963	11,396	169,919

4.1.b Account 217– Fuel storage building

The fuel service building contains the spent fuel pool, cask loading and decontamination areas, new fuel receipt and inspection areas, and the necessary truck locks and handling (Holcomb et

al., 2011). For the I²S-LWR, since the equipment related to the fuel storage is contained in the nuclear island, the costs of this account were set to zero. Account 217 costs are shown in Table 15.

Table 15 – Fuel Storage Building—account 217

		<i>PWR12-BE</i>		<i>I²S-LWR</i>		
		<i>Total</i>	<i>Equipment</i>	<i>Site Labor</i>	<i>Site Material</i>	<i>Total</i>
<i>217</i>	<i>Fuel Storage Building</i>	<i>26,260,551</i>	-	-	-	-
	Excavation work	-	-	-	-	-
	Substructure concrete	10,848,993	-	-	-	-
	Superstructure	10,631,885	-	-	-	-
	Plumbing and drains	442,153	-	-	-	-
	Heating, ventilation, air conditioning	1,458,840	-	-	-	-
	Special HVAC (safety-related)	2,538,619	-	-	-	-
	Lighting and service power	340,063	-	-	-	-

4.1.c Account 218– Other structures

218A - Control and diesel generator building

As the I²S-LWR relies only on completely passive safety systems, there is no need for safety diesel generators. Significantly smaller emergency generators are still included to minimize disruption at the site. The diesel-generators building is assumed to contain one quarter of the diesel generators needed for a standard PWR, and they are not safety grade (assumed half the cost), and the cost assigned to its structure is reduced to one eighth.

218B - Administrative and Service Building

In the I²S-LWT design, the administrative and service building functions are performed by the annex building. Therefore, the cost of this item was left unchanged.

218E - Emergency Feed Pump Structure and 218T - Ultimate heat sink structure

These two accounts address cost for systems that are not part of the I²S-LWR concept. Since the I²S-LWR relies on the passive DHRS, DHRS costs are addressed in accounts 223 and there is no need for a separate safety-related emergency feed pump structure or a separate ultimate heat sink structure.

218J – Main steam and FW pipe enclosure

This account represents the piping needed to transport the steam and feedwater between the containment building and the turbine building. As the mass flow rate in the secondary system is proportional to the thermal power of the reactor, this cost was scaled through thermal power ratios. An exponent equal to 0.8 was used (Phung, 1987). Accounts costs of other structures are summarized in Table 16.

Table 16 – Other Structures—account 218 (2016 USD)

		<i>PWR12-BE</i>		<i>I²S-LWR</i>		
		<i>Total</i>	<i>Equipment</i>	<i>Site Labor</i>	<i>Site Material</i>	<i>Total</i>
218	<i>Other Structures</i>	116,116,967	3,089,027	32,243,876	17,975,422	53,308,325
218A	<i>Control and Diesel Generator Building</i>	48,109,679	486,386	3,714,986	1,812,338	6,013,710
218B	<i>Administrative and Service Building</i>	17,667,268	2,180,712	9,015,429	6,471,127	17,667,268
218C	<i>Main Steam and Feedwater Pipe Enclosure</i>	-	-	-	-	-
218D	<i>Fire Pump House w/foundations</i>	1,134,586	104,863	636,538	393,184	1,134,586
218E	<i>Emergency Feed Pump Bldg</i>	6,641,396	-	-	-	-
218F	<i>Manway Tunnels</i>	2,025,279	-	1,432,819	592,460	2,025,279
218G	<i>Electric Tunnels</i>	180,146	25,606	112,107	42,432	180,146
218H	<i>Non-essential switchgear bldg</i>	1,424,517	50,904	768,795	604,818	1,424,517
218I		-	-	-	-	-
218J	<i>Main steam and FW pipe enclosure</i>	20,912,432	80,458	12,804,493	6,174,774	19,059,724

218K	pipe tunnels	843,447	-	543,669	299,778	843,447
218L	Tech Support Center	2,098,496	138,016	1,321,983	638,498	2,098,496
218P	Containment equipment hatch	584,611	-	445,460	139,151	584,611
218S	waste water treatment	2,039,610	22,082	1,285,967	731,561	2,039,610
218T	Ultimate heat sink structure	12,218,569	-	-	-	-
218V	Control room emergency air intake structure	236,932	-	161,631	75,301	236,932

4.1.d Summary of account 21 cost

Costs of account 21, for the PWR12 and the I²S-LWR, are summarized in Table 17. The cost reduction in the structures account is \$139.5 M. The cost saving is mainly due to the more compact nuclear island and to the absence of the diesel generators building.

Table 17 – Structures and Improvements—account 21 (2016 USD)

	PWR12-BE	I ² S-LWR	Cost difference
21 Structures and Improvements	533,616,353	394,149,983	- 139,466,369

4.2 Reactor Plant Equipment – account 22

The dimensions of the main reactor plant components are shown in Table 18.

Table 18 – PWR12 and I²S-LWR reactor plant components dimensions

	PWR12 (Westinghouse Electric Corporation, 1984)			I ² S-LWR (Petrovic, 2017)		
	Number	OD	Height	Number	OD	Height
Vessel	1	4.96	13.6	1	5.42	22.9
Steam generators	4	4.5	20.6	-		
Steam drum	-			4	6.26	21.92
Core	1	3.38	3.66	1	2.87	3.66
Pressurizer	1	2.3	16.1	-		
Pumps	4	1.96	8.5	8	0.9	2.79

4.2.a Account 221 – Reactor Equipment

Reactor Pressure Vessel

As the I²S-LWR design is based on an integral configuration, the RPV needs to accommodate the pressurizer, the primary heat exchangers, and the DHRS heat exchangers. A schematic of the RPV concept is shown in Figure 7, with further details available in (Marchese and Petrovic, 2013; Memmott et al., 2017a; Memmott et al., 2014).

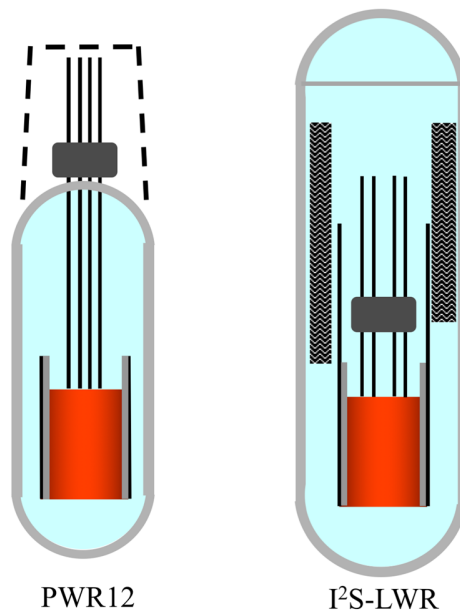


Figure 7 – PWR12, steam generator, primary loop and piping as compared to I²S-LWR integral RPV concept (schematic, to scale)

Three sets of data regarding costs and parameters of different RPVs were found in literature and are shown in Table 19. Equipment cost and RPV mass for a Molten Salt Breeder Reactor (MSBR) was taken from (Oak Ridge National Laboratory, 1971). As in Holcomb et al. (2011), the PWR12-BE RPV equipment cost was estimated as 16% of the nuclear steam supply system (NSSS). taken from Holcomb et al. (2011) (Holcomb et al., 2011) while the mass of the RPV

carbon-steel structure was calculated from the dimensional parameters found in 2009). Cost of the International Reactor Innovative and Secure (IRIS) RPV was taken from an expert assessment.

Equipment costs for the three reactor designs were broken down into material cost and labor cost (Table 19). For the PWR 12-BE and IRIS, costs of the stainless steel internal clad were neglected. The material costs were calculated from the carbon steel unit cost shown in Section 3.4 , while labor costs were calculated as difference between equipment cost and material cost. MSBR equipment and material costs were taken from (Oak Ridge National Laboratory, 1971), from which the labor cost was derived. The MSBR has a monolithic RPV made of Hastelloy N, a high temperature nickel based alloy, which has a unit cost two orders of magnitude higher than carbon steel.

Table 19 – RPV equipment costs breakdown

	Mass (t)	Material cost (\$)	Labor cost (\$)	Labor cost/mass (2016 USD/t)
MSBR	289.95	33,427,750	59,500,980	125,173.37
PWR12-BE	369.01	369,015	81,392,994	161,877.46
IRIS	683.09	693,086	116,184,372	177,229.14

As material cost depends on the specific material of the RPV, only the relationship between labor cost and mass was studied. Under this assumption, the amount of labor does not depend on the type of metal used but only on the component mass. A direct proportionality between labor cost and mass was assumed. From the three data points, the proportionality constant, calculated as a ratio between labor cost and mass, were calculated. The average proportionality constant, equal to \$154,759.99/t, is used to estimate RPV labor cost of any size, material and design.

The RPV labor cost is then estimated as the product between the average specific labor cost and the mass of the RPV. The material cost is calculated as the product of the material unit cost and the mass (in tons). The equipment cost of the I²S-LWR RPV is then \$94,241,791.

Internals

In Holcomb et al. (2011), the cost of the reactor internals is divided into lower and upper internals. I²S-LWR internals are detailed in (Marchese and Petrovic, 2013; Memmott et al., 2014). Lower internals include the barrel and the lower core plate, while the upper internals represent the core upper plate and CR guide plates. The cost of the core plates depends on two factors: quantity of steel and number of features. The number of features determines the amount of machine and labor hours required for the component fabrication. As detailed design of the I²S-LWR plates are not available at the stage of this analysis, a simplifying assumption is made. As the quantity of material decreases as the number of features increases, the cost of the core plates for the I²S-LWR are scaled from those of the PWR12-BE based on the solid volume of the component. The account covering the lower internals was scaled based on the volumes of the lower core plate and lower portion of the barrel; the upper internals account was scaled based on the volumes of the control rod drive mechanism upper plate and the upper portion of the barrel. Typical PWR internals dimensions were taken from public sources (Seabrook Power Station, 2002).

Summary

Cost of account 221 items are summarized in Table 20. The cost of transporting the equipment to site for the PWR12-BE was expressed as a percentage of the total equipment cost of account

221. The entry representing the equipment transport to site is the 7.63% of account 221 equipment cost. For the I²S-LWR, sub account “transport to site” was calculated as the 7.63% of account 221 equipment cost.

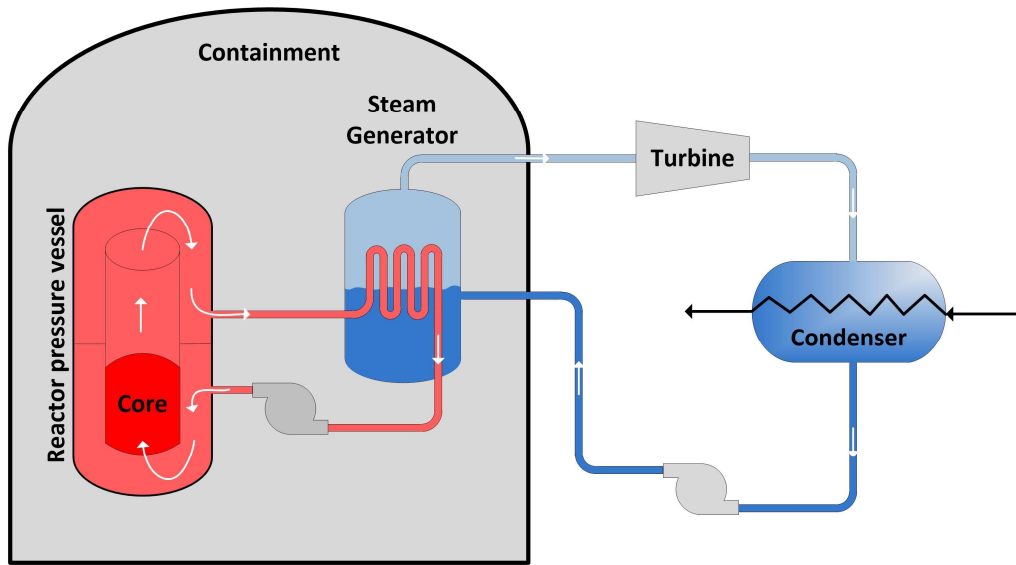
Table 20 – Reactor equipment - account 221 (2016 USD)

		PWR12-BE		I ² S-LWR		
		<i>Total</i>	<i>Equipment</i>	<i>Site Labor</i>	<i>Site Material</i>	<i>Total</i>
<i>221</i>	<i>Reactor Equipment</i>	<i>218,643,943</i>	<i>209,031,833</i>	<i>3,132,498</i>	<i>26,168,752</i>	<i>238,333,083</i>
	Reactor supports (field cost)	3,647,765	3,446,119	2,153,472	215,347	5,814,938
	Reactor vessel structure (NSSS allocation)	76,275,225	94,241,791	-	-	94,241,791
	Reactor vessel structure (field cost), including vessel body and attachments, studs, fasteners, seals, gaskets, and insulation	6,565,218	-	-	8,111,650	8,111,650
	Lower internals (NSSS allocation)	28,603,209	29,279,141	-	-	29,279,141
	Lower internals (field cost)	967,504	-	-	990,368	990,368
	Upper internals (NSSS allocation)	28,603,209	36,848,989	-	-	36,848,989
	Upper internals (field cost)	621,968	-	-	801,270	801,270
	Transport to site	14,722,396	-	-	15,952,213.99	15,952,214
	Control rods (NSSS allocation)	28,603,209	22,581,481	-	-	22,581,481
	Control rod drives (NSSS allocation)	28,603,209	22,581,481	-	-	22,581,481
	Control rod drives (field cost)	1,181,739	-	848,138	84,814	932,952
	Control rod drive missile shield (field cost)	135,089	-	96,954	9,695	106,649
	CRDM seismic supports (field cost)	114,201	52,832	33,934	3,394	90,159

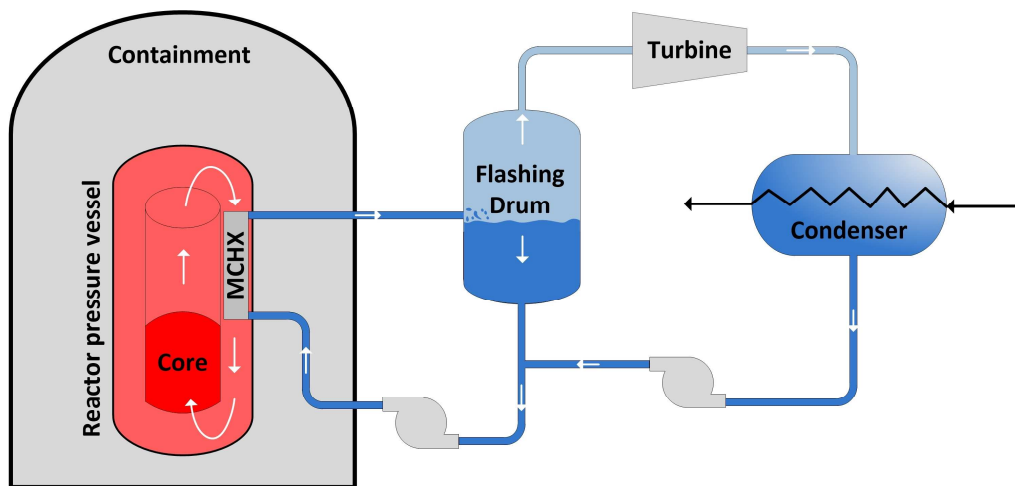
4.2.b Account 222 – Main Heat transfer transport system

As explained in Section 2. , the PWR12-BE account 21 cost was increased by \$100 M (in 2011 USD) to match the current supply chain data (Mack, 2016). With respect to the original EEDB data escalated to 2011 by Holcomb et al. (2011), the \$100 M correspond to a 73.48% cost increase. Therefore, the \$100 M increase was shared between all subaccounts, increasing each subaccount by 73.48%.

Account 222 contains costing regarding the main heat transfer transport system. The I²S-LWR main heat transport system is different than that of a loop PWR. Instead of loops and large pumps, it includes compact primary heat exchangers (microchannel heat exchangers, MCHX, also referred to as Printed Circuit Heat Exchanger, PCHE), inside the vessel, and the secondary fluid loop and a flashing drum, where the steam is generated, outside the vessel (Memmott et al., 2017a; Memmott and Manera, 2015; Memmott et al., 2017b). A schematic of the system is shown in Figure 8.



(a)



(b)

Figure 8 – PWR12 and I²S-LWR main heat transport system and Rankine cycle concepts (Kromer, 2017)

Cost of the equipment for the PWR12-BE was increased to reflect the differences in equipment costing. The system for the I²S-LWR differs from the one of the PWR12 as different components are adopted. The I²S-LWR has eight relatively small primary coolant pumps attached to the

reactor vessel, instead of four outside-vessel large main coolant pumps in PWR12. \$25 M was estimated as reactor coolant pumps equipment cost from industry assessment, based on scaling from similar designs. The I²S-LWR utilizes integrated primary heat exchangers and a flashing drum steam generation system as compared to the standard PWR U-tubes steam generation system. The pressurizer is integrated in the RPV. Steam generators cost was replaced by the cost of Micro channel primary heat exchangers (MCHX), and the cost of flashing drums was added.

MCHX

I²S-LWR primary heat exchangers consist of four MCHX units (Kromer et al., 2017). Each MCHX unit consists of two stacks of 11 microchannel modules. Each module is made of a set of sheets with etched microchannels, alternating between primary and secondary coolant sheets. A schematic of the MCHX plates is shown in Figure 9. The MCHXs are shown in Figure 10.

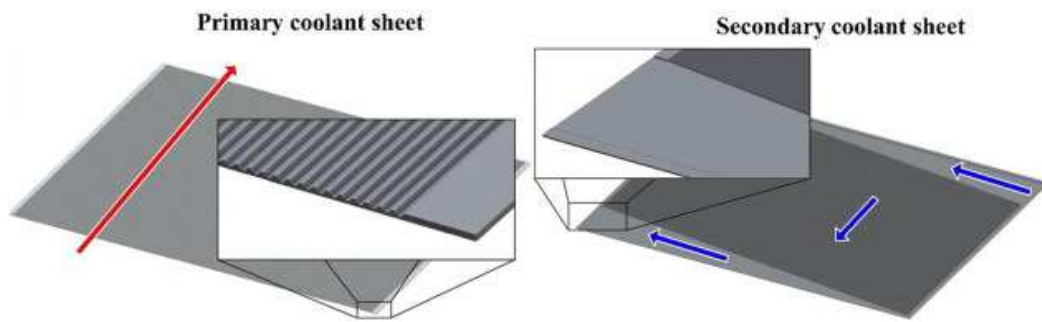


Figure 9 – MCHX primary (red) and secondary (blue) coolant sheets (Kromer et al., 2017)

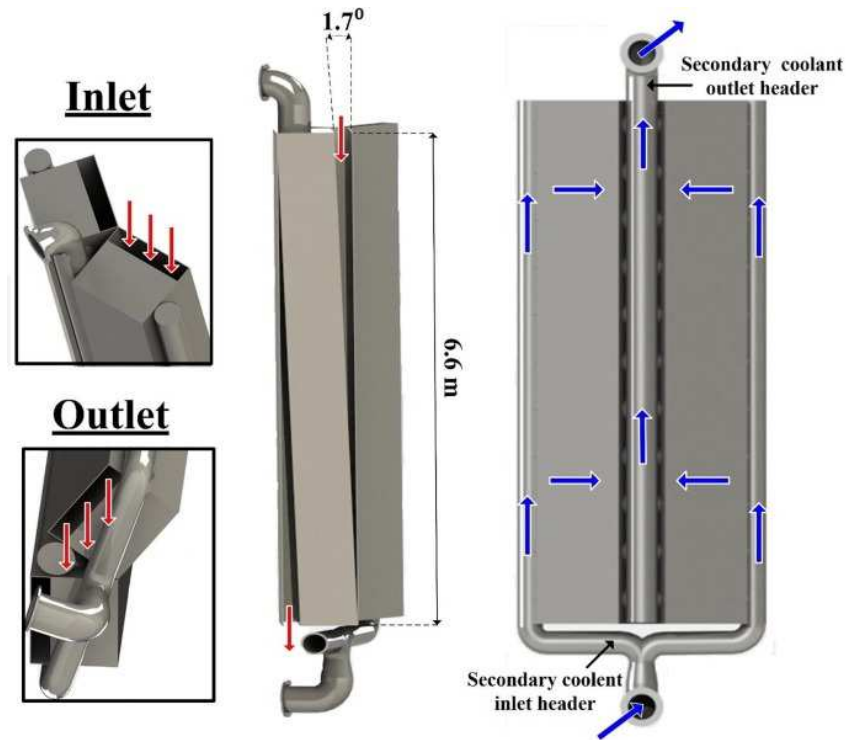


Figure 10 – Primary (red) and secondary (blue) flow through a MCHX (Kromer et al., 2017)

The total reactor thermal power is 2850 MW and each heat exchanger unit is designed to provide a thermal heat removal capability of 712.5 MW. The steel used to fabricate the MCHX is expected to have a lower material cost, but a higher fabrication cost due to the microchannel design. However, the overall expected effect is a cost decrease as compared to standard shell and tube heat exchangers with pressure vessels. The factory labor cost can be estimated through the following equation:

$$C_{eq} = C_{mat} + C_{lab} = M_{plate} \cdot (C_{mat} + N_{block} \cdot C_{lab,b,mass}) \quad (9)$$

Where:

- M_{plate} is the total plate mass for the heat exchanger;

- C_{mat} is the material cost;
- N_{block} is the total number of HX blocks (modules);
- $C_{fab,b, mass}$ is the labor (machining) cost per unit of mass and block.

Moisseytsev and Sienicki (2011) show prices and parameters of printed circuit heat exchangers based on quotes received from the manufacturer Heatric Division of Meggitt (UK). They considered four different MCHX designs and obtained fabrication factors 10.28, 7.97, 9.75 and 6.60. These data was used to compute the fabrication cost for each unit, which was then used to estimate the fabrication cost of the P²S-LWR MCHX. As a conservative assumption, the highest fabrication factor (10.28) was used, giving a labor cost of \$13,653,816. Once the material cost is added, the equipment cost is \$14,154,198. The installation cost of the MCHX was estimated from the equipment cost, using the upper bound of the installation factor range found in Peters et al. (2003).

The schematic of a steam drum is shown in Figure 11. Equipment cost of the steam drums was evaluated through Peters et al. (2003), which shows 2002 tank costs for carbon steel, SS 304 and SS 316 steel as a function of the tank capacity. Equations (5)-(6) were then used to estimate the equipment cost for a different operating pressure and to account for the cost of the stainless steel liner (assumed as SS-316).

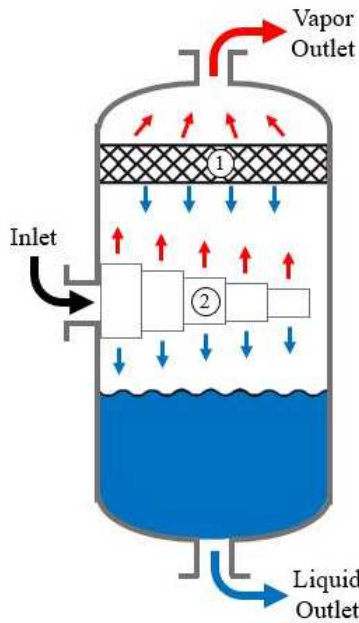


Figure 11 – Steam drum (Wikipedia, 2017)

For I²S-LWR, new entries are provided for the MCHX and the steam generation system. The cost of the pressurizer and the pressurizer relief tank were deleted. Account 222 costs are shown in Table 21.

Table 21 – Main heat transfer transport system—account 222 (2016 USD)

		PWR12-BE		I ² S-LWR		
		Total	Equipment	Site Labor	Site Material	Total
222	Main Heat transfer transport system	280,085,945	51,212,408	11,653,943	6,251,448	69,117,799
	Main coolant pumps (NSSS allocation)	74,432,407	25,000,000	-	-	25,000,000
	Fluid circulation drive (field cost)	10,607,586	2,055,199	1,370,569	137,057	3,562,825
	Reactor coolant piping (NSSS allocation)	37,216,203	-	-	-	-

Reactor coolant piping (field cost)	18,773,658	-	-	-	-
Primary to intermediate heat exchangers (4 units)	-	14,154,198	8,492,518.60	-	22,646,716
Steam generators (NSSS allocation)	99,243,209	-	-	-	-
Steam generator equipment (field cost)	2,283,038	110,835	1,790,855	179,085	2,080,776
Steam drum	-	9,892,176	-	5,935,306	15,827,482
Pressurizer (NSSS allocation)	24,810,802	-	-	-	-
Pressurizing system (field cost)	313,637	-	-	-	-
Pressurizer relief tank (NSSS allocation)	12,405,401	-	-	-	-

4.2.c Account 223 – Safeguards systems

Safety systems for the I²S-LWR differ compared to the reference PWR. The I²S-LWR has passive cooling system that allows an indefinite decay heat removal capability from the core, the spent fuel pool and the containment vessel (Banzatti, 2015; Wang et al., 2017a; Wang et al., 2017b). The passive DHRS provides indefinite cooling to the reactor and the containment vessel. It consists of two subsystems dedicated to cooling each component. The DHRS is made of four in-vessel helical coil intermediate heat exchangers (IHXs) connected through an intermediate loop to two external cooling towers. A schematic of the DHRS is shown in Figure 12.

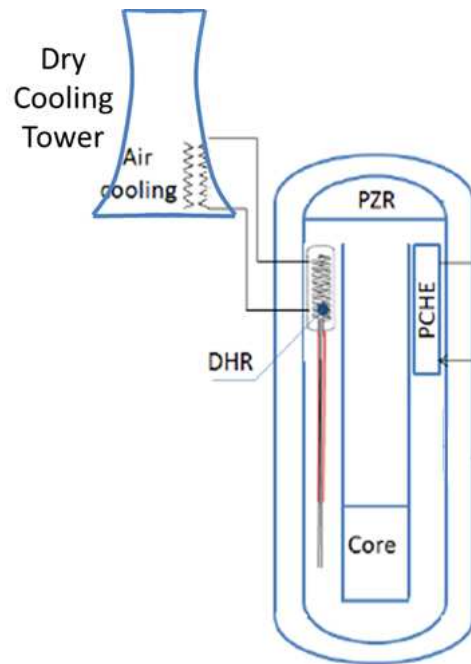


Figure 12 – DHRS and primary heat transport system schematic

The Passive Cooling Containment System (PCCS) consist of an air-to-water heat exchanger placed in the containment, an intermediate loop with water and a cooling tower. All three cooling towers are dry towers containing water-to-air heat exchangers. The costs of the intermediate heat exchangers and the containment heat exchanger were calculated applying fabrication cost factors found in literature.

Factory equipment cost of the heat exchangers can be scaled based on the heat exchange surface area. According to Table 3, the scaling exponent is 0.62; it can be used for heat transfer areas greater than 100 m². The steam generator was chosen as the reference design to be used for the cost scaling of the I²S-LWR DHRS heat exchangers. The IRIS steam generating system is made of eight helical-coil heat exchangers, each having a heat exchange area (calculated from

parameters in Cinotti et al. (2002)) of 1,639.3 m². The cost of the eight steam generator pack was assessed in Paparusso (2012). After the first steam generator fabricated, each steam generator would cost 4,626,485 euros (in 2011 euros). The cost was escalated to 2016 euros using the Harmonised Index of Consumer Prices (HICP) (European Central Bank, 2017), and converted to 2016 USD through the average exchange rate in January 2016 (X-Rates, 2016). The resulting factory equipment cost, used in the scaling law, is \$5,288,796. The IRIS and I²S-LWR DHRS and PCCS heat exchangers parameters and costs are shown in Table 22.

Table 22 – IRIS steam generator and DHRS heat exchangers parameters (costs in 2016 USD)

	IRIS	DHRS IHX	DHRX AHX	PCCS
Number of units	4	4	3	1
Surface (single unit, m ²)	1,639.3	138.8	10,911.6	628.3
Equipment (single unit)	5,288,796	1,144,364	17,129,864	2,918,326
Installation (single unit)	-	686,619	10,277,918	1,750,996
Total (single unit)	-	1,830,983	27,407,782	4,669,322
Total (all units)	-	7,323,932	82,223,345	4,669,322

Installation cost was calculated through Eq. (6) using *MF* factors found in Peters et al. (2003).

As a conservative assumption, the *MF* upper bound for heat exchangers (0.60) was used.

The cost of the cooling towers containing the AHXs were scaled from the reference PWR12BE condensing system cooling towers that are allocated under account 262, mechanical equipment, through the scaling law represented by Eq. (4) using the volume of material. The three cooling towers were assumed to have the same design. An exponent of 0.62 was used. (Peters et al., 2003). The *MF* factor for the PWR12-BE was calculated from the equipment and installation cost inverting Eq. (6) and it was used to compute the installation cost for the DHRS cooling

towers. The main parameters of the DHRS and PWR12-BE cooling towers are shown in Table 23.

Table 23 – Cooling towers parameters (cost in 2016 USD)

	PWR12-BE	I ² S-LWR DHRS
Number of units	1	3
Mass (single, tons)	1281.78	167.54
Equipment Cost (single)	49,510,414	7,219,193.18
Site labor cost (single)	17,792,028	2,873,377.35
Site material cost (single)	1,776,600	286,917
Cost (single)	69,079,042	10,379,488
Cost (all units)	-	31,138,464

Values for carbon steel taken from Peters et al. (2003) (Peters et al., 2003) were used to compute cost of accumulators and boron injection tanks. Inflation rates and costs of steel in 2011 were used to correct the values. Installation costs for these components were estimated through Eq. (6) using *MF* factors found in Peters et al. (2003). The *MF* upper bound (0.60) was used for tanks. Safeguard systems costs, for the PWR12-BE and the I²S-LWR are shown in Table 24.

Table 24 – Safeguard systems - account 223 (2016 USD)

		<i>PWR12-BE</i>		<i>I²S-LWR</i>		
		<i>Total</i>	<i>Equipment</i>	<i>Site Labor</i>	<i>Site Material</i>	<i>Total</i>
223	<i>Safeguards systems</i>	104,512,827				127,412,416
	Residual heat removal pumps and drives (NSSS allocation)	14,301,605	-	-	-	-
	Residual heat removal heat exchanger (NSSS allocation)	14,301,605	-	-	-	-
	Residual heat removal (field cost)	6,353,233	-	-	-	-
	Safety injection pumps and drives (NSSS allocation)	14,301,605	-	-	-	-
	Safety injection system (field cost)	9,686,404	-	-	-	-
	DHRS HX	-	4,577,458	-	2,746,475	7,323,932

Containment cooling HX	-	2,918,326	-	1,750,996	4,669,322
Water to air heat exchanger	-	51,389,591	-	30,833,754	82,223,345
Cooling Towers	-	21,657,580	8,620,132	860,752	31,138,464
Accumulator tank (NSSS allocation)	7,150,802	1,136,552	-	681,931	1,818,484
Boron injection tank (NSSS allocation)	7,150,802	149,293	-	89,576	238,869
Boron injection surge tank (NSSS allocation)	7,150,802	-	-	-	-
Boron injection recirculating pump and drive (NSSS allocation)	7,150,802	-	-	-	-
Containment spray system	14,091,865	-	-	-	-
Combustible gas control system	2,873,302	-	-	-	-

New entries are provided to reflect the changes in Safeguards systems components.

4.2.d Accounts 224-228

Accounts 224 through 228 cover the cost equipment related to radwaste processing, fuel handling storage, other reactor plant equipment, reactor instrumentation and control and reactor plant miscellaneous items. In absence of a scaling factor for these accounts, a general scaling exponent equal 0.62 was used (Carelli et al., 2007a). Costs of these accounts are shown in Table 25.

Table 25 – Other equipment - accounts 224-228 (2016 USD)

	PWR12-BE	P'S-LWR			Total
	Total	Equipment	Site Labor	Site Material	
224 Radwaste Processing	55,668,939	39,108,337	9,711,153	1,860,959	50,680,450
225 Fuel Handling and storage	32,254,927	27,032,504	2,076,089	255,973	29,364,566
226 Other Reactor Plant Equipment	124,208,038	67,083,172	40,012,147	5,982,447	113,077,766
227 Reactor Instrumentation and Control	164,202,555	129,205,996	18,651,309	1,631,072	149,488,377
228 Reactor Plant Miscellaneous items	19,809,578	-	10,340,818	7,693,625	18,034,443

4.2.e Summary of Account 22 Cost

Because of the use of innovative components and integral configuration, the cost of the reactor plant equipment of the I²S-LWR is lower than that of the reference PWR-12BE. The cost saving of account 22 is \$203.9 M (Table 26).

Table 26 – Reactor Plant equipment - account 22 (2016 USD)

	<i>PWR12-BE</i>	<i>I²S-LWR</i>	Cost difference
22 Reactor Plant Equipment	999,386,752	795,508,899	203,877,853

4.3 Turbine Generator Equipment – account 23

Account 23 includes the turbine generator equipment, from the steam generation to the mechanical-electrical conversion system. The I²S-LWR is based on a traditional Rankine cycle and the equipment needed is analogous to that of the reference PWR12. As Economic Modeling Working Group (2007) suggests, cost of turbine generator equipment is function of the electric power level of the plant through the power-law expressed by Eq. (4), with a 0.5 exponent (Economic Modeling Working Group, 2007). Costs of account 23, for the PWR12-BE and the I²S-LWR are shown in Table 27.

Table 27 – Turbine Plant equipment - account 23 (2016 USD)

	<i>PWR12-BE</i>		<i>I²S-LWR</i>		<i>Total</i>
	<i>Total</i>	<i>Equipment</i>	<i>Site Labor</i>	<i>Site Material</i>	
231 <i>Turbine Generator</i>	356,155,922	302,713,878	18,489,536	207,631	321,411,045
233 <i>Condensing Systems</i>	77,039,683	44,678,686	18,211,293	1,059,506	63,949,486
234 <i>Feedwater Heating system</i>	62,703,562	38,154,137	17,274,728	778,552	56,207,417
235 <i>Other turbine plant equipment</i>	59,339,335	27,079,222	24,084,758	2,595,562	53,759,542
<i>Secondary Pumps</i>	-	60,000,000	-	-	60,000,000
236 <i>Instrumentation and control</i>	18,219,812	4,525,688	11,123,977	2,349,783	17,999,448
237 <i>Turbine plant miscellaneous</i>	21,387,547	-	11,164,449	8,328,299	19,492,747

items

23	Turbine Plant Equipment	594,845,861	477,151,611	100,348,742	15,319,333	592,819,686
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4.4 Electric Plant equipment – account 24

Electric equipment costs were reduced using scaling factors based on the electrical power. As the I²S-LWR does not rely on active safety systems, Class 1E equipment is not required. Cost associated to Class 1E equipment in the PWR-12 was further reduced by 25% to reflect standard construction (Holcomb et al., 2011). Costs of account 24, for the PWR12-BE and the I²S-LWR are summarized in Table 28.

Table 28 – Electric Plant equipment - account 24 (2016 USD)

		PWR12-BE		I ² S-LWR		
		Total	Equipment	Site Labor	Site Material	Total
241	<i>Switchgear</i>	31,755,515	25,658,493	1,372,816	207,229	27,238,538
	Class 1E equipment	11,264,700	7,496,589	414,004	41,401	7,951,994
	Non Class 1E equipment	20,490,815	18,161,904	958,812	165,827	19,286,543
242	<i>Station service equipment</i>	53,598,156				49,318,179
	Class 1E equipment	4,802,003	2,288,321	307,804	30,780	3,389,837
	Non Class 1E equipment	48,796,154	42,746,894	3,493,621	705,070	45,928,341
243	<i>Switchboards</i>	5,446,364	3,832,367	853,963	308,970	4,995,301
	Class 1E equipment	556,604	297,879	86,401	8,640	392,919
	Non Class 1E equipment	4,889,760	3,534,488	767,563	300,331	4,602,382
244	<i>Protective equipment</i>	11,327,583	-	6,236,525	4,425,321	10,661,846
245	<i>Electric structure and wiring</i>	59,282,155	-	43,493,331	10,197,217	53,690,548
	Class 1E equipment	8,956,459	-	4,487,551	1,835,006	6,322,557
	Non Class 1E equipment	50,325,696	-	39,005,780	8,362,211	47,367,991
246	<i>Power and Control wiring</i>	54,761,642	3,901,351	28,916,510	17,950,767	50,768,628
24	Electric Plant equipment	216,171,415	33,392,211	80,873,146	33,089,504	196,673,040

4.5 Miscellaneous plant equipment – account 25 (account 26 on FHR (Holcomb et al., 2011))

Miscellaneous plant equipment is part of account 26 in the Generation IV cost code of accounts, but it is part of account 25 in the EEDB database. Here, the EEDB data base is used, while the cost analysis shown in (Holcomb et al., 2011) utilizes the Generation IV cost code of accounts. The two are then swapped and the cost amounts are unchanged. Account 25 costs are shown in Table 29. The largest cost subaccount (252) covers air, water, and steam service systems. Other accounts cover lift equipment (251), communications equipment (253), fixtures and furnishings (254), and waste water treating equipment (255). Account 252 and 255 costs were scaled through the total plant economy of scale factor of 0.62 (Carelli et al., 2007a).

Table 29 – Miscellaneous plant equipment - account 25 (2016 USD)

		<i>PWR12-BE</i>		<i>P²S-LWR</i>		
		<i>Total</i>	<i>Equipment</i>	<i>Site Labor</i>	<i>Site Material</i>	<i>Total</i>
	<i>Transportation and</i>					
251	<i>Lifting equipment</i>	15,932,751	13,449,016	2,257,940	225,795	15,932,751
	<i>Air, water and steam</i>					
252	<i>service systems</i>	118,683,609	73,730,778	30,486,866	3,830,736	108,048,380
	<i>Communication</i>					
253	<i>equipment</i>	17,052,425	5,180,285	10,295,548	1,576,593	17,052,425
	<i>Furnishing and</i>					
254	<i>Fixtures</i>	7,272,771	5,767,131	1,335,846	169,794	7,272,771
	<i>Waste water treatment</i>					
255	<i>equipment</i>	7,526,363	1,814,994	4,537,484	499,448	6,851,926
	Miscellaneous plant					
25	equipment subtotal	166,467,918	99,942,204	48,913,684	6,302,365	155,158,253

4.6 Main Condenser heat rejection system – account 26 (account 25 on FHR (Holcomb et al., 2011))

As components sizes of the main condenser heat rejection system are function of the thermal power level of the plant, costs were scaled from the thermal power ratios (Eq. (4).). As before, an exponent equal to 0.8 was used (Phung, 1987). Costs of account 26 are shown in Table 30.

Table 30 – Main Condenser heat rejection system - account 26 (2016 USD)

		PWR12-BE		I ² S-LWR		
		Total	Equipment	Site Labor	Site Material	Total
261	Structures	11,517,202	424,221	6,498,094	3,574,536	10,496,851
262	Mechanical Equipment	76,358,303	21,145,218	37,726,859	10,721,369	69,593,446
26	Main Condenser heat rejection system	87,875,505	21,569,438	44,224,953	14,295,906	80,090,297

4.7 Direct capital cost summary

Direct capital costs for the PWR12-BE and the I²S-LWR, without accounting for the impact of seismic isolation, are shown in Table 31. With a reduction in direct capital cost of about \$384 M, the specific capital cost of the I²S-LWR is about 1% lower than that of the PWR12-BE (2,252 vs. 2,271 \$/kW, Table 31).

Table 31 – Direct cost summary—20 series accounts (2016 USD)

	PWR12-BE	I ² S-LWR (no seismic isolation)	Cost difference
Direct Capital cost	2,598,363,804	2,214,400,157	- 383,963,645
Direct Capital Cost/kW	2,271	2,252	- 19.17

5. Overnight capital cost

5.1 Indirect capital cost evaluation

As Holcomb et al. (2011) states, “Indirect capital cost addresses design, quality assurance, project management, and construction management and supervision both at the architect-engineer’s home office and on the construction site. It also includes all of the temporary facilities needed to support the construction personnel, laydown and storage areas for materials and equipment, and tools”.

The Gen IV cost code of accounts was used to account for I²S-LWR indirect costs. The Gen IV cost code of accounts differs from the EEDB code of accounts. The PWR12-BE construction supervision on site (from (US Department of Energy, 1987a, 1987b, 1987c)) was increased by \$250 M (Mack, 2016). As a conservative approach, indirect costs could be unadjusted, assuming that the construction techniques do not differ from historically built PWRs, resulting in analogous project duration, management and supervision needed on site.

However, this approach does not reflect the decrease in construction duration, management and supervision load caused by a simplification in design. Indirect costs can also be expressed as a percentage of direct cost. Under this assumption the cost of design, quality assurance, project management, and construction management and supervision is directly proportional to the cost of components fabrication and installations. Using this approach, estimations for indirect costs are lower for NPP that are simplified in the design. This approach was used to estimate the indirect cost of the I²S-LWR. Results of the indirect cost estimate are shown in Table 32.

Table 32 – Indirect cost summary - 30 series accounts (2016 USD)

	PWR12-BE	I ² S-LWR
Home Office Design		
31 services	533,953,685	455,050,645
32 PM/CM at home office	31,555,397	26,892,415
33 Design services at site	-	-
34 PM/CM at site	22,092,234	18,827,635
35 Construction Supervision	488,760,877	416,536,038
36 Field Indirect	635,398,267	541,504,627
37 Plant Commissioning	29,949,849	25,524,121
Total Indirect Cost	1,741,710,309	1,484,335,480

5.2 Capitalized Preconstruction Cost

Capitalized preconstruction costs include such items as land, site permits, plant licensing and plant permits, studies, and reports. 2011 \$6 M were allocated for the PWR12-BE, and the same amount was allocated for the I²S-LWR. The amounts, escalated to 2016, are shown in Table 33.

Table 33 – Capitalized Preconstruction Cost (2016 USD)

	PWR12-BE	I ² S-LWR
Capitalized Preconstruction Cost	6,645,480	6,645,480

5.3 Capitalized Owner's Cost

Capitalized owner's cost includes several categories of cost incurred prior to commercial operation, but not covered in the direct or indirect cost categories. The capitalized owner's costs are mainly function of the value of direct costs and can be expressed as a percentage of direct cost. For the PWR12-BE, capitalized owner's cost amounts to 2011 \$300 M, which corresponds to 12.79% of direct cost. For the I²S-LWR the value of capitalized owner's costs were calculated as 12.79% of the value of direct cost. These amounts, converted to 2016 USD, are shown in Table 34.

Table 34 – Capitalized Owner’s Cost (2016 USD)

	PWR12-BE	I ² S-LWR
Capitalized Owner’s Cost	332,274,000	283,173,433

5.4 Overnight Capital Cost summary

Overnight capital costs are summarized in Table 35. As compared to the PWR12-BE, the I²S-LWR provide a cost decrease of about \$690.4 M, equivalent to 33.53 \$/kW, or about 0.8%.

Table 35 – Capital cost (2016 USD)

	PWR12-BE	I ² S-LWR	Cost difference
Overnight Capital Cost	4,678,993,592	3,988,554,550	- 690,439,041
Overnight Capital Cost/kW	4,090	4,057	- 33.53, -0.82 %

5.4.a Overnight capital cost correction for seismic isolation

The I²S-LWR reference design includes seismic isolators. The isolators are made practical and economically effective by the I²S-LWR compact design and footprint. The I²S-LWR seismic isolators are shown in Figure 13. The reduction in peak ground acceleration due to building seismic isolation has been measured on many occasions. In 1994 the Northridge Earthquake shook in the Los Angeles area. During the earthquake, the peak ground acceleration (PGA) recorded at the site was 0.37g. The USC University Hospital, a seismically isolated building, measured a peak horizontal acceleration at the roof of .21g, almost a 50% decrease from the PGA (Stojadinovic, 2011). The Kobe Earthquake shook in 1995 in Kobe, Japan. Two identical structures were built, one was isolated and the other was not. In the seismic isolated structure the measured PGA was ten times lower than in the non-isolated building (Stojadinovic, 2011).

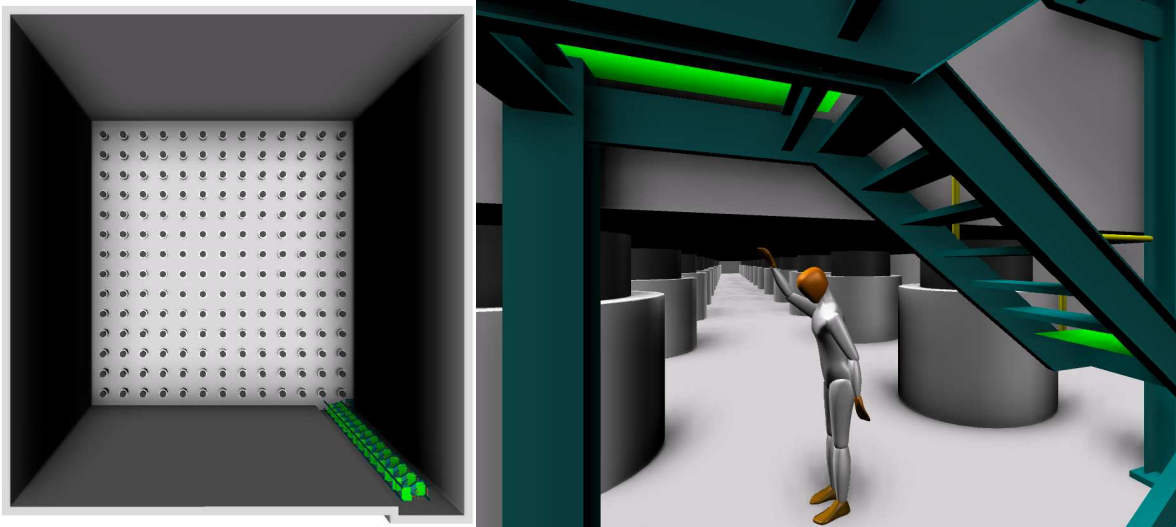


Figure 13 – Array of seismic isolation devices below bottom floor of Nuclear Island (Ammerman et al., 2017)

Simulations on the performance of seismic isolators for a 500 MWe pool type fast breeder reactor were carried out by Ravi et al. (1993). The authors show a 2 to 2.5 times reduction in the floor response spectra peak. Analyses were carried out for the isolation of a Liquid Metal Reactor. Analysis shows that the isolation system reduces the peak spectral acceleration from 2.5g to less than 0.6g (Wu et al., 1988). Seismic isolation was proposed for IRIS. Analysis performed under a reference earthquake (0.3g PGA) showed a building acceleration reduction by a factor 1.5-2 at the vessel attachment level and 5-6 at the roof level (Forni, 2010). 0.3 is the standardized US design typical acceleration level used for generic design purposes. It covers most of the central and eastern region of the US. The typical acceleration level considered for designing buildings in the western US is 0.7-0.8g. Higher acceleration levels (above 1g) are observed in other regions of the world (e.g. Japan). Figure 14 (Stevenson, 2003) shows the percentage cost of NPP seismic construction as a function of increased acceleration levels as compared to total nuclear power plant costs in the U.S.. Stevenson (2003) highlights that

additional structural integrity and testing operability as the ground peak acceleration increases adds significant cost to nuclear power plants.

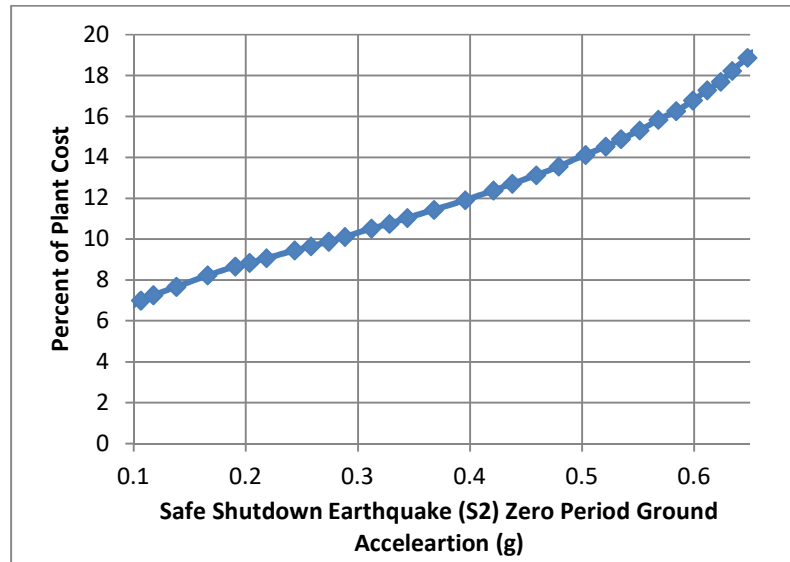


Figure 14 – Percent of Capital Cost as a function of the ground peak acceleration (extracted from (Stevenson, 2003))

Seismic isolation allows a reduction in the horizontal acceleration that a structure is subjected during an earthquake. A sensitivity analysis was performed to evaluate the effect of different types of seismic isolators on NPP total cost for different base ground acceleration. Data points expressed by Figure 14 were first converted to express seismic cost as a percentage of NPP total non-seismic related cost. Non-seismic related cost does not vary as the location and the ground acceleration is changed. The percentage of seismic cost over total plant cost was first converted.

$$\frac{cost_{s,g}}{cost_{ns}} = \frac{\frac{cost_{s,g}}{cost_{TOT,g}}}{1 - \frac{cost_{s,g}}{cost_{TOT,g}}}$$

Where:

- $cost_{s,g}$ represents the seismic related cost for a nuclear power plant designed for a ground acceleration value g
- $cost_{tot,g}$ represents the total cost for a nuclear power plant designed for a ground acceleration value g
- $cost_{ns}$ represents the non-seismic related cost for a nuclear power plant

A sensitivity analysis was performed to evaluate the cost savings due to the acceleration reduction from seismic isolators for different regions and different isolators performances. Practically, seismic isolators allow the structures to be designed for a lower ground acceleration. Considering a ground acceleration value g , the seismic cost is first calculated. Then, the reduction in ground acceleration that the structure has to tolerate is calculated through a peak acceleration reduction factor, defined as:

$$g = \frac{g_{reference}}{RF}$$

Where $g_{reference}$ is 0.3g for central-eastern US and 0.7g for western US.

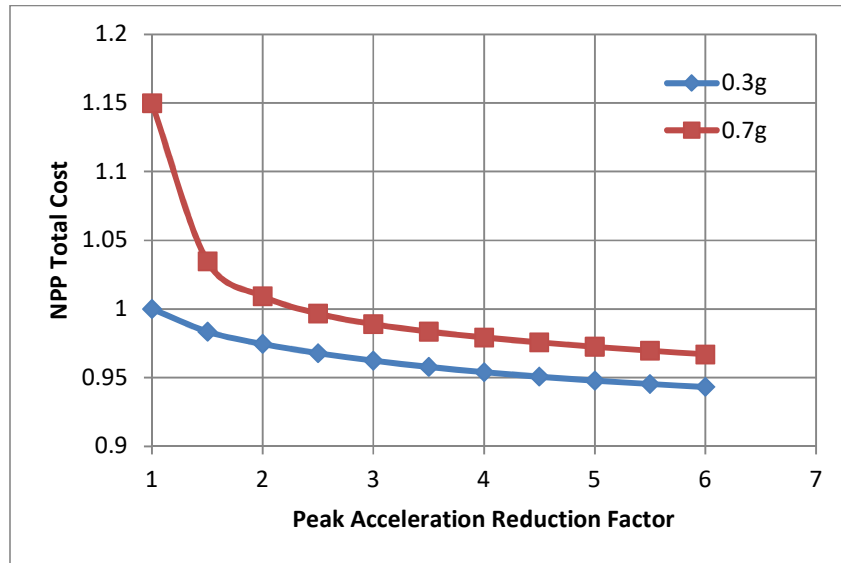


Figure 15 – Capital Cost as a function of the peak acceleration reduction factor. 0.3g: Central-Eastern US; 0.7g: Western US

For example, considering a location with 0.3g, if seismic isolators allow a ground acceleration reduction by a factor of 6 ($0.3g/6=0.05g$), the resulting cost of the plant is nearly 95% of the non-isolated plant. However, the cost of the additional concrete to isolate the structure and the equipment and installation cost of the isolators have to be accounted for.

Forni (2011) discusses the performance and cost of seismic isolation for IRIS. Seismic isolation cost consists of the cost of the seismic isolators themselves and the additional concrete structures to be built to disconnect the building from the ground. The number of total isolators required is 99 (Forni, 2011). The additional concrete amount is estimated between 10,000 and 12,000 m³. Cost of isolating the IRIS Nuclear Island is estimated as € 10 M (2012 €). The authors evaluated the cost to isolate large reactors, like the AP1000 and the EPR. Isolation cost of the whole Nuclear Island of EPR should require 500-700 isolators and an amount of additional concrete between 15,000 and 20,000 m³. The cost of a single isolators ranges between €20 k and €30 k

(2012 €). The upper bound of these cost ranges were used to estimate the isolation cost for the I²S-LWR nuclear island. The number of isolators needed for the I²S-LWR nuclear island was scaled from the EPR using the volume of the nuclear islands. The volume of additional concrete was calculated from the additional concrete, surrounding the nuclear island, needed to disconnect the building from the ground. The dimensions of the EPR nuclear island were taken from US NRC (2008) and AREVA (2005). The cost in 2012 EUR was first escalated to 2016 EUR, and then converted to 2016 USD applying the average EUR-USD exchange rate in January 2016. Results of this calculation are shown in Table 36.

Table 36 – Seismic isolators cost (2012 € and 2016 USD)

	EPR	IRIS	I ² S-LWR
Number of isolators	500-600	99	464
Isolators cost (2012 EUR)	21,000,000	2,970,000	11,597,052
(2016 USD)			12,914,528
Volume of concrete	17,500	11,000	6,765
Concrete cost (2012 EUR)	11,970,000	7.525 M	9,255,678
(2016 USD)			10,307,163
Total cost (2012 EUR)	32,970,000	10,000,000	20,852,730
(2016 USD)			23,221,691

This analysis was conducted to calculate the I²S-LWR total cost as seismic isolators are adopted. For both the 0.3g and 0.7g cases a conservative reduction of the ground acceleration by a factor of 2 was considered. All costs of the PWR12-BE were assumed to be referred to a NPP designed for a 0.3g peak ground acceleration. For the Central Eastern US case, seismic isolation provides an overnight capital cost reduction with respect to the PWR12-BE of 113.35 \$/kW, equivalent to 2.77%. (Table 37). For the Western US case, overnight capital costs of both the PWR12-BE and the I²S-LWR were increased by a factor 1.15, according to Figure 15. In this case, the reference

I²S-LWR design with seismic isolation provides a total capital cost reduction of 478.36 \$/kW which corresponds to a reduction of 10.18% (Table 37).

Table 37 – Total Cost for PWR12-BE and I²S-LWR. Isolated and non-isolated cases. Central-Eastern US (0.3g) and. Western US (0.7g)

	Central-Eastern US (0.3g)		Western US (0.7g)	
	PWR12-BE	I ² S-LWR	PWR12-BE	I ² S-LWR
Overnight cost (w/o isolation)	4,678,993,591	4,075,215,963	5,375,695,738	4,682,015,620
Isolation additional cost	-	23,221,691	-	23,221,691
Isolators saving		101,708,141		455,692,357
Overnight cost (w/ isolation, reference design)	-	3,910,068,101	-	4,149,979,657
Overnight cost (\$/kW)	4,090	3,977	4,699	4,221
Overnight cost difference (\$/kW)	-	-113.35 (2.77%)	-	-478.36 (10.18%)

5.5 Interest during construction and total capital investment cost

Interest during construction (IDC) is the cost of financing overnight cost over the construction period. Under the assumption that the cash flow is constant during the project duration, Economic Modeling Working Group (2007) calculates IDC as:

$$IDC = LT \cdot OCC \cdot \frac{r}{2} \quad (10)$$

Where *LT* is the lead time (project duration), *OCC* the overnight capital cost, and *r* the weighted average cost of capital. Economic Modeling Working Group (2007) states that a 5% yearly real weighted average cost of capital “is appropriate for plants operating under the more traditional

regulated utility model where revenues are guaranteed by captive markets, while the 10% real yearly weighted average cost of capital “would be more appropriate for a riskier deregulated or merchant plant environment where the plant must compete with other generation sources for revenues”. For the purpose of this paper, a 7.5% discount rate was used. A project duration of 5 years was assumed for the PWR12-BE. To reflect new construction techniques, simplicity in design, standardization of components, and higher degree of modularization, a project duration of 4 years was assumed for the I²S-LWR. Total capital investment cost is then calculated as the sum of the interest during construction and overnight capital cost. The values of IDC, TCIC and specific TCIC for the PWR12-BE and I²S-LWR are shown in Table 38. The lower project duration, along with the lower value of overnight capital cost, provide a TCIC reduction for I²S-LWR M with respect to the PWR12-BE of 283.73 \$/kW for the Central-Eastern US (Table 38), and of 726.33 for the Western US case (Table 39).

Table 38 – Interest during construction and total capital investment cost (2016 USD). Central-Eastern US (0.3g)

	PWR12-BE	I²S-LWR	Cost difference
Overnight capital cost	4,678,993,591	3,910,068,101	- 768,925,491
Interest during construction	877,311,299	586,510,215.10	- 290,801,083
Total capital investment cost	5,556,304,891	4,496,578,316	- 1,059,726,574
Total capital investment cost /kW	4,857	4,573	- 283.73 (-5.84%)

Table 39 – Interest during construction and total capital investment cost (2016 USD). Western US (0.7g)

	PWR12-BE	I²S-LWR	Cost difference
Overnight capital cost	5,375,695,737	4,149,979,657	- 1,225,716,080
Interest during construction	1,007,942,951	622,496,949	- 385,446,002
Total capital investment cost	6,383,638,688	4,772,476,605	- 1,611,162,082
Total capital investment cost /kW	5,580	4,854	- 726.33 (-13.02%)

6. PWR10-BE

The I²S-LWR key requirement is to be economically attractive when compared with conventional large light water reactors, such as the PWR12. However, additional insight is provided by comparison of the I²S-LWR with a conventional reactor of a similar power rating, whose direct cost details however are not available. Therefore, for such comparison the I²S-LWR costs are compared to an “artificial” reactor of the same power, denoted as PWR10-BE. The PWR12-BE direct cost data is scaled through an economy of scale factor to the PWR10-BE, using an overall economy of scale factor of 0.62 (Carelli et al., 2007a). Indirect cost, capitalized preconstruction cost, capitalized owner’s costs are then added to the value of direct cost under the same assumptions used for the I²S-LWR to obtain the value of overnight capital cost of 4,333 \$/kW. Interest during construction was calculated considering a construction time of 5 years, and then added to the overnight capital cost to calculate total capital investment cost. For the base case of peak ground acceleration (0.3g), I²S-LWR total capital investment cost is \$562.5 M lower than the one of the PWR10-BE, which is equivalent to 572.12 \$/kW (4,573 \$/kW against 5,145 \$/kW, Table 40). Considering a peak ground acceleration of 0.7g, the I²S-LWR has a total capital investment of 1,058 \$/kW lower than the total capital investment cost of the PWR10-BE (Table 41). Direct costs, overnight capital costs and total capital investment costs for the PWR10-BE and the I²S-LWR are shown in Table 40 and Table 41. **Error! Reference source not found..**

Table 40 – Direct, overnight capital, total capital cost summary (PWR10-BE and I²S-LWR, 2016 USD). Central-Eastern US (0.3g)

	PWR10-BE	I ² S-LWR	Cost difference
Direct cost	2,365,524,631	-	-

Overnight capital cost	4,260,304,853	3,910,068,101	-350,236,752
Total capital investment cost	5,059,112,012	4,496,578,316	-562,533,696
Total capital investment cost /kW	5,145	4,573	-572.12 (-11.12%)

Table 41 – Direct, overnight capital, total capital cost summary (PWR10-BE and I²S-LWR, 2016 USD). Western US (0.7g)

	PWR10-BE	I²S-LWR	Cost difference
Overnight capital cost	4,894,664,245	4,149,979,657	-744,684,588
Total capital investment cost	5,812,413,791	4,772,476,605	-1,039,937,186
Total capital investment cost /kW	5,911	4,854	-1,057.65 (-17.89%)

7. Conclusions

A systematic differential economics methodology was developed and applied for the evaluation of the I²S-LWR capital cost. This methodology relies on the Code of Accounts and aims to evaluate the cost difference with respect to a representative conventional reactor.

The differential economics methodology presented in this work was developed as a general approach that can be applied to evaluate the economics of various nuclear power plants of different sizes and designs, both in pre-conceptual and late design stages. Moreover, the use of the differential economics approach significantly reduces the uncertainties in relative costs, as they cancel out the cost of common components. The differential economic approach here presented is a reliable tool intended to evaluate the competitiveness of NPP designs, and can support decision makers.

A typical four-loop PWR with an electric output of 1,144 MWe was taken as a reference and cost estimating techniques were applied to assess the cost difference between the reference reactor

and the I²S-LWR. Costs for the reference plant were prepared in 1978 by EEDB, averaging actual cost incurred in the construction of several NPPs, itemized with a great level of detail according to the Code of Accounts. The last version of the report, released in 1988, was taken as reference (US Department of Energy, 1987b). Industry experts at Westinghouse Electric Company performed a “sanity check” of the cost items (escalated to 2011 USD by Holcomb et al. (2011), adjusting the cost of several items to match the current market and supply chain data. Specifically, the equipment cost of account 222 (Main heat transfer transport system) was increased by \$100 M, the equipment cost of account 227 (Reactor instrumentation and control) was increased by \$75 M, and construction supervision on site cost was increased by \$250 M. The resulting overnight cost of PWR12-BE was converted to 2016 USD, resulting in \$4,090/kW. Furthermore, the cost of PWR12-BE (with 1,144 MWe) was scaled (assuming traditional PWR technology) to I²S-LWR power level (983 MWe) and denoted PWR10-BE. Indirect cost, capitalized preconstruction cost, capitalized operations costs, and interest during construction were then calculated under the same assumptions used for the I²S-LWR to obtain a total capital investment cost value of f \$5,145/kW for PWR10-BE.

The detailed cost assessment of I²S-LWR was performed, systematically analyzing cost for each account, and applying the differential economics approach. First, relative importance of each account, i.e., its contribution to the total cost was established, to help focus analysis on the most significant contributors. Moreover, the accounts describing components that are different than that of the PWR12-BE were identified.

The main component contributing to the 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 of I²S-LWR is different from that of a standard PWR as it is made of innovative components (microchannel heat exchangers). The integral configuration has another implication on Account 221, which includes the RPV, which is larger in size with correspondingly larger internals. On the cost reduction side, the reactor coolant piping (in Account 222) is not present and the pressurizer is integrated into the hemispherical head of the vessel. Safety systems are allocated to Account 223. The passive DHRS of the I²S-LWR consists of a helical coil intermediate heat exchanger placed in the RPV, a water intermediate loop, and a cooling tower with a water-to-air heat exchanger. A careful cost analysis of the items included in this account was performed. Turbine generator equipment (Accounts 23x) is not believed to be much different than that of the reference design. Factors were applied to scale the cost of these components to the power level of the I²S-LWR. I²S-LWR structures (Accounts 21x) mainly differ from that of a standard LWR as several buildings (containment building, shield building, auxiliary building, waste processing building, fuel storage building) are integrated into a single building (nuclear island). Yardwork has a higher cost for the I²S-LWR, as the NI is partially below grade.

On the other hand, due to its compact Nuclear Island footprint, I²S-LWR facilitates— and includes in its reference design—the use of seismic isolators which contribute to reducing the overnight capital cost. The seismic isolators are installed on the nuclear building sub-foundation and are also included in these accounts. Two cases were considered, the first one with an

assumed 0.3g peak ground acceleration (representing Central Eastern US), and the second one with an assumed 0.7g peak ground acceleration (representing Western US).

For a base case having a 0.3g peak ground acceleration, the overnight capital unit cost per kW_e installed of I²S-LWR is 2.85 % lower than that of the same power PWR12-BE. For the Western US (0.7g), benefits of the compact footprint and consequent feasibility of seismic isolation become more important, and the I²S-LWR overnight capital cost is 10.18% lower than that of PWR12-BE. The I²S-LWR integral configuration, together with the adoption of innovative construction technologies such as modularization, proposes to decrease the construction time and, therefore, the interest accrued during construction. Assuming a project duration of 5 years and 4 years for the PWR12-BE and I²S-LWR respectively, for the base case of 0.3g, the I²S-LWR total capital investment cost is 5.84% lower than that of the PWR12-BE. Considering a case of 0.7g ground peak acceleration, the I²S-LWR total capital investment cost is 13.02% lower than that of the PWR12-BE.

Thus, the analysis performed in this study estimates that the advanced I²S-LWR design will enable cost reduction in the range of 5.84% to 13.02% as compared to a traditional design of a higher power level (PWR12-BE). If the PWR12-BE costs are scaled to represent a PWR design with the same power level as the I²S-LWR, the total capital investment cost reductions are in the range 11.12%-17.89%. That is, the significantly enhanced safety of I²S-LWR comes together with an economically attractive design, with an overnight cost lower than that of a nuclear power plant based on a traditional PWR design.

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