POLITECNICO DI MILANO

Facoltà di Ingegneria dei Processi Industriali

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Bottom-up cost estimation of small modular PWR

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ABSTRACT

Con “deliberately small reactors” si intende una categoria di reattori che sta riscuotendo grande attenzione nella comunità internazionale. Ridurre l’output elettrico di impianto è apparentemente contrario alla logica di efficienza economica, ma si motiva con vantaggi a livello di progetto.

In un impianto nucleare, la taglia ridotta permette di adottare soluzioni tecnologiche differenti e semplificate rispetto agli impianti di dimensione maggiore: snellendo il layout di impianto, introducendo maggiore sicurezza intrinseca e riducendo il numero di componenti attivi.

Il presente lavoro di tesi si inserisce nel quadro della ricerca economica degli SMR, dando un contributo all’analisi dei vantaggi di costo legati alle peculiari soluzioni tecnologiche adottabili dagli impianti di ridotta dimensione. L’analisi adotta un approccio bottom-up, con la valutazione delle macro-aree di costo di costruzione dell’impianto, che richiede necessariamente il riferimento a progetti di impianto specifici. Il presente lavoro si propone come un tentativo concreto di stima dei vantaggi economici di design e dovrà far riferimento a 3 modelli di PWR di taglia compresa tra i 50-300MWe.

Si è fatto riferimento ai dati disponibili in letteratura per ricavare i dati necessari alle analisi.

Data la difficoltà nel quantificare gli effetti della modularizzazione e del project management il risultato delle analisi mostra gli effetti dovuti all’economia di scala contrapposti agli effetti benefici introdotti dalla semplificazione del design.

I risultati possono essere sintetizzati comparando i fattori di scala ricavati dalle stime top-down e quelli ricavati a partire dai risultati delle stime bottom-up qui effettuate, che mostrano una minor performance economica associata agli SMRs.

Ciò è dovuto ai costi dei materiali che rappresentano il driver principale di molte categorie di costo rilevanti; l’economia di scala incide in maniera più significativa rispetto alle previsioni: la riduzione di output elettrico è molto più importante della riduzione di peso e non riesce ad essere alleggerita da semplificazioni di design.

INTRODUCTION

A new kind of reactors, called "Deliberately Small Reactors", looks promising for future electrical and thermal energy production.

Energy output diminution seems apparently disadvantageous looking at economical efficiency, but lower size allows for some design enhancements: simpler plant layout and higher safety standards using less active components.

This work of thesis gives a contribution to the economical research about SMRs, investigating the costs and benefits of specific technological solution adopted in smaller size reactors.

The analysis focuses on a "bottom-up" approach to the estimation of construction costs, that are proven to be among the most sensitive variables in the economic performance of a nuclear investment. Construction costs are divided in macro-areas and analyzed from the point of view of the fabrication, assembling and transportation activities. The aim is to model trends and possible discontinuities generated by the adoption of different technological solution or methods by each specific design.

"Bottom-up" approach necessarily requires to refer to some specific plant designs. Thanks to the wide knowledge accumulated on LWR, the most promising design are those related to the water technology, and in particular to advanced PWR. Therefore this analysis will apply to three reference reactor designs of the LWR type, between 50 and 300 MWe.

This analysis will be carried on in partnership with some Italian first-ranking industries involved in the nuclear business worldwide, in order to achieve the most correct estimation possible.

Research literature offers lot of works dealing with advantages of small reactors. Literature states that the reduced plant size favors higher modularization and factory-fabrication, with consequent economical benefits.

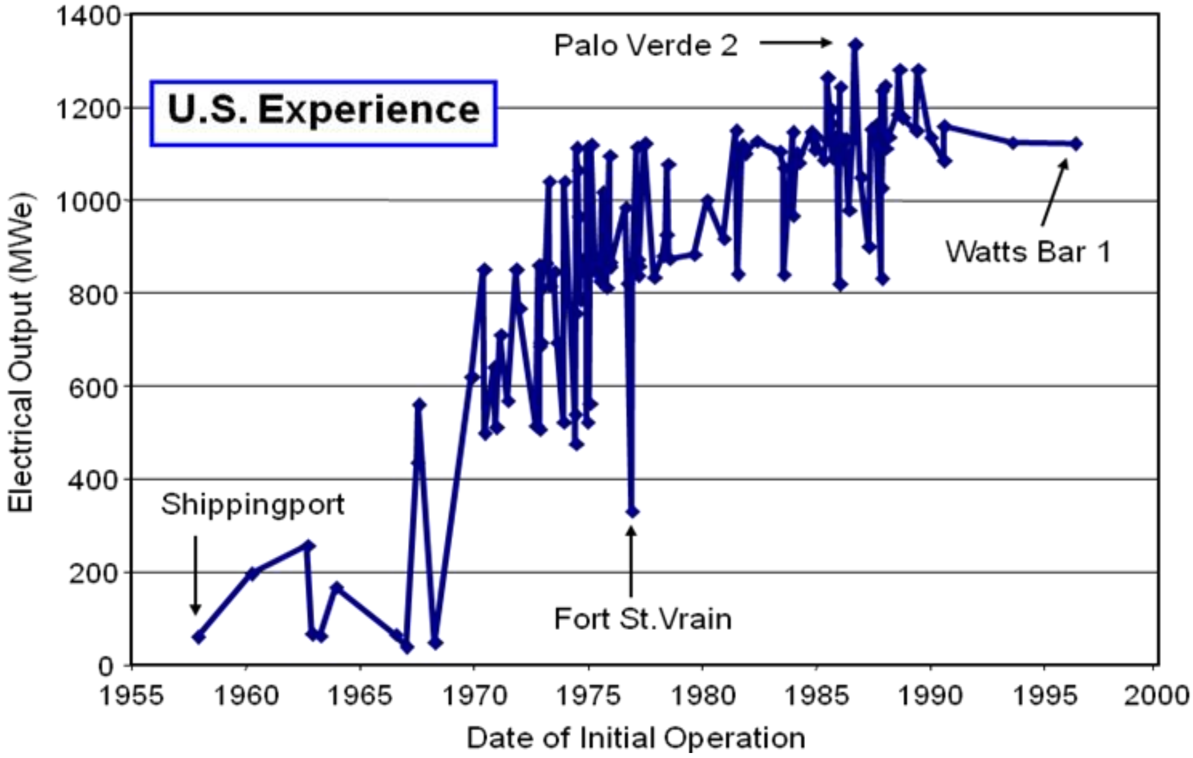
In addition, multiple unit construction on the same site favors a "learning" accumulation process on the assembling activity and the sharing of fix costs "site-related". SMRs require shorter construction time, reducing financial interests capitalization upon the invested capital. Furthermore consecutive multiple unit construction makes possible a self-financing plan.

Several authors deal with design simplification achieved by SMRs and its economical benefits, through qualitative considerations.

From these premises, this works aims to bring a more quantitative approach in the construction cost modeling upon specific plant design references.

1 SMR IN HISTORY AND NEW TRENDS

Light water reactor systems for propulsion were the forerunner of commercial nuclear power systems we see nowadays. Light-water reactors (LWR) were chosen because of their simplicity and compactness at this small scale. U.S. Air Force and Army also started a nuclear power program. From 1946, the Air Force studied the use of small nuclear reactors to power long-range bombers, but this application proved too difficult and politically unattractive and was terminated in. The Army Nuclear Power Program ran between 1954 and 1976 and led to the construction of eight reactors. These included six 1–2MWe pressurized water reactors (PWR), one 10MWe barge-mounted PWR reactor and one 0.5MWe gas-cooled reactor (GCR).



1-1 Progression of power level for the commercial nuclear power plants built in the United States (Energy Information Administration, 2008).

The Army program was discontinued because of the poor economics of the nuclear plants compared to cheaper alternative fuels available at that time. The early commercial reactors commissioned in the late 1950s and early 1960s were essentially scaled-up versions of the naval power plants. The 60MWe Shippingport plant began operation in 1957, the 200MWe Dresden plant in 1960, and the 250MWe Indian Point Unit 1 plant in 1962. Due to the rapidly growing demand for electricity, the high level of confidence in the safety of nuclear plants, and the economic principle of ‘‘economy of scale,'' reactor size began to grew up till 1300MWe. Much of this growth occurred over a 15-year period without the benefit of operating experience from smaller predecessors of these new large-size reactors. Fig. 1 shows the progression of power level for the commercial nuclear power plants built in the United States (Energy Information Administration, 2008). Analyzing this progression one can notice that power plants commissioned before 1973 were SMRs by IAEA's definition.

The apparent anomaly in the growth trend in 1976 was the startup of the demonstration gas-cooled reactor, Fort St. Vrain. No subsequent gas-cooled reactors have been built in the U.S. As plant sizes grew and as operational issues began to moderate the industry's confidence in the ultimate safety of the plants, more stringent safety requirements were imposed. This fact led to a growing complexity in the plant designs, adding redundant safety and auxiliary systems. This escalation of plant complexity contributed to rapidly increasing costs, construction and operational delays, licensing delays, and eventually decreased confidence by the owners and lenders in the profitability of the plants. Almost every reactor was built to accommodate the interests of individual customers, making every reactor a "one of a kind" construction process. Obviously this contributed to increased licensing, construction, and operational complexities. These and many other factors contributed to the eventual demise of the first nuclear era, which was punctuated by the accident at the Three Mile Island (TMI) plant in 1979.

Interest of many countries to the development and application of SMRs reactors continued as continued operation, construction of new small power plants, and progress in design and technology development. SMRs designers explored innovative design approaches to reach a higher level of plant safety, economics, and proliferation resistance. These facts ensure that such reactors could competitively meet the needs of potential users in those markets that cannot be effectively served by the economy of scale nuclear deployments. The potential SMRs users are diverse, spacing from small towns and industrial sites in off-grid locations to growing cities in developing countries.

There's also the possibility to use such reactors for non-electrical applications. The requirements of these user groups are also diverse, ranging from small capital outlay and incremental capacity increase to autonomous operation, advanced cogeneration options and long refueling interval. To facilitate SMRs development, the IAEA is carrying out new activities for SMRs that include:

- -Design and deployment strategies to overcome loss of economies of scale, for example, advantages in reduced design complexity, modularity and accelerated learning;
- -Definition of investor requirements for innovative SMRs and consolidation of methodologies to help public and private investors in developing countries to assess the overall potential of innovative SMRs;

- -Dynamic simulations of energy systems with innovative SMRs.

The potential for small and medium size reactors, SMRs is under study in the USA, Japan, Russia and other countries, and lately even in France.

France's naval construction firm DCNS together with Areva, Electricité de France, EDF and the Commissariat a L'Energie Atomique, CEA research organization decided to set up a joint study of DCNS' submerged reactor. it could provide wide energy for coastal locations all over the world.

The concept is called Flexblue and involves a cylindrical vessel about 100 meters long and 15 meters in diameter that encase a complete power plant producing from 50 to 250MWe.

AREVA, a world leader in nuclear energy has launched a program to study small reactors rated at 100 MWe with a view to rounding out its range of third generation reactors comprising EPR, ATMEA and Kerena types. This study draws-on AREVA's expertise in small shipboard reactors to assess the product's feasibility and market potential.

U.S. government nowadays gives to nuclear energy an important role. Nuclear power's objective is to assist in the revitalization of the U.S. industry through R&D. Developing these technologies through R&D could help accelerating the deployment of new plants in the short term, supporting development of advanced concepts for the medium term, and promoting design of revolutionary systems for the long term. This target will be achieved in partnership with industry to the maximum extent possible. Elements of nuclear energy's strategy in this area include:

- Assist industry to improve light water reactors using existing technologies and designs.
- Explore advanced LWR designs with improved performance.
- Research and develop small modular reactors that have the potential to achieve power's objective is to assist in the revitalization of the U.S. industry through R&D.

Smaller reactors have the possibility to be built in modules. This might help reduce the capital costs associated with large plants. It's always possible to incrementally "step up" to larger electrical capacities while generating revenue and repaying initial debts.

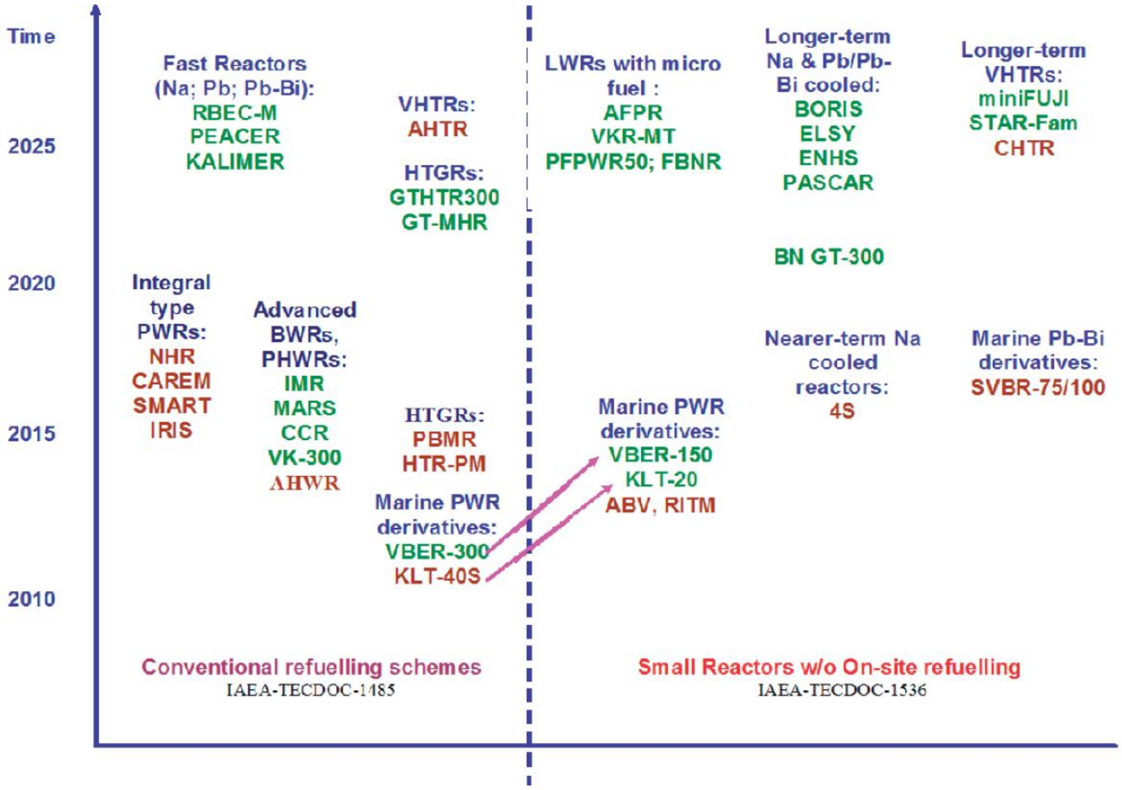
To help SMRs' development President Obama has earmarked $500 million over the next five years for SMR research and demonstration projects. Moreover Energy Secretary Steven Chu predicts that an SMR will be producing electricity by the end of this decade.

Congressmen also included in their speech to the Senate issues about SMRs (e.g. Sen Mark Udall**,** Colorado; Jeff Bingaman, New Mexico; Congressman Jason Altmire, Pennsylvania).

IAEA published a document (Design Features to Achieve Defence in Depth in Small and Medium Sized Reactors, Vienna 2009) showing SMRs future and describing the most important project.

Looking at Fig.2 it is possible to understand which prospective exist for small-size reactors, having an idea of the time scale connected to the major projects.

Not all of the project showed in figure are going to be licensed. Brown color indicates project in a more advanced stage of development.



1-2 Time schedule for the development and possible deployment of innovative SMRs, with and without on-site refuelling. (IAEA, 2010)

2 SMR CLASSIFICATION

2.1 LWR (PWR)

Pressurized water reactors (PWRs) constitute a majority SMRs. In a PWR the primary coolant, high pressure light water, flows in the reactor core where it is heated and, passing through a steam generator, it transfers its thermal energy to a secondary system where steam is generated. This steam flows to turbines which provides electrical energy. Small PWRs were originally designed to serve as nuclear propulsion for nuclear submarines.

In this category we can find: Nuscale, mPower, IRIS, SMART, KLT-40

2.2 LMFBR

LMFR reactor uses liquid metal as primary coolant. Liquid metal cooled reactors were first adapted for nuclear submarine use but have also been extensively studied for power generation applications. They don't need to be kept under pressure, and they allow a much higher power density than traditional coolants. Difficulties of inspection and repair of a reactor immersed in opaque molten metal, corrosion, production of radioactive activation products are the most discussed issue.

The most significant LMFBR SMR project is Toshiba's 4S.

2.3 "Exotic" or "Unconventional" Projects

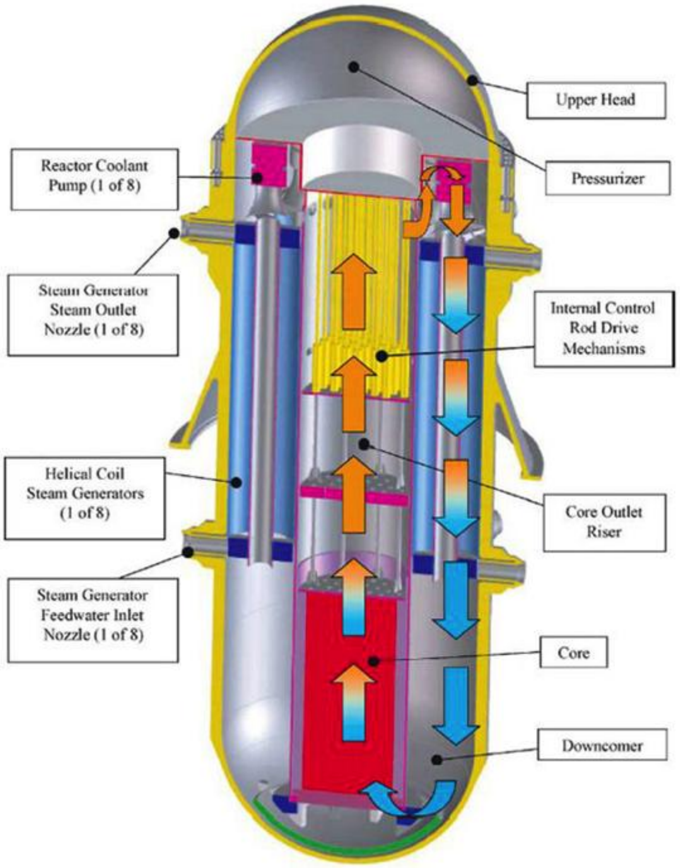
Under the name of "Exotic" projects it is possible to find out innovative and non conventional reactor projects as PbBi Hyperion (US) or CANDLE (JP) or the new French project of an underwater Integral PWR named Flexblue. These projects usually have different fuel cycle process (e.g. sealed core).

2.4 MSR (Molten Salt Reactor)

In the MSR, the fuel is a molten mixture of lithium and beryllium fluoride salts with dissolved enriched uranium, thorium or U-233 fluorides. Heat is transferred to a secondary salt circuit and thence to steam. It is not a fast neutron reactor, but with some moderation by the graphite is epithermal. The fission products dissolve in the salt and are removed continuously in an on-line reprocessing loop and replaced with Th-232 or U-238. MSRs have a negative temperature coefficient of reactivity, so will shut down as temperature increases beyond design limits.

3 REFERENCE DESIGNS

3.1 IRIS



3-1 IRIS core and primary flow path

	IRIS
Power	1000MWt 335MWe
Reactor Vessel	6.2m x 22.2m H; 25cm thickness
Outlet Condition	330°C
Coolant	Light water
Weight	1070 ton
Reactor Containment	25m D; 4.4cm thickness; steel
Reactor Building	50mD x 39mH
Steam Generator	1149m^2*8 units; 8,5m height
Steam Pump	1600 kg, 1800 rpm, 4500 kg/s
Steam Flow	502.8kg/s
Steam Temperature	223-317°C
Steam Pressure	5.8MPa

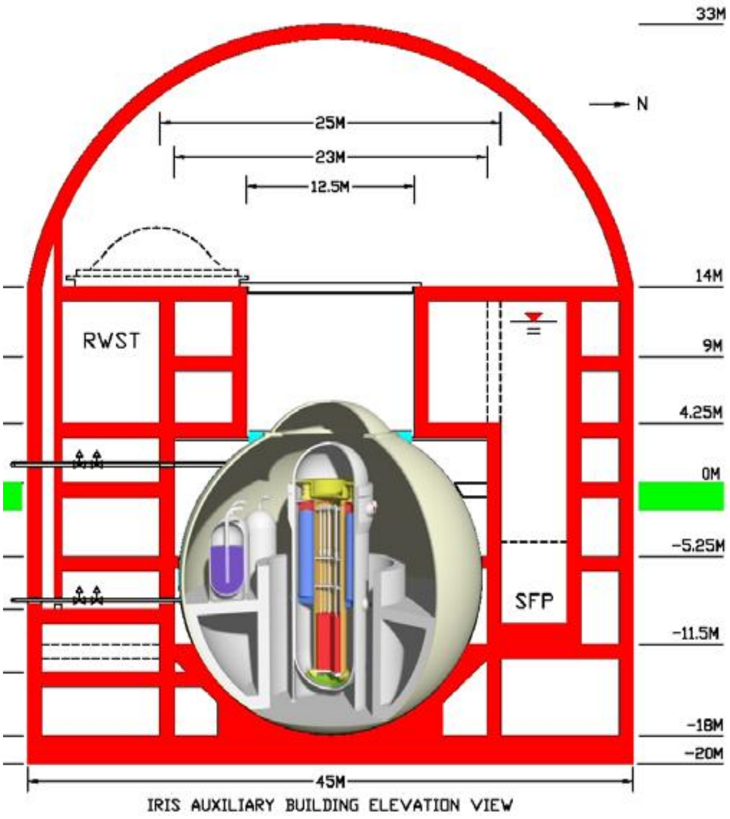
	IRIS
Condenser Pressure	0.005MPa
Transportation	Barge or special truck
Fuel Design	17x17 assemblies
Enrichment	4.95%
Plant Footprint	358080 m^2
Refueling	3-3.5 years

IRIS is a pressurized light water reactor with an integral primary system configuration with a net electrical output of about 300 MWe/module. Its design is characterized by four milestones: enhanced safety, improved economics, proliferation resistance and waste minimization.

Integral design means that steam generators, pumps, and pressurizer are located inside the reactor vessel. Integral design eliminates accidents scenarios like: LOCA, control rod ejection, feed line break, steam line break, SG tube rupture.

Thanks to this configuration it is allowed the use of a small, high pressure, spherical steel containment resulting in a great reduction of the size of the nuclear island.

Safety-by-design approach aims to eliminate by design some accident initiator events, or when elimination is not possible, to limit accident consequences and probability. This enhances defense in depth and lowers core damage frequency for example; it also allows IRIS to claim no need for an emergency response zone.



3-2 Schematic view of IRIS reactor building

Among active systems there are: stand-by diesel generators, startup feedwater system to fill the SG to remove heat from the core, boron injection systems. Passive systems are simpler and cheaper: pressure suppression system, emergency heat removal system (natural circulation+ heat exchanger), automatic depressurization system.

The entire reactor is the pressurizer; pressure is maintained using sprayer and the core heat. Each reactor has eight once-through helical steam generators, placed inside the reactor vessel near the walls.

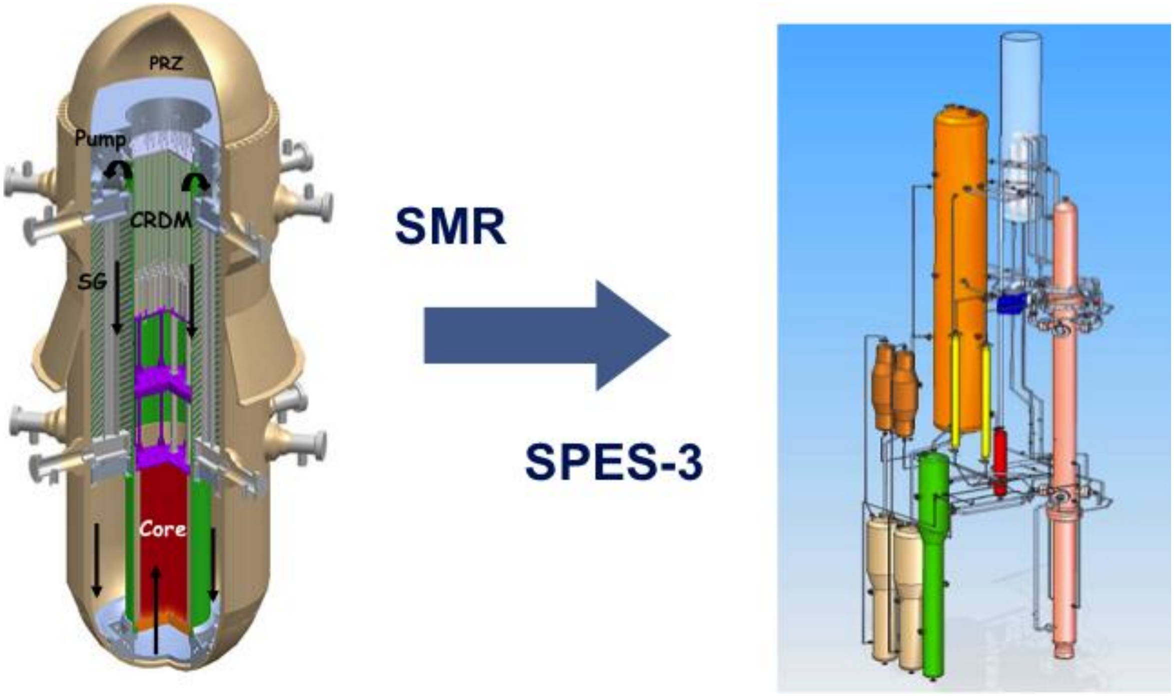
Reactivity coefficients remain negative throughout all reactor life. Burnable poisons are added to the fuel to flatten neutron flux. Reactivity is controlled both with boron and control rods

Shut down maintenance is scheduled every four years because of its simplified design, with less pumps, valves, pipes, and other components. There’s also the possibility to operate maintenance while reactor is operating thanks to, modular, easily replaceable components.

The basic feature of a modular reactor is to match the need of generating capacity to a utility’s future power requirements. IRIS offers flexibility, with a defined construction time of two to three years. This makes IRIS a good economic option to produce electricity power required, instead to have bigger power plants with the consequent higher investments and difficulty in injecting big electrical power on the grid.

It is also possible to establish a process lead to desalination of water. The development of a region is usually based on two main components: water and energy. An analysis was set up to study the possibility of building three IRIS modules to produce the amount of energy needed plus 7 reactor used for desalination of water in the Sonora region.

A key step in the R&D phase for SMR concepts as well as for IRIS, is the testing phase of the reactor safety features. This effort is currently under way in Italy: the SPES-3 facility will represent a reference facility worldwide for such a new type of reactors.



3-3 Layout of the SPES-3 integral testing facility under construction at SIET labs (Italy)

3.2 Mpower

3-4 mPower reactor core

	mPower
Power	500MWt 160MWe
Dimension	4.5mx29.6m reactor vessel
Reactor Containment	33m Diam x 45m H; 1.5m thickness; concrete
Foundation	47m
Reactor Building	100mx73mx19m
Weight	500 tons
Transportation	Barge, truck or train
Fuel	Standard LWR fuel, 17 x 17
N° Fuel Assemblies	69
Core Flow Velocity	2.5m/s

	mPower
Enrichment	4.95%
Plant Footprint	170000 m^2
Refueling	4.5 years
Lifetime	60 years

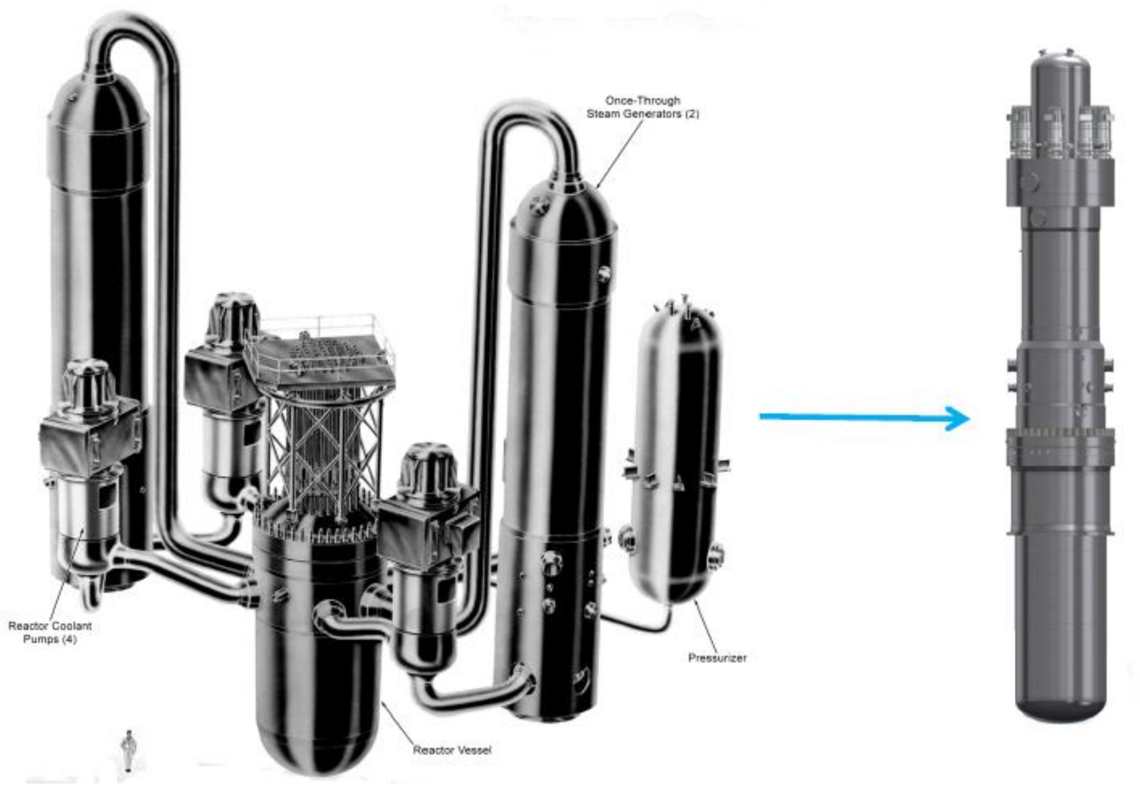
The B&W mPower is a direct descendent of the Otto Hahn reactor, used from 1968 to 1979 for surface ship. It incorporates the key features of that reactor are clearly noticeable in the use of an integral, once-through steam generator, PWR type fuel assemblies ,passive safety systems and so on.

Each 160MWe reactor is produced in a factory, cost about half a billion dollars, and could be built and installed, in multiples of two or four reactors, in only three years. mPower initial site designs show that the reactor should be installed in group of two or four modules, for a total of 320-640 MWe of generation capacity with a footprint of 170000 square meters for the twin configuration.

mPower is designed with an integral layout, that means the vessel holds all the components of the nuclear steam supply system. Fuel rods are on the bottom of the reactor, to make refueling easier. The reactor provides 500MWt, or 160MWe and it is designed to be air-cooled, for a cycle efficiency of 31%. In case of a water-based heat sink, cycle efficiency increases and power generation reaches 175MWe.

A difference between mPower and conventional PWRs occurs in SG configuration: in conventional PWRs primary coolant flows inside the tubes and secondary coolant flows all around them. In mPower, the primary coolant flows outside while secondary coolant is in the tubes. This is necessary thinking at its layout, and comes from experiences in naval propulsion.

Between SG and the reactor, are the control rod system; there’s one control rod per fuel assembly and there’s no soluble boron to control reactivity, to make the whole system simpler.



3-5 mPower integration concept

The integrated layout makes the safety case simpler as there are no primary loop penetrations, except for a 2in-diameter clean-up valve at the top of the reactor. In this way we find no large piping going put of the primary, so LOCA possibilities are lowered by design. It must be stressed that due to the height of the unit, a design-basis accident would not drain the reactor core. Gravity fed systems are proposed to remove decay heat from the reactor.

The fuel has a single five-year burn, instead of the standard three-burns as it happens in PWRs; at the end of fuel life the entire core is replaced in one load. Refueling would be expected to last about a week. A nearby spent fuel pool can store 12 cores, enough for a 60-year lifetime. During refueling it would also be possible to substitute the steam generator and inspect it while a new steam generator is put in operation, without lose time and money. This could be done alternatively every 5 years.

So an improved plant availability must be stressed, thanks to simpler and smaller components and the use standard technology, as well as an extended refueling cycle.

The project requires the core and reactor containment to be built entirely underground, to enhance security.

Containment building is built with a reinforced concrete, with an internal steel liner, to reduce leakage possibilities.

Two hatches grant the access to the reactor, one used by the personnel, the other one allows access for large components, in case of maintenance for example.

3-6 mPower containment

Transportation is a key point: mPower vessel size is the largest unit that can go by rail from the factory, plus the reactor is small enough to be forged in North America, instead of Europe or Japan . almost the whole unit would be assembled in factories, rather than in situ, granting higher standards and low costs; the construction process results more similar to a combined-cycle gas turbine.

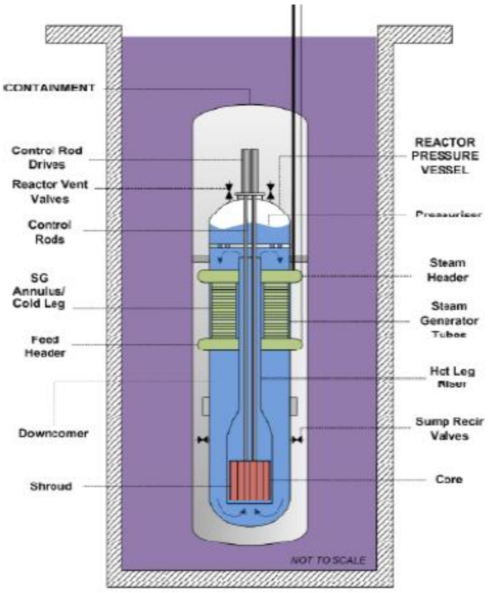
Designers plans are to invert the standard nuclear construction process. The new approach is to build the power plant first and then bring the reactor on site and connect it to the plant. So it’s possible to build modules in parallel with field activity to shorten construction times. On the contrary in a large plant it’s necessary to build the reactor first and then the rest of the power plant.

Different mPower reactors can be joined in a single power station to provide multiples of 160MWe power. Single modules can be twinned to drive a single generator; this process gives the possibility to fit electricity layout on customer needs: 640-960MWe, 160-320MWe etc. It’s possible to go up till 1000MWe or above, to grant an output similar to large scale reactors.

The capacity can be added in steps, thanks to the modularity of the base project, rather than all at once, allowing stepwise capital investment.

Late in 2013 the company aims to apply for certification, and a COL (combined Construction and Operating License) application to start siting analysis at TVA's Clinch River site in 2012. Construction should begin in 2015 and operation of the first unit in 2018.

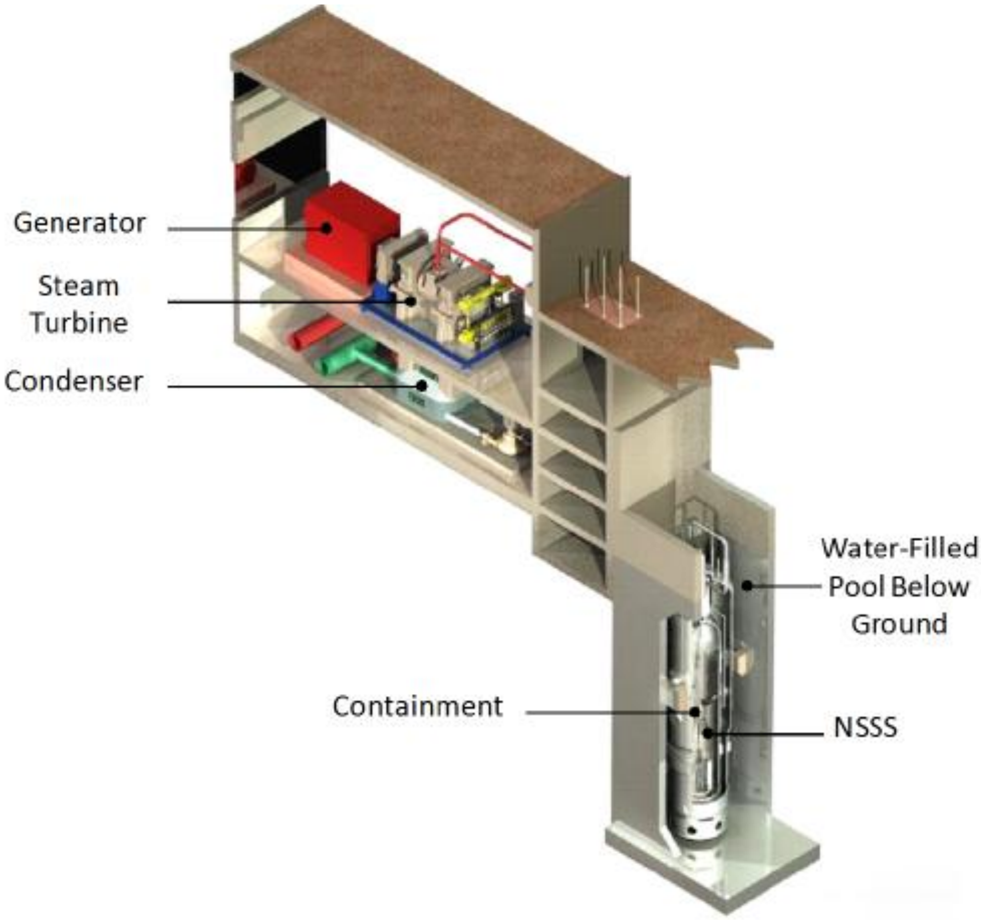
3.3 Nuscale



3-7 Nuscale module layout

	Nuscale
Power	160MWt 45MWe
Dimension	2.7m Diam x15m Height
Vessel Thickness	7.6cm
Primary Pressure	10.7MPa
Primary Flow	600kg/s
Layout	12x in pool
Weight	300 tons
Transportation	Barge, truck or train
Fuel	Standard LWR fuel in 17 x 17 configuration
Enrichment	4.95%
SG Length	22.3m
Secondary Flow	70kg/s
Feedwater Temp.	150°C
Secondary Pressure	3.1MPa
Refueling	24 month

A single Nuscale module produces 45,000 kilowatts of electricity. Heat is transferred from primary circuit, the core, to the secondary one by steam generators, integrated in the vessel itself. Produced steam is sent to a steam turbine connected by a single shaft to the electrical generator. Nuscale power plant will operate at full power for about 95% of the time. This makes it a really reliable generation system.

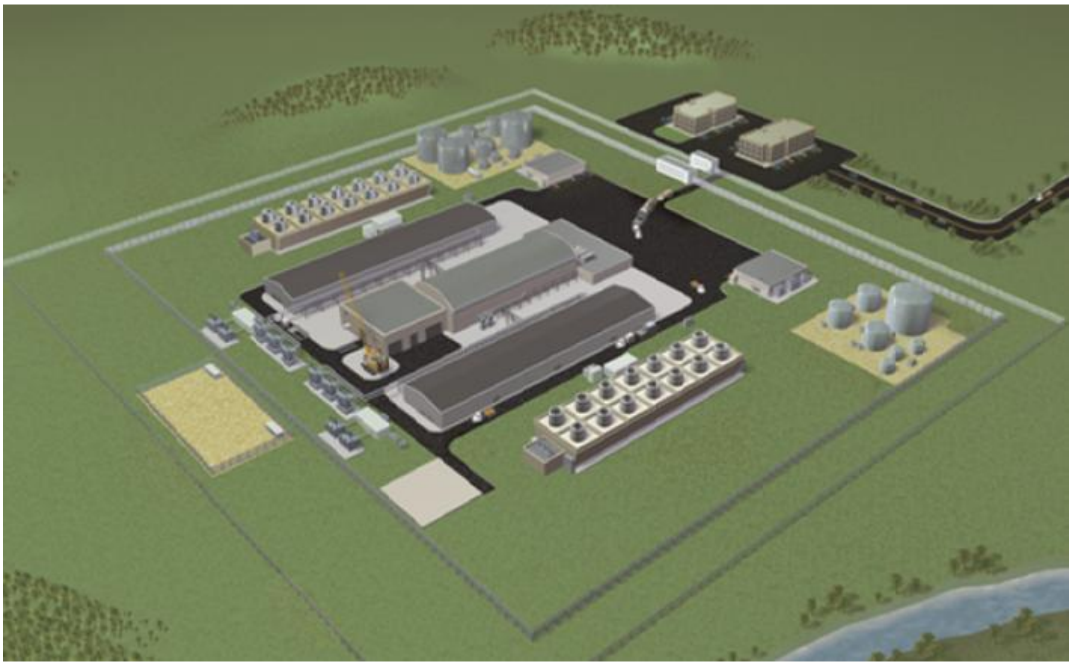


3-8 NSS and BOP of a Nuscale module

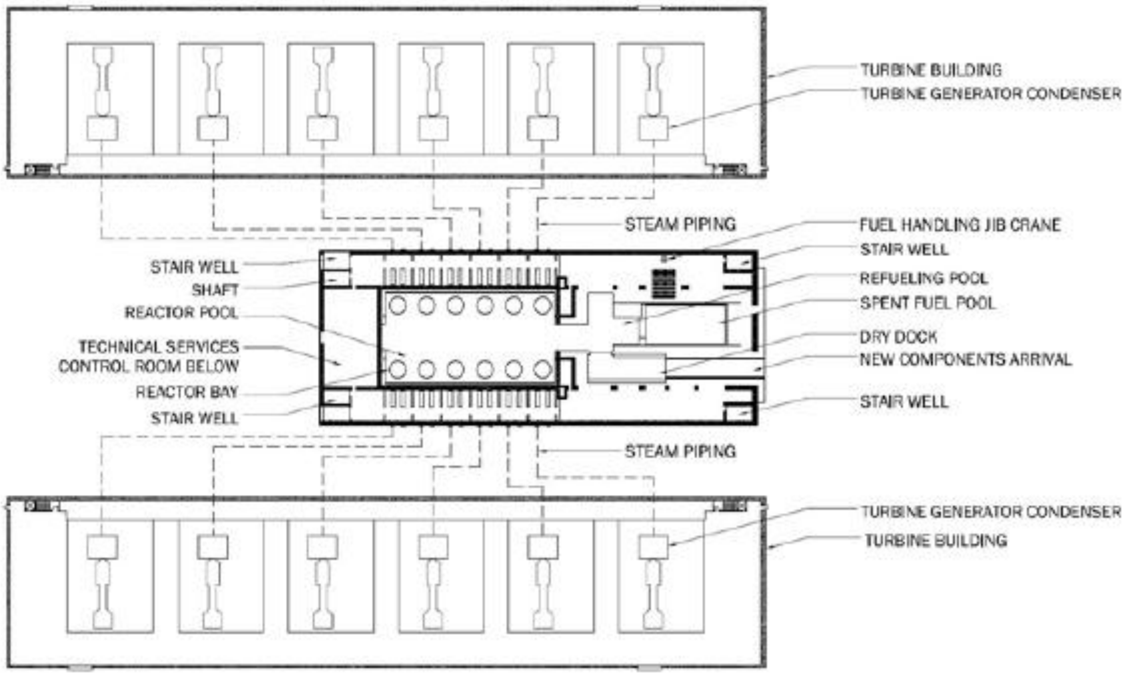
Nuscale design is based on MASLWR (Multi-Application Small Light Water Reactor) developed by the Oregon State University.

Because of its modular design it is possible to join each Nuscale, self contained anyway and independent from the others, in a multi-module configuration. However, all are managed from a single control room, placed below grade.

A plan view of a layout made of a 12 module array with a total capacity of 540 MW(e) is shown in Figure 3.1.4. The design layout shows a building which houses the pool containing the modules, a turbine building, and a separate refueling building which contains an area used as the spent fuel storage pool.



3-9 Nuscale 12 unit layout



3-10 Schematic view of 540MW layout

There are multiple barrier between fuel and environment, starting from cladding, to the reactor pressure vessel that sits in a containment vessel. This entire module operates inside a pool built below grade and covered by an individual concrete impact shield.

No pumps are needed to move water inside the reactor, because of natural circulation. This enhances safety and cut off the possibility of pump failures.

Secondary circuit is a standard 45MWe cycle, so, after steam passes through the turbines, it is cooled in a condenser and returns to the steam generator inside the reactor.

The steam generator is a once-through helical-coil type, located between the hot leg riser and the reactor vessel wall in an annular configuration.

There is the possibility to use steam, after it passes through the turbines, for low temperature, low pressure applications requiring heated water.

It is possible to use Nuscale system only to produce steam, using its 160MW thermal, for industrial applications, such as district heating for communities, large facilities and installations, or to synthesize fuels.

Enhancing safety means, in a Nuscale module, working with passive safety systems using natural circulation for emergency feedwater cooling, decay heat removal, and containment cooling. In this way, primary pipes and pumps are avoided as well as failures associated with pipe breaks and pump failures. This systems also operate without external power and there’s no need for emergency power on site or off site. In case of a simultaneous rupture of any or all of the reactor piping internal the containment vessel is capable of resisting to deriving pressure transient.

For what concerns earthquakes, the pool grants particular resistance to seismic. The possibility of a big radioactive material releasing is very low compared to the large-scale reactors: each 45 MWe Nuscale power module uses about 4% of the fuel inventory of a big-size nuclear reactor. the reduced amount of piping, low pressure and simpler design are a contribution to safety enhancing.

Security must also be stressed in a Nuscale plant. The most important features are:

- Lower reactor building profile.
- The reactor and containment vessel are located in a water-filled pool underground creating a low profile and protected target.
- Nuscale high pressure containment vessel is capable of seven times the internal pressure of conventional containments.
- Submerging the reactor further reduces post-impact jet fuel fire concerns.
- No external power is needed to cool the core, which limits plant vulnerability and loss of off-site power is not an issue.

The Nuscale containment vessel has several characteristics distinguishing it from other existing containment systems designs.

During standard power operation, an insulating vacuum is maintained between vessel and containment. providing a big reduction of heat loss from the reactor vessel. Thanks to this solution, the reactor vessel does not need surface insulation.

Furthermore, when safety valves vent steam into containment atmosphere, the deep vacuum improves steam condensation rates. Further, in case of a severe accident, eliminating containment air grants a security margin against the creation of a combustible hydrogen mixture (no need for hydrogen recombiners), and eliminates corrosion and humidity problems inside containment.

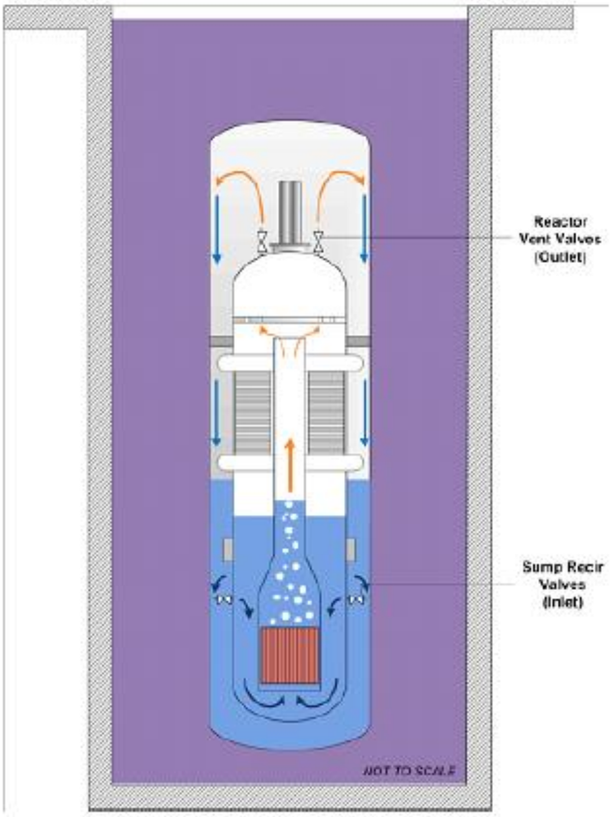
Plus, thanks to the reduced dimensions, it can sustain a pressure greater than 3.4 MPa (500 psia). In this way, the final pressure in the event of a small LOCA will always be below the containment design pressure.

Every Nuscale module has its own set of passive safety systems and it is immersed in a pool that can absorb decay heat after a shutdown for 72 hours granting a bulk fluid temperature of 93°C.

The pool in built entirely below grade: it’s made of concrete with a stainless steel liner.

Decay heat must reach the pool, so each Nuscale is designed with two redundant passive systems providing a path to the containment pool: the Decay Heat Removal System (DHRS) and the Containment Heat Removal System (CHRS).

To transfer heat generated to the containment pool, the DHRS uses the two steam generator tube bundles. Before natural circulation starts the feedwater accumulators provide initial water flow.



3-11 Schematic CHRS scheme

The CHRS, shown in Figure 3.1.4, acts in case the steam generator tube are not available. It works opening the vent valves on the reactor head. Steam of the primary system is vented into the containment and it condenses on the containment surfaces. Recirculation valves are then opened when the liquid level rises above the top of the recirculation valves, to start natural circulation from the sump through the core and out of the reactor vent valves.

The effect of these systems combined together eliminate Large Break Loss of Cooling Accident (LOCA) by design. Even in case of design basis small break LOCA, there is no scenario in which the core is exposed, as it will be under water all the time. Thus cooling pathways are always available to remove decay heat.

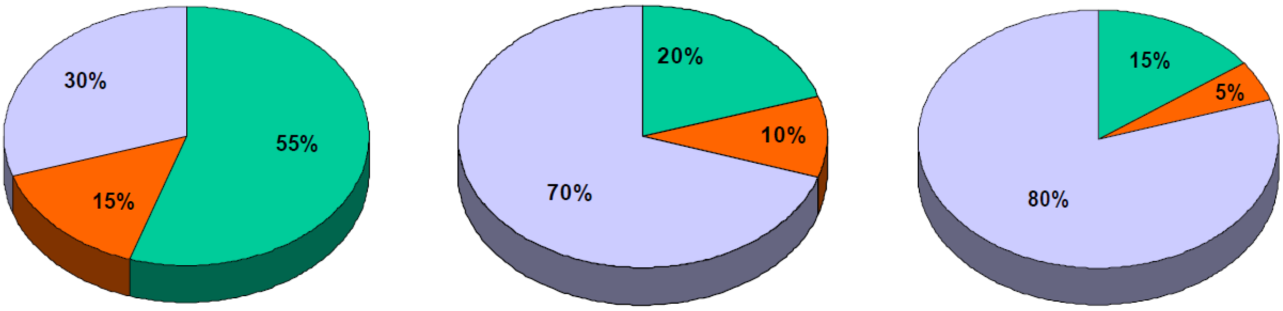
An application for US design certification is expected in 2012. For a first operating unit it maybe necessary to wait till 2018.

4 TOP-DOWN APPROACH AND “ECONOMY OF MULTIPLES”

4.1 TOP DOWN IN LITERATURE

Nuclear power plants are very capital-intensive. Construction costs are very high, as well as construction periods and financial interests.

It is clear that the emphasis of a cost estimate has to be put on capital costs, as the main component of the nuclear electric generating cost.



4-1 Costs distribution in a Nuclear, Coal and Oil power plant. In green construction costs, in orange O&M, in cyan fuel costs.

SMR are a new category of NPP with specific features in terms of fabrication, deployment and design. Their economic soundness has to be verified and cost estimated has to be performed.

There are two main approaches for the cost estimate:

- Top-down
- Bottom-up

Top-down estimate techniques are often used to estimate construction costs of very complex projects or in the early project stages. It has been proved that in some cases top-down cost estimates are more reliable than bottom-up approach.(Flyvbjerg, 2006)

In other words top-down models are based on the concept of a cost benchmark and historical data of similar projects. On the other hand side bottom-up models deal with technological options or project specific design characteristics. The differences between the results of these two methods are linked in a complex interplay among differences in purpose, input hypothesis and model structure. The terms ‘top’ and ‘bottom’ stand for aggregate and disaggregated models. Historically top-down name comes from the way modelers apply macroeconomic views and techniques to historical data on incomes, consumption, prices, and factor costs to predict the final demand for goods, services, or the supply from sectors like energy sector, transportation, agriculture, and industry.

Top-down estimation approach is able to predict results from previous or similar experiences.

If an identical project has been done in the past, it is useful to analyze it and try to adapt the information obtained to the new project. This is possible, obviously, only if there is a valid data background. It is also possible to obtain data from similar projects. This would require more time spent on the analysis of analogies between the project.

Some critics, however, underline that aggregate models is not able to capture the needed details and complexity.

In literature some basic steps can be identified to perform such an analysis(Flyvbjerg, 2006):

- Identification of useful reference class similar past projects. It is necessary to have a class wide enough to be statistically meaningful, but small enough to be easily comparable with the specific project under analysis.

- Calculating a probability distribution for the reference class chosen at the previous step. This relies on the possibility to have access to credible, empirical data for a sufficient number of projects belonging to the reference class to have the possibility to draw statistically meaningful conclusions.
- Comparing the project under analysis with the reference class distribution, in order to come out with the most likely outcome for the specific project.

Top-down approach seems to be more reliable when applied to non-routine projects.

This means projects that decision-makers and managers belonging to a certain organization have never attempted before.

This happens because it is in the planning of new strains that the biases toward optimism and strategic misrepresentation appear to be largest.

Finally, choosing the correct reference class of comparative past projects is obviously more difficult when managers are trying to forecast new initiatives, for which precedents are not easily found; for example, the introduction of new and unfamiliar technologies.

Top down estimation starts from a reference cost of a similar plant technology that is adjusted to feature specific size, deployment strategy and design of the project considered. In the following paragraphs each of these corrective factors will be discussed.

4.2 (DIS)ECONOMY OF SCALE

Looking at economical indicators most commonly involved in an energy plant analysis it’s possible to think that “economy of scale” is the main parameter to consider, so that small reactors appear not to be a valid option in nuclear energy production.

Capital cost in fact is proportional to the power output and of course, applying traditional scaling laws, SMRs appear to be characterized by an higher specific cost.

Literature suggests the following function to estimate economy of scale(IEA/NEA):

$$\mathrm{Cost}(P_1) = \mathrm{Cost}(P_0)\left(\frac{P_1}{P_0}\right)^n$$

where:

Cost(P1) = Cost power plant for unit size P1,

Cost(P0) = Cost power plant for unit size P0,

n = scaling factor for reactor with size between 300 and 1300MWe. Its range is (0.4-0.7).

This is true only if there is no change in reactor design, so could not be considered a reliable method in a top-down economic evaluation process; the scaling factor n concerns the entire plant, so different components may different scaling exponents, lowering the reliability of that method. (IAEA, 2010)

For example, Korean power plants have scaling factor 0.45, French experience suggests 0.51 while another study, based on AP-1000 and AP-600 brings a value of 0.6. (Paulson, 2006)

Moreover it is also true that dimensions of components have physical limitations, that obviously affect the economy of scale.

It is important, on the other hand, to investigate SMRs costs using a bottom-up approach.

In this way it’s possible to consider all the possible aspects relating the economy of small size reactors, starting from design savings factors.

In fact, smaller output results in smaller dimension and design peculiarities.

We can find advantages at several steps of the construction process: fabrication, assembling on site and transportation.

4.3 ECONOMY OF MULTIPLES: LEARNING, MODULARIZATION, CO-SITING ECONOMIES

As said before, classic scaling laws application leads to the result that economy of scale appears to be the most important factor affecting plant cost.

This is partially true if we look only at the fact that fixed costs are related to a single SMR, so that these costs are distributed on a minor power output, increasing specific cost. A closer look shows that the effect of the "economy of scale" can be largely mitigated by other benefits, some of which are typical of small plants.

These factors, costs related, are:

- **Modularization**: the reactor can be divided into different modules fabricated at the same time; these modules are then transported on site, so that the site work is required only to assemble components, rather than to build the entire rector, as it happens in stick-built large sized power plant. Modularization and factory fabrication are obviously strictly related.

- **Co-siting Economies**: modularization can be associated also to the site. SMRs grant the possibility to build several units on the same sites, sharing site related fixed costs, enhancing the economic competitiveness of the investment.

- **Learning factor**: learning is a key factor. In fact first of a kind reactors cost, on average, 35% more than next ones. Obviously learning factor is maximized due to the fact that the same people work on the same products on the same site. In fact it is not applicable if NPPS are built consecutively but in different countries, or in case of regulatory changes or if the interval between building consecutive plants is too long.

4.4 THE INCAS EVALUATION TOOL

Politecnico di Milano’s nuclear economics research group, within an international research effort fostered by IAEA on SMRs competitiveness, has developed the INCAS (INtegrated model for the competitiveness Assessment of SMR) model as a conceptual model and a software tools for the economic comparative assessment of investment projects in SMR versus large sized NPP.

This tool performs an investment project simulation and assessment of SMRs and LRs deployment scenarios, providing monetary indicators (e.g. IRR, LCOE, total equity employed) with the option to integrate them with not-monetary indicators (e.g. design robustness, required spinning reserve).

The INCAS code is specially designed to account for the so-called “economy of multiples” that represents a benefit for the SMR investment paradigm.

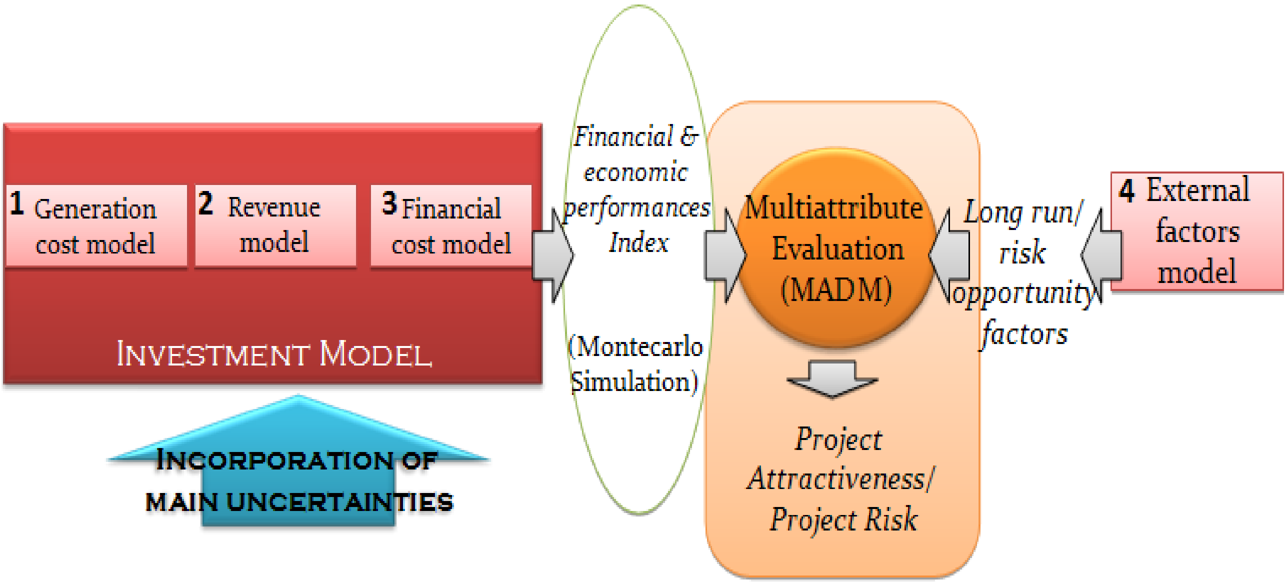
INCAS code allows great flexibility in the input parameters setting in order to represent different investment strategies and scenario conditions (sources of financing, operating performances electricity price..).

This makes sensitivity analysis possible, appreciating the impact of each input variable on the economic overall performance, on the investment project or to set the best investment strategy to reach desired objectives (profitability maximization., LCOE minimization, risk control..).

A comparative methodology to evaluate the differential economic and financial advantages/disadvantages, offered by the two different plant configurations and technologies, is adopted.

The “Investment Model” of the INCAS code elaborates all the key elements of an economic and financial analysis (revenues, financial costs, operating and capital costs) and is based on a cash flow analysis over the entire plant life.

The output of the “Investment Model”, is a set of indexes quantitative financial performances indicators from the point of view of investors: profitability, value generated by the project, Pay Back Time, etc.



4-1 INCAS conceptual scheme

Moreover, the Investment Model's dynamic cash flow analysis is able to catch the "self-financing" feature of a multiple SMR project, representing the capability of the project to finance itself. It is made possible by the re-investment of the cash inflows from the early deployed NPPs' operations into the later NPP units under construction.

External factors (e.g. social acceptance) must be included in the analysis: even if they are not fully quantifiable, their influence on the investment economic performance investment is undoubted. The "External Factors Model" of INCAS analyzes these factors to assess the project attractiveness for a private or a public investor (at governmental, ministry, public administration level) once the decision to invest in NPP has been taken.

Construction costs are estimated by the "Generation Cost Model" through a top-down approach, starting from reference cost information on LR of the same basic technology. The code have models to feature the so-called "Economy of Multiples" as explained in the previous paragraph; in particular:

- economies of scale;
- co-siting economies, thanks to the possibility of sharing fixed costs by NPP built and operated on the same site;
- construction cost savings, due to modularization effects, that are size-dependent;

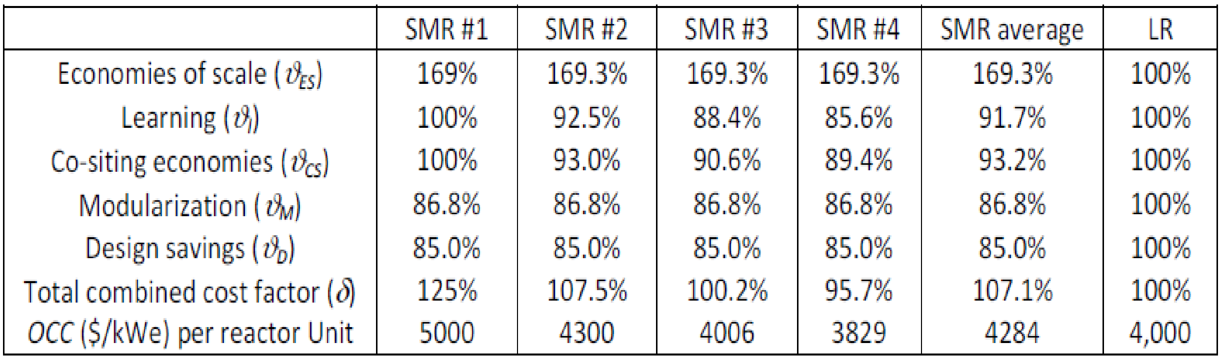
- learning factor, both at single site level and worldwide, with proper learning accumulation and decay laws;
- effect of delay in the construction period;
- cost of financing during construction period.

As previously underlined co-siting economies, modularization and learning factors contribute to the economies of multiples. Obviously they apply to multiple NPP projects, so it is more evident for SMR projects that require more NPP units to be installed to produce a given total power output.

Furthermore SMRs are usually affected from design technology simplification, resulting in construction cost saving: specific saving factors has to be provided to the model on the basis of a deep design analysis.

All of these factors have been modeled starting from literature values and then implemented in the INCAS code: specific parameters ϑ_i are calculated and applied to the construction cost of a reference large sized reactor, so that construction cost of a small sized NPP is scaled from it. These factors refers to economies of scale, co-siting, modularity, learning and design saving features.

An example could be represented from the following picture:



	SMR #1	SMR #2	SMR #3	SMR #4	SMR average	LR
Economies of scale (ϑ_{ES})	169%	169.3%	169.3%	169.3%	169.3%	100%
Learning (ϑ_l)	100%	92.5%	88.4%	85.6%	91.7%	100%
Co-siting economies (ϑ_{CS})	100%	93.0%	90.6%	89.4%	93.2%	100%
Modularization (ϑ_M)	86.8%	86.8%	86.8%	86.8%	86.8%	100%
Design savings (ϑ_D)	85.0%	85.0%	85.0%	85.0%	85.0%	100%
Total combined cost factor (δ)	125%	107.5%	100.2%	95.7%	107.1%	100%
OCC ($/kWe) per reactor Unit	5000	4300	4006	3829	4284	4,000

4-2 Example of Overnight Construction Cost factors

The discounted cash flow model is able to catch the full financial profile of the investment plan and of the operation period, allowing to estimate further benefits of the multiple SMR deployment, that are described in the following paragraph.

4.5 FINANCIAL SAVING FACTORS

There are also financial factors specific to the economy of SMRs.

Modularization of the investment and a staggered deployment strategy enable a partial self-financing of the project, decreasing the capital up-front investment. That’s possible thanks to the fact that the first unit constructed can generate revenues while the other units are under construction.

In the following picture, cumulated cash flows of a LR investment project is compared to 4 SMR with equivalent power. It can be highlighted that, with a lower generation capacity installed rate, the average capital at risk during the construction phase is lower.

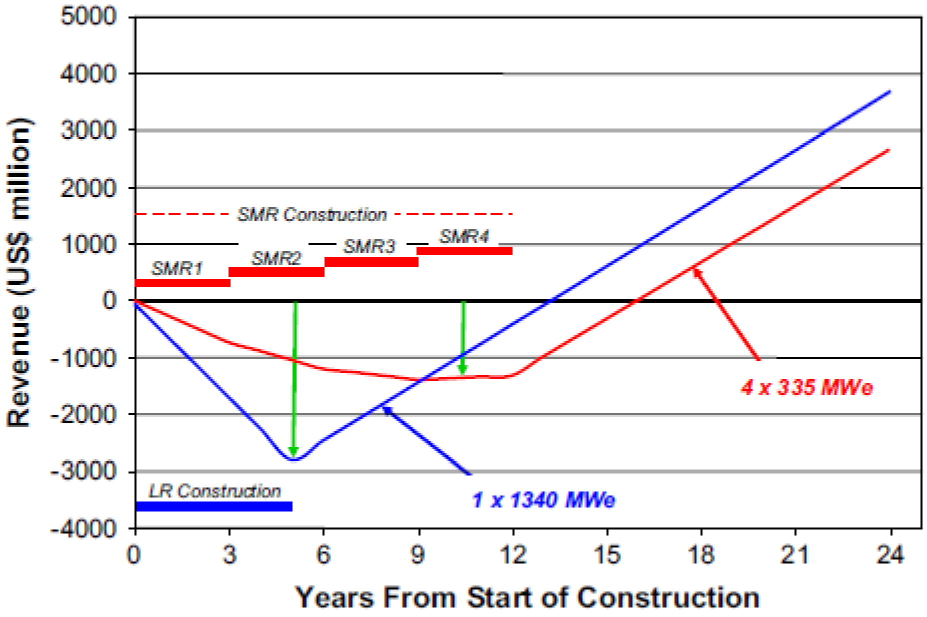


Figure 3 1 Self financing effects on cash flow

The financial impact of construction delays might be reduced, as a direct consequence of both the shorter time needed to build single units and the lower capital invested in the reactor construction.

Considerably lower capital invested and reduced construction time (thanks to the high factory fabrication grade) are key factors to reduce interests charges. SMR represent a limited and gradual resource commitment to approach a nuclear investment, allowing smaller investors to participate in the nuclear investment process. This can open considerably new scenarios in developing counties, were funds can be limited and where the electrical grid cannot stand a large power input on the electrical grid.

Although several rectors share same equipment, during reactor life, modularization allows energy production while some units may be under refueling or maintenance process, that results considerably less time-expensive thanks to their particular design and to the high grade of factory fabrication. This is very important because it grants an higher availability compared to bigger size reactors.

5 BOTTOM UP APPROACH

5.1 BOTTOM UP IN LITERATURE

In general, bottom-up estimate of project costs is a valuable approach because it relies upon the cost estimate of each single component or at least, of the key components. A cost structure breakdown is needed in order to identify the key cost items.

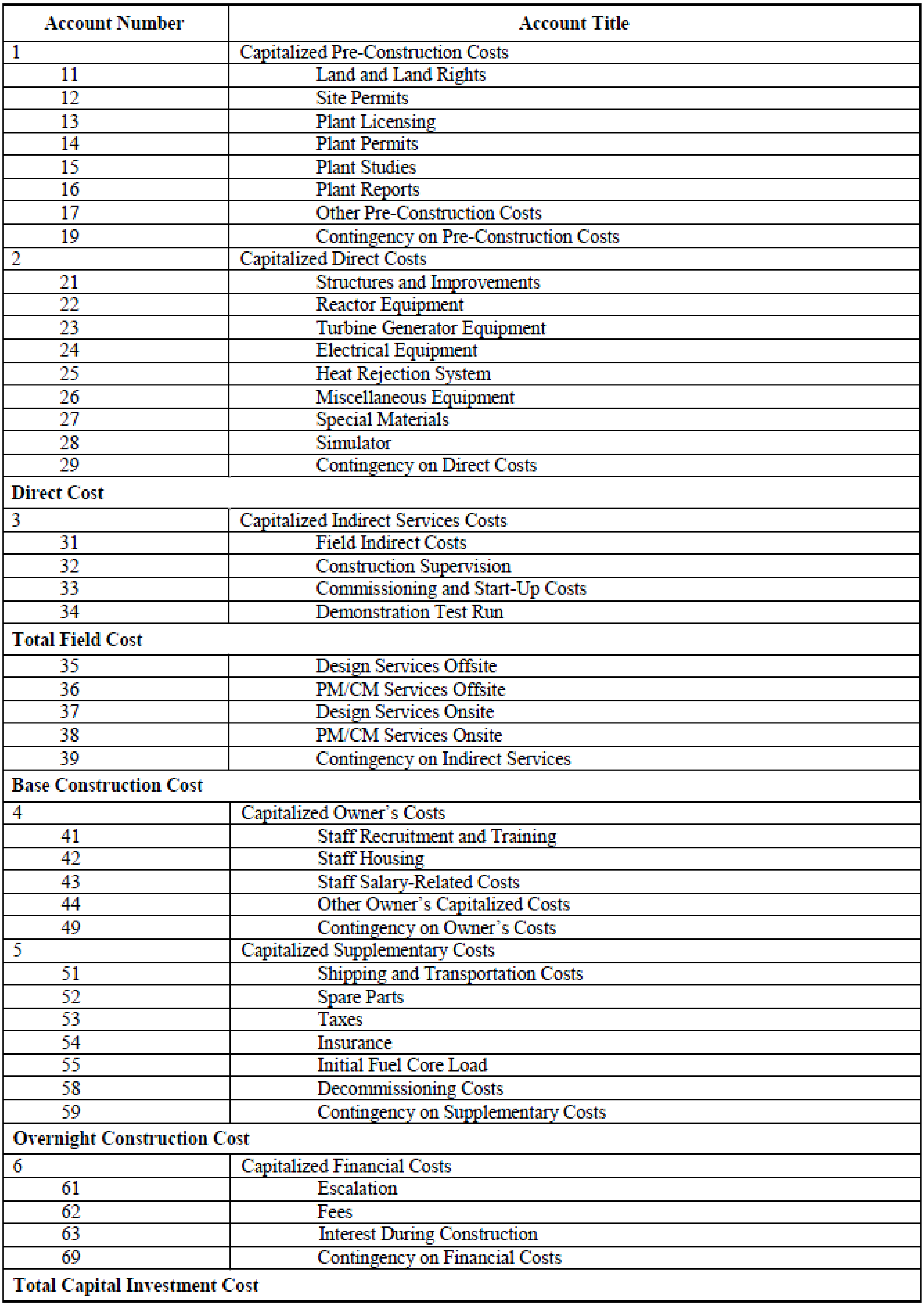
Each of them is investigated in order.

This is the more common costs estimation applied to near construction projects.

For large nuclear projects, generally a bottom-up estimating is performed in collaboration with a utility. The starting point is a detailed design with layout diagrams for all major systems and very detailed items, such as equipment lists or commodity quantity estimates.

To the estimated quantities are applied unit prices and unit labor-hour rates; all cost items of a nuclear power plant are summarized through the Code Of Account (COA) defined by the GEN-IV EMWG (GIF/EMWG, 2007)

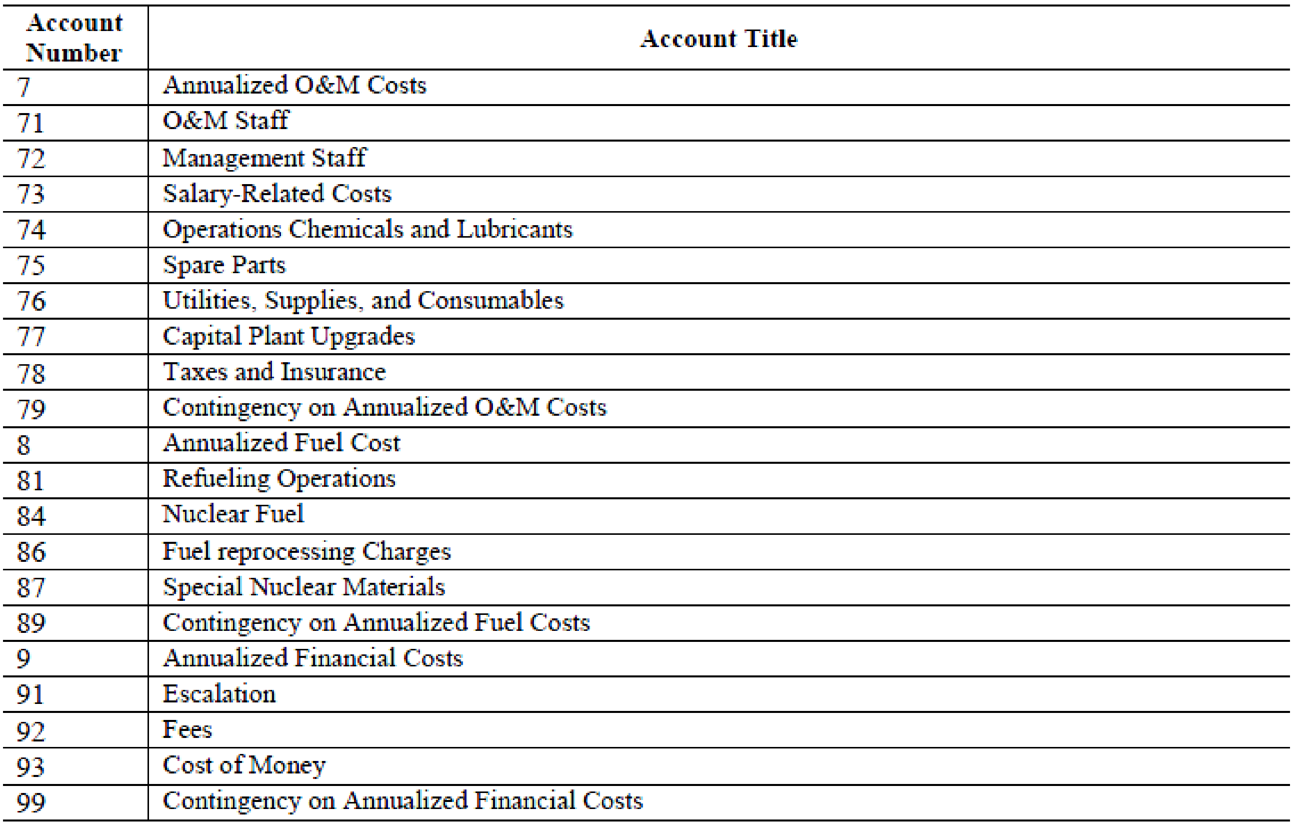
Here’s an example of 2 digit COA:



Account Number	Account Title
1	Capitalized Pre-Construction Costs
11	Land and Land Rights
12	Site Permits
13	Plant Licensing
14	Plant Permits
15	Plant Studies
16	Plant Reports
17	Other Pre-Construction Costs
19	Contingency on Pre-Construction Costs
2	Capitalized Direct Costs
21	Structures and Improvements
22	Reactor Equipment
23	Turbine Generator Equipment
24	Electrical Equipment
25	Heat Rejection System
26	Miscellaneous Equipment
27	Special Materials
28	Simulator
29	Contingency on Direct Costs
Direct Cost	
3	Capitalized Indirect Services Costs
31	Field Indirect Costs
32	Construction Supervision
33	Commissioning and Start-Up Costs
34	Demonstration Test Run
Total Field Cost	
35	Design Services Offsite
36	PM/CM Services Offsite
37	Design Services Onsite
38	PM/CM Services Onsite
39	Contingency on Indirect Services
Base Construction Cost	
4	Capitalized Owner`s Costs
41	Staff Recruitment and Training
42	Staff Housing
43	Staff Salary-Related Costs
44	Other Owner`s Capitalized Costs
49	Contingency on Owner`s Costs
5	Capitalized Supplementary Costs
51	Shipping and Transportation Costs
52	Spare Parts
53	Taxes
54	Insurance
55	Initial Fuel Core Load
58	Decommissioning Costs
59	Contingency on Supplementary Costs
Overnight Construction Cost	
6	Capitalized Financial Costs
61	Escalation
62	Fees
63	Interest During Construction
69	Contingency on Financial Costs
Total Capital Investment Cost	

5-1 Generation IV International Forum nuclear energy plant Code of Accounts

To this first costs account list, it has been added a second chart, including operation and maintenance costs as well as taxes, fees decommissioning and miscellaneous costs:



Account Number	Account Title
7	Annualized O&M Costs
71	O&M Staff
72	Management Staff
73	Salary-Related Costs
74	Operations Chemicals and Lubricants
75	Spare Parts
76	Utilities, Supplies, and Consumables
77	Capital Plant Upgrades
78	Taxes and Insurance
79	Contingency on Annualized O&M Costs
8	Annualized Fuel Cost
81	Refueling Operations
84	Nuclear Fuel
86	Fuel reprocessing Charges
87	Special Nuclear Materials
89	Contingency on Annualized Fuel Costs
9	Annualized Financial Costs
91	Escalation
92	Fees
93	Cost of Money
99	Contingency on Annualized Financial Costs

5-2 Structure of the Generation IV International Forum operations and maintenance Code of Accounts

We considered the “GIF COA account system structure” that allows us to refer to a standard and proven cost partition.

This system includes costs related to land acquisition, labor, components construction and so on.

It is possible to obtain different level of detail looking at different “Digit” level (one, two or three digit level of detail).

Following this path it is very important because it allows different t level of detail at different stage of design and, moreover, allows easy comparison between different kind of reactor, analyzed using this method. This kind of analysis provides the overnight cost, that’s to say the cost of the plant if it could be built “in a night”, avoiding any financial effect during the “real construction time”.

Thanks to construction schedule and project execution plans it is possible to obtain the basis for detailed estimates of the field indirect costs.

This process usually requires lot of time and staff working from very beginning of the project, organizing all detailed items and activities into a COA at least to the three- or four-digit level for all categories.

Scheduling activities are also reported with high level of detail, usually using scheduling software.

As bottom-up estimating proceeds, cost contingencies (as a percentage of base costs at a fixed confidence level that an overrun of the base cost plus assigned contingency will not occur) decline.

By the way, this method has to be supported by other data such as unit costs of labor, siting requirements, installation rates, commodities and construction labor-hour estimates.

As said before, classic scaling laws application leads to the result that economy of scale appears to be the most important factor affecting plant cost. This is a typical result of a top-down process.

It is important, on the other hand, to investigate SMRs costs using a bottom-up approach.

In this way it's possible to consider all the possible aspects relating the economy of small size reactors, starting from design savings factors.

In fact, smaller output results in smaller dimension and design peculiarities.

We can find advantages at several steps of the construction process: fabrication, assembling on site and transportation.

5.1.1 FABRICATION

As introduced in the previous chapter modularization is the key factor during fabrication process. Producing smaller modules opens the market to other manufacturers, that can now enter the nuclear market. This can provide less expensive components.

Large size reactor are almost entirely built on site (stick-built). This is a very time-expensive process due to the fact that, most of the time, it is a first of a kind project, and every part of its construction is made for the first time and for the particular site.

A deeper design analysis is required in case of modular projects.

The reactor has to be divided into different modules that can be fabricated at the same time; these modules are then transported on site, so that the site work is required only to assemble components.

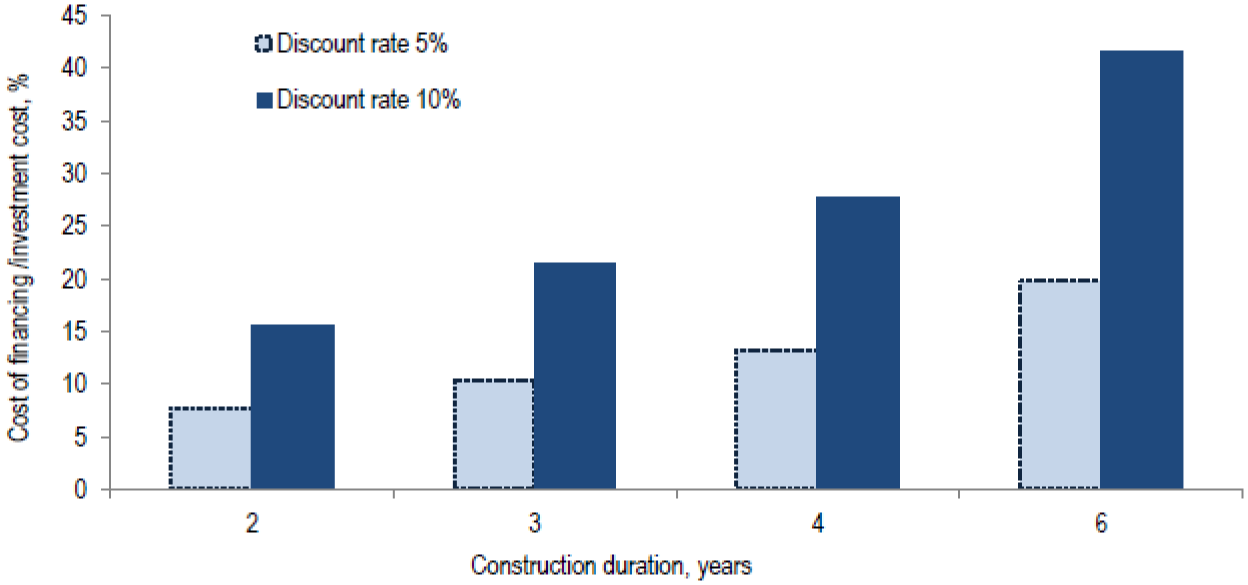
Obviously modularization and factory fabrication are deeply connected.

This fact brings several advantages:

- **Higher quality standard**: thanks to a controlled environment it is possible to achieve better performance in modules construction. It is also easier to perform quality checks.

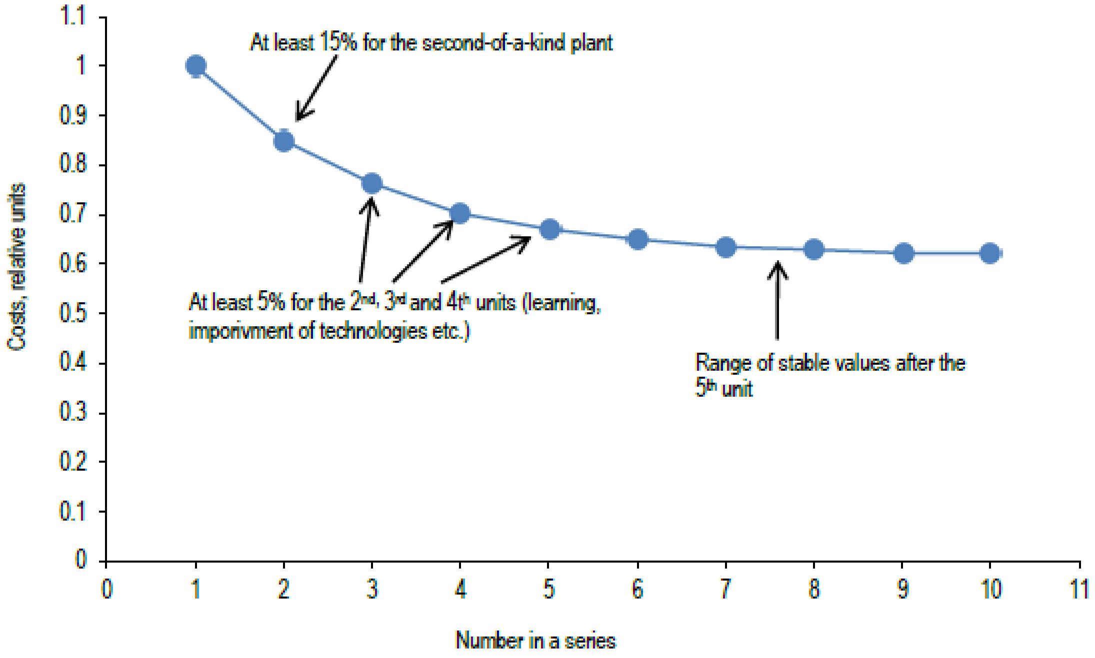
- **Learning**: learning is a key factor. In fact first of a kind reactors cost, on average, 35% more than next ones. Obviously learning factor is maximized due to the fact that the same people work on the same products on the same site. In fact it is not applicable if NPPS are built consecutively but in different countries, or in case of regulatory changes or if the interval between building consecutive plants is too long.

- **Faster construction time**: total overall costs are really sensitive to construction duration, because of the financing. Reducing construction time results in a reduction of the interest during construction as illustrated above. As shown reduction increases with the discount rate. Reduction in construction time results from the best fabrication condition and the possibility to assemble modules on site, opposed to a stick-built procedure.



5-1 Cost of financing as a function of construction duration and interest rate

From the experience gained y the OKBM Afrikantov, serial factory production brings advantages only for a small number of unit produced. (Mitenkov, 2004)



5-2 Cost of equipment fabrication and assembly in serial production of nuclear reactors for propulsion

This trend is also verified for land-based unit.

Reducing size introduces also different technical solutions that allows a highly simplified design. This allows component reduction, increasing safety and reducing costs. A design simplification factor has been evaluated for IRIS reactor and for VBER-300 as 0.85 and 0.84 respectively. This is a correction for the scaling law presented above. (IAEA, 2010)(IAEA, 2006)

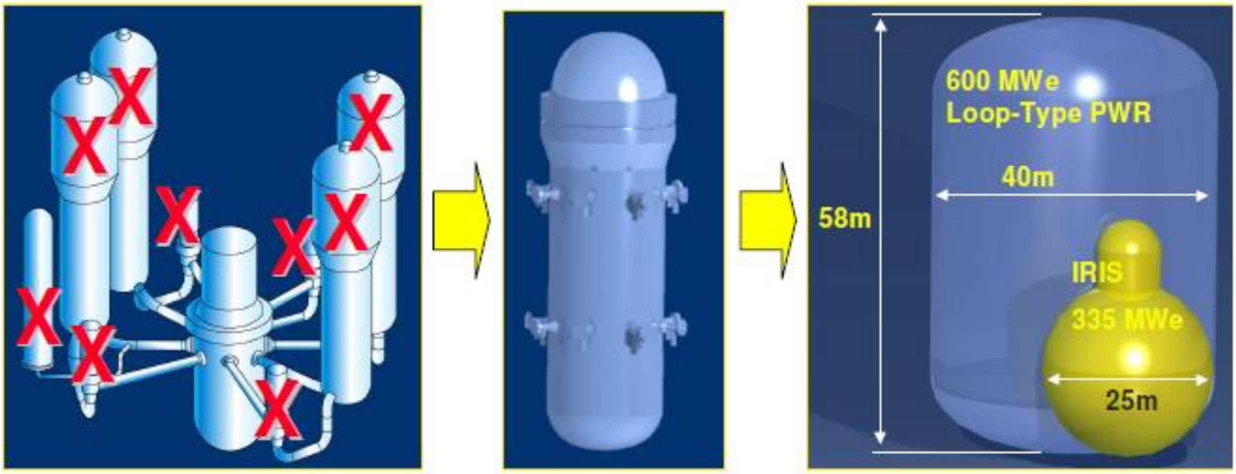
A practical example of design simplification could be primary coolant natural circulation.

This solution provide enhanced safety, because recirculation doesn't rely on mechanical active component but simply on physics laws; the absence of pumps is obviously an economical advantage too, making the whole plant less expensive.

As we introduced, capital cost reduction is one of the most important features in the analysis of nuclear power plant competitiveness and it can be achieved mainly thanks to design simplification and components reduction.

Large size reactors designs relies on systems redundancy, and the number of components involved introduce a high grade of complexity, increasing plant capital cost.

Cubic meter of concrete and tons of metal used are some of the most useful parameters in the simplification analysis, and it can be referred to the power produced



5-3 Simplification introduce by SMRs, the IRIS project

5.1.2 ON-SITE ASSEMBLING

As a consequence of modularization, on-site work consists in assembling modules, shipped directly on the site.

Obviously the reduced size of modules makes them easier to assemble, especially compared to some large power plants that take advantages of modularization (AP1000).

This aspects allow to decrease construction time and costs as shown in this brief example.

An AP1000 reactor’s steam generator dimensions are approximately 22.5m x 5.6m diameter, and it weighs about 700 ton.

On the other hand SMRs containment vessel has similar dimensions of a large reactor component.

The advantage of an integral design, typical of small size reactors, allows to fit all components inside the reactor vessel, and weigh less than 500 ton.

It is becomes clear that from a manufacturing point of view the components can be easily managed.

The problem is simpler, thanks to necessity of transport the reactor as a single-unit direct for installation to-site, moving more tasks to the factory a controlled environment.

This in fact it makes possible to use smaller and cheaper cranes and, generally, all the equipment needed is less expensive, more standard and easily available on the market.

Thanks to the reduced size and simplicity of components, more equipment suppliers are available, thus avoiding bottle-neck In the assembling phase.

Parallel assembly represents another perk typical of on-site work related to small reactors.

Dealing with large size reactor, although modular, is more difficult, and workers are used to assemble a single module at time.

5.1.3 TRANPORTATION

Transportation is a crucial point in SMRs construction.

It is strictly related to the modularization process, which must provide modules easy to manage and to be transported on the site. It is obviously requested a good grade of standardization and knowledge of critical aspects during components shipment.

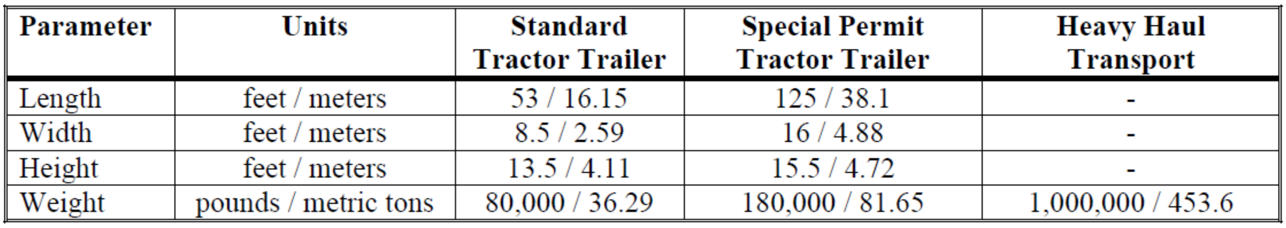
Easy transportation is also closely connected to the possibility of SMRs construction in the so called developing countries. In this particular areas infrastructures system may be inadequate to heavy components transport.

Large component transportation is always performed by waterways, with barges, and its cost is basically independent from the size of the object transported. However it could be necessary to build a dock in order to manage heavy modules, increasing slightly the cost of transportation.

The possibility of moving components on the land, by truck or train, it’s strictly related to the dimension of the element, and plays an important role in SMRs diffusion.

Small reactor modules are specifically designed to be transported by common truck or by railways, so they can be built in difficult to reach zones. This matches also with the necessity of a distributed power generation or the need of energy in isolated areas, with a poor infrastructure system.

USA road transportation limits can be summarized in the chart below (5-4):



Parameter	Units	Standard Tractor Trailer	Special Permit Tractor Trailer	Heavy Haul Transport
Length	feet / meters	53 / 16.15	125 / 38.1	-
Width	feet / meters	8.5 / 2.59	16 / 4.88	-
Height	feet / meters	13.5 / 4.11	15.5 / 4.72	-
Weight	pounds / metric tons	80,000 / 36.29	180,000 / 81.65	1,000,000 / 453.6

5-4 Main transportation constraints

These data could be useful to have a general idea of limitations also in other countries.

It is easy to find that most of SMRs elements must be considered under the Heavy Transportation category.

In this chapter factors affecting SMR competitiveness have been briefly reviewed.

The focus was obviously on the relative impact of each factor, rather than on the exact value, reflecting capital costs.

It is really difficult to provide estimation of transportation costs, because of the high specificity shown by each carriage.

It is really complicated to produce an evaluation of these costs, especially for what concerns land transport, that must consider a massive quantity of variables, very difficult to estimate, first of all infrastructural system.

It may be inadequate, and it could be necessary to entirely build roads or pull down overpasses, for example.

This analysis can only be performed thanks to an on-site inspection.

6 IRIS

6.1 FABRICATION

The main component of a nuclear island is the Reactor Pressure Vessel. This is particularly meaningful in case of integral layout. In fact RPV of SMR houses all main component of the nuclear island, including Steam Generators. This means that Vessel dimensions should increase considerably, as well as cost and fabrication challenges.

After a deep analysis of fabrication process and methods we spotted some parameters and limitations affecting components production.

Difficulties arise from the handling of big and heavy ingot, from which components are obtained through mechanical processing.

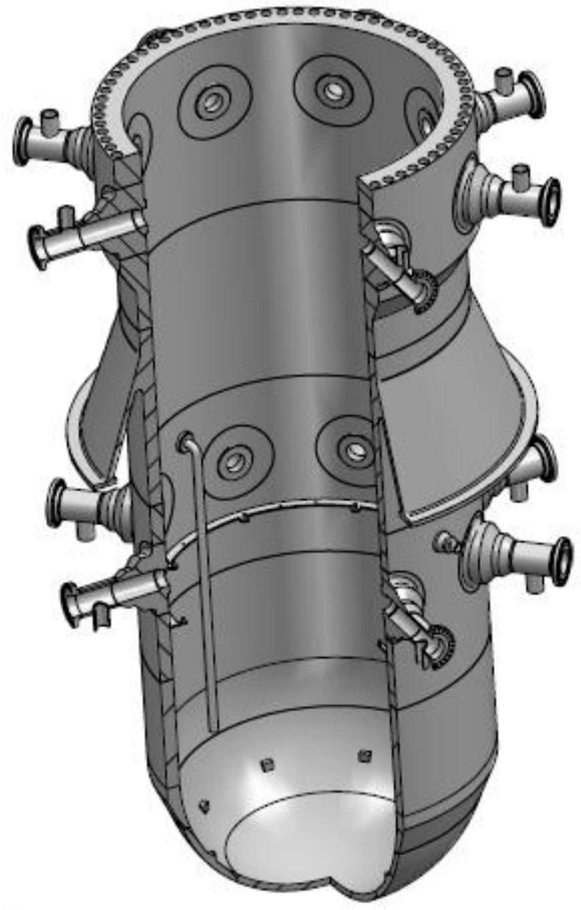
According to manufacturers’ expert judgment we can identify these average boundary conditions as, for rings, 7m in diameter, 4m in height and 150t.

For bushes the same limits are 4m in diameter, 6m in length and 120t. It is important to underline that these limitations are at the reach of a number of manufacturers in the world; this fits perfectly the SMRs construction philosophy, aimed at widening the range of possible manufacturing enterprise involved in SMRs fabrication.

Another important feature of this analysis is to research all possible cost drivers involved in RPV fabrication.

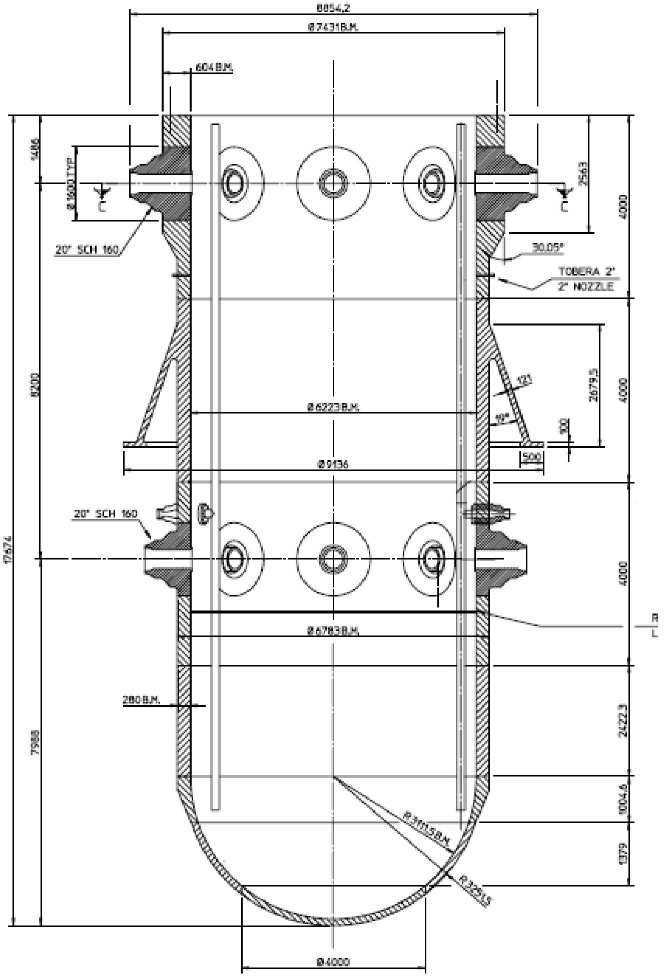
The result of our analysis, shows that the key cost driver is the cost of the prime material.

Thanks to these considerations we tried to perform a cost analysis of the vessel, considering its design specifications.



6-1 IRIS Reactor Pressure Vessel

Different critical points were spotted: dimensions and weight of most vessel section exceeded the limitations reported above, as shown in figure 6-2.



6-2 Original IRIS Vessel Subsections

For the purpose of the estimation, the RPV has been divided into sections, according to usual fabrication practice.

More precisely the lower cylindrical shell exceeded the weight limit, so it’s been decided to split it in two identical halves, as well as the mid cylindrical shell as reported in picture 6-3:

	Diam Max(m)	Diam min(m)	Height (m)	Noz Diam (m)	Thickness
Lower shell	4	0	0,8679		0,14
Joint	5,8926	4	1,379		0,14
Sec Joint	6,783	6,223	1,0046		0,14-0,28
Low Cyl Shell	6,783	6,223	3,3175		0,28
Low Cyl Shell (low)	6,783	6,223	1,65875		0,28
Low Cyl Shell (up)	6,783	6,223	1,65875		0,28
Lover Nozzle	6,783	6,223	3,1048	1,6	0,28
Shell Skirt	7,431	6,223	4,6753		0,28
Shell Skirt lower	7,431	6,223	2,3378		0,28
Shell Skirt upper	7,431	6,223	2,3375		0,28
Skirt	8,8542	7,431	1,94		0,121

6-3 IRIS Vessel Sub-components dimensions

From this simple data set it is possible to obtain information about the weight of components, assuming steel density as 7860 kg/m^3. As said before weight is the main cost driver so it is possible to obtain a cost estimation as shown in the following chart 6-4:

	Vol (m^3)	Weight (kg)	Weight (t)	€/kg
Lower shell	3,90	30682,40	30,68	13,66
Joint	3,74	29433,47	29,43	13,66
Sec Joint	2,78	21885,94	21,89	13,66
Low Cyl Shell	18,97	149085,33	149,09	8,61
Low Cyl Shell (low)	9,48	74542,67	74,54	8,61
Low Cyl Shell (up)	9,48	74542,67	74,54	8,61
Lover Nozzle	13,25	104144,97	104,14	8,61
Shell Skirt	30,23	237628,35	237,63	6,90
Shell Skirt lower	16,20	127349,62	127,35	6,90
Shell Skirt upper	16,20	127335,46	127,34	6,90
Skirt	7,38	58021,14	58,02	6,00

6-4 Vessel Sub-components cost estimation

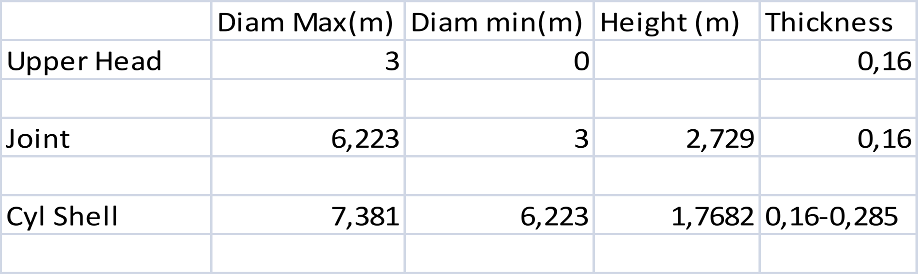
The mid cylindrical shell was designed with a particular support that has been denoted as “skirt”, because of its shape. This support originally was not welded to the shell, but it should have been obtained from the ingot by mechanical process.

With respect to this characteristic a bigger diameter is needed, but it is very difficult to produce.

Introducing the hypothesis of welding the so called skirt, it is possible to decrease the diameter and the support can be produced by bending a steel slab.

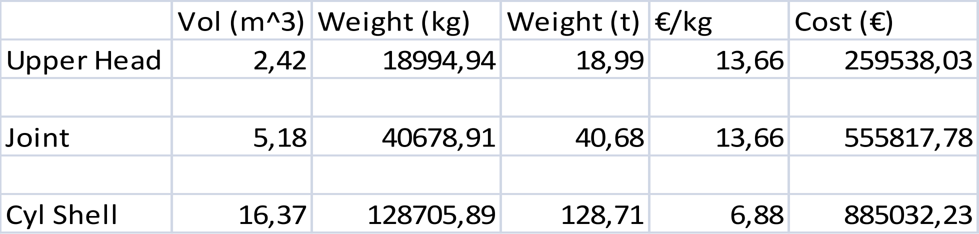
As it is possible to see in the previous picture, specific cost of sub-component, derived by similar component fabrication, are applied to actual components.

We must also account for the vessel head that is produced in three different parts welded together as shown as follows (6-5):



	Diam Max(m)	Diam min(m)	Height (m)	Thickness
Upper Head	3	0		0,16
Joint	6,223	3	2,729	0,16
Cyl Shell	7,381	6,223	1,7682	0,16-0,285

6-5 Vessel Head Sub-components dimensions

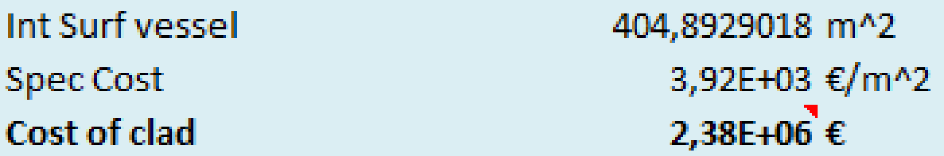


	Vol (m^3)	Weight (kg)	Weight (t)	€/kg	Cost (€)
Upper Head	2,42	18994,94	18,99	13,66	259538,03
Joint	5,18	40678,91	40,68	13,66	555817,78
Cyl Shell	16,37	128705,89	128,71	6,88	885032,23

6-6 Vessel Head Sub-components cost estimation

Further works are needed on the vessel, as, for example, internal surface cladding.

IRIS reactor pressure vessel requires 6.5mm of cladding. We must account for these kind or operations, drawing information from previous projects, obtaining a specific cladding cost for unit of area, as shown in the following picture (6-7):



Int Surf vessel	404,8929018	m^2
Spec Cost	3,92E+03	€/m^2
Cost of clad	**2,38E+06**	**€**

6-7 Cost of cladding

At the end of this estimation, carried on with all the hypothesis provided in this description, we obtained the following results concerning weight and cost of IRIS vessel and head based on prime material's cost:

Vessel Weight (t)	**739,888**	**Cost (M€)**	**5,4566**
Head Weight (t)	**188,380**	**Cost (M€)**	**1,7004**
TOTAL WEIGHT (t)	**928,268**	**TOTAL COST (M€)**	**7,1570**

6-8 Total Cost and Weight of IRIS Vessel

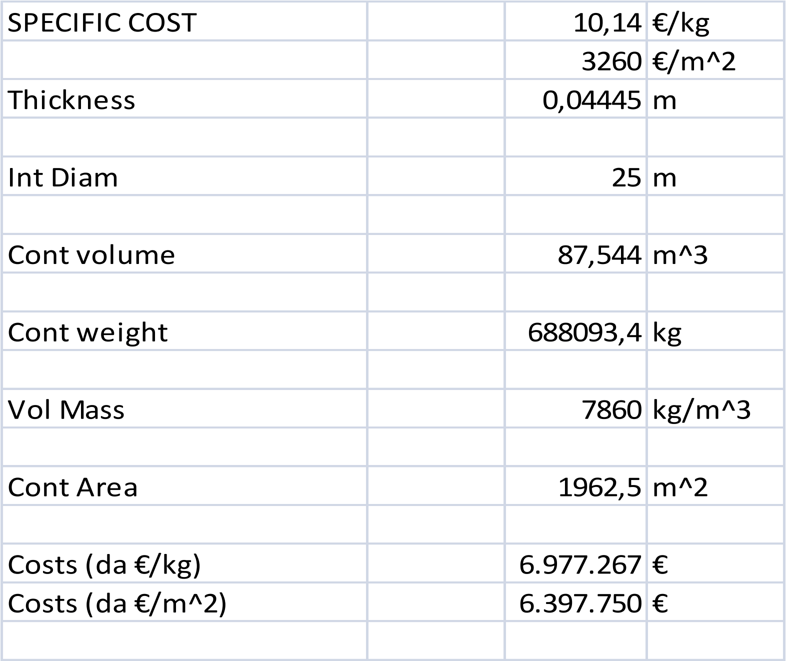
The total cost of IRIS reactor pressure vessel is about **9.54M€** considering fabrication and work.

Spherical containment must be evaluated to perform a complete cost analysis of primary components.

It is a steel sphere with an internal diameter of 25m and a wall thickness of 44.45mm.

We supposed as cost of materials 10.14€/kg and carbon steel as fabrication material.

The following chart (6-9) summarized the containment cost evaluation:



SPECIFIC COST		10,14	€/kg
		3260	€/m^2
Thickness		0,04445	m
Int Diam		25	m
Cont volume		87,544	m^3
Cont weight		688093,4	kg
Vol Mass		7860	kg/m^3
Cont Area		1962,5	m^2
Costs (da €/kg)		6.977.267	€
Costs (da €/m^2)		6.397.750	€

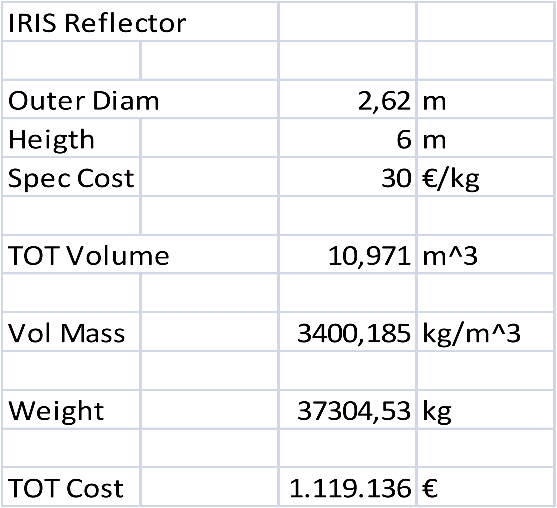
6-9 Metal containment cost

Costs include work needed in factory and on site, that represent a large part of the total cost evaluated, about 73%.

These consideration lead to a containment cost of about **6.5M€** and total primary cost of about **15.9M€**.

Reflector is another important cost driver to be evaluated.

Experts suggest to consider a specific cost of about 30€/kg. thanks to data available in literature we can perform a cost analysis as follows:



IRIS Reflector			
Outer Diam		2,62	m
Heigth		6	m
Spec Cost		30	€/kg
TOT Volume		10,971	m^3
Vol Mass		3400,185	kg/m^3
Weight		37304,53	kg
TOT Cost		1.119.136	€

6-10 IRIS reflector cost

Thanks to this analysis costs arise to **17M€**.

6.2 STEAM GENERATOR

IRIS helical steam generators are positioned in the upper part of the vessel, increasing its diameter, unlike the other reactor designs.

This is useful because the lower part houses a massive amount of water that shields the vessel from radiation, allowing the vessel to be less damaged during its life.

There are 8 steam generators made of 655 bended tubes each.

Their positioning and design make this component realization really challenging. It is very difficult to perform thermal treatment on 32m long tubes; in fact IRIS steam generator tubes have a maximum length of 36 meters , while ovens usually have a maximum capacity of 25-28 meters.

This fact requires suppliers to provide new ovens or special equipment to produce tubes with that characteristics.

This maybe only possible for few industries, since the investment could be really demanding. So the range of suppliers reduces only to few partners, leading to an increase of costs.

According to expert’s judgment only 3 suppliers in the world can provide this kind of equipment needed for the steam generators.

It must be underlined that bending tubes increase considerably costs; on the other hand side it produces superheated steam at the outlet.

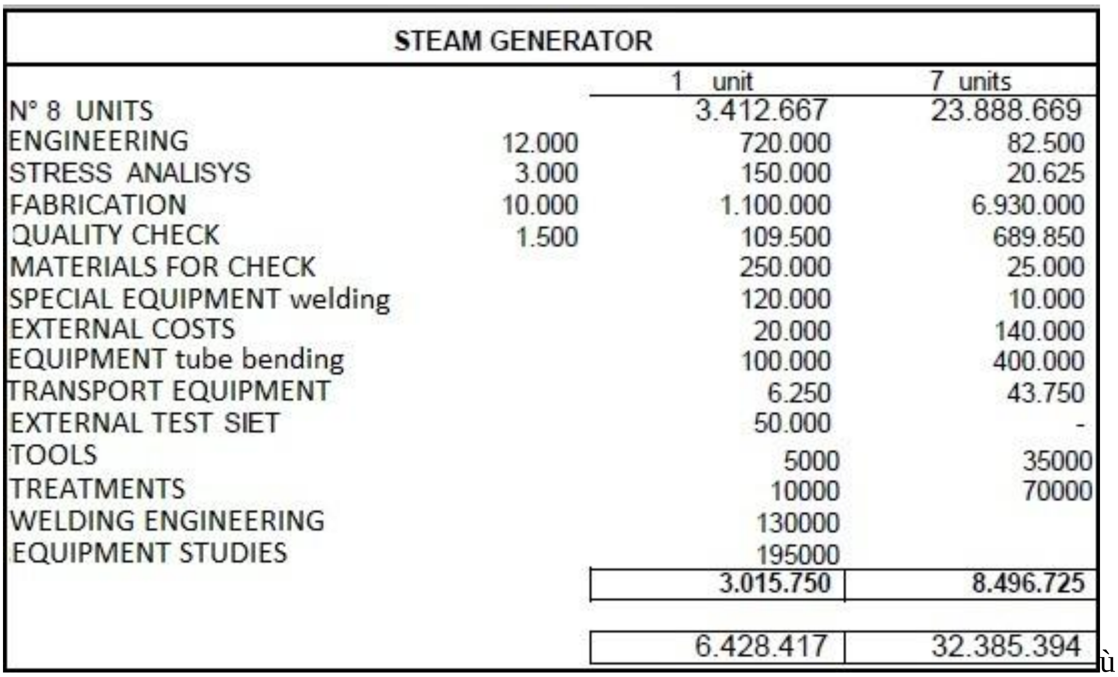
We should add the fact that produce and process a vessel of 7.4m in diameter is also very demanding so, IRIS fabrication may result to be really challenging.

To perform a significant cost analysis on the steam generators we draw information from past experiences.

It has been suggested to analyze costs of the 8 units as a production of 1+7 units, to underline the effects of fixed costs.

The first unit absorbs the cost of engineering, such as design, expenses regarding testing facilities or studies concerning equipment needed to the fabrication.

All these concepts can be summarized in the following chart (6-11):



STEAM GENERATOR			
		1 unit	7 units
N° 8 UNITS		3.412.667	23.888.669
ENGINEERING	12.000	720.000	82.500
STRESS ANALISYS	3.000	150.000	20.625
FABRICATION	10.000	1.100.000	6.930.000
QUALITY CHECK	1.500	109.500	689.850
MATERIALS FOR CHECK		250.000	25.000
SPECIAL EQUIPMENT welding		120.000	10.000
EXTERNAL COSTS		20.000	140.000
EQUIPMENT tube bending		100.000	400.000
TRANSPORT EQUIPMENT		6.250	43.750
EXTERNAL TEST SIET		50.000	-
TOOLS		5000	35000
TREATMENTS		10000	70000
WELDING ENGINEERING		130000	
EQUIPMENT STUDIES		195000	
		3.015.750	8.496.725
		6.428.417	32.385.394

ù

6-11 IRIS Steam Generator breakdown cost

There’s the possibility to divide costs in labor work and raw materials. This costs are expressed in the top line of the previous chart as 3.412.667€ but they can be split as follows (6-12):

WEGHT T	€ / kg	h	tot. Mat	tot. Work	
38.196		2.776	2.844.962	567.705	3.412.667

6-12 Labor work and raw materials in SG fabrication

As revealed previously in the cost analysis of the reactor pressure vessel the most important cost deriver is once again represented by raw materials. The 83% of the total cost is covered by materials with a medium specific cost of about 74€/kg.

Total cost and weigh of the entire SGs packs are about: **38.8M€** and **305t**.

The whole primary system, consisting in the reactor pressure vessel and the steam generators, have a total weight of about **1234t**.

This is clearly a heavy module to transport and to assemble on site.

In fact SMR philosophy suggest to have the entire module assembled in factory and then shipped easily to the site.

This could not be true for IRIS reactor because of its dimensions and weight. In fact it seems to be needed a greater amount of work on site then the other reactors. So it could be built thanks to a sort of stick built process that link IRIS to le large sized reactors.

6.3 SAFETY SYSTEM

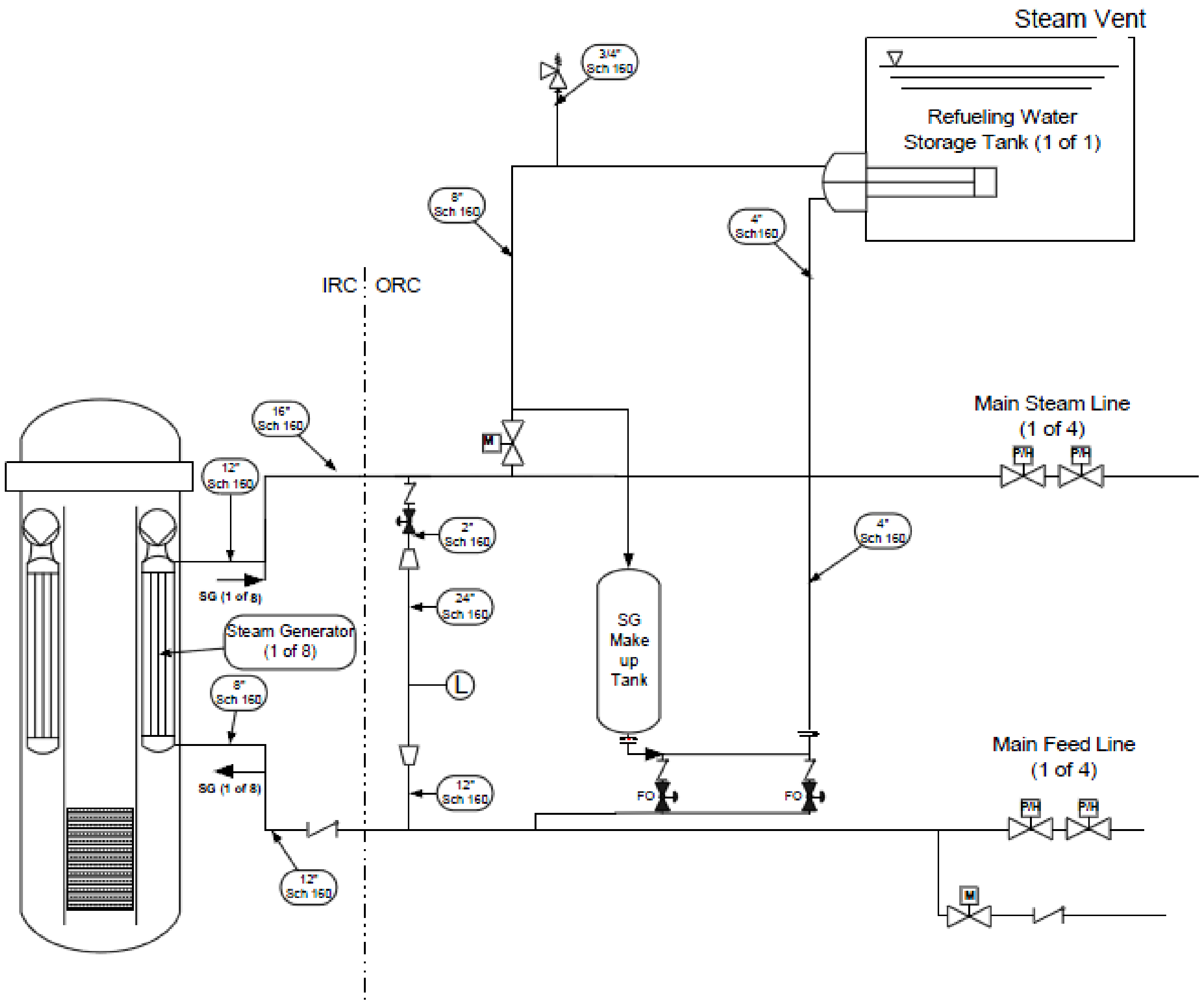
The Emergency Heat Removal System (EHRS) is designed to perform the following major functions:

- Emergency Core Decay Heat Removal: in case of accidents, transients or whenever the normal heat removal paths are lost this system transfers core heat from the reactor coolant to the environment This heat removal function is available during all plant operating conditions except refueling.

- Emergency Containment Pressure Reduction: the EHRS is able to minimize the mass and energy release from the reactor vessel into the containment reducing containment pressure severe accidents.

- In case of reduced reactor coolant system water inventory the EHRS provide condensation of steam within the reactor vessel. This function is very important because it reduces the coolant loss following a LOCA adding to the core the condensed steam reducing also the reactor vessel pressure. Thus, the EHRS ensures core cooling granting that a sufficient quantity of water is retained within the vessel to deal with LOCAs (including the double-ended rupture ones)

The EHRS consists of four subsystems each having an EHRS heat exchanger, a steam generator water addition tank, and associated valves, piping, and instrumentation. Heat exchangers are in the Refueling Water Storage Tank, located within the auxiliary building while each of the EHRS subsystem is linked to one of the four steam generator connection line. A simple sketch of the EHRS is shown in the figure below (6-13):



6-13 EHRS simplified sketch

In the EHRS subsystem water flows thanks to the natural circulation from a pair of steam generators to its associated EHRS heat exchanger; thanks to that design steam flows from the steam generator to the heat exchanger where it condenses, and return condensate to the steam generator through the normal feed water piping. Fail-open isolation valves grants the actuation of the EHRS systems. A steam generator water addition tank, provide sufficient water to refill a dry SG, is installed in each subsystem to compensate for leakage.

The EHRS heat exchangers heat the refueling water storage tank (RWST) water, which eventually boils. The steam produced is vented to atmosphere.

Obviously the RWST must be design properly, to ensure heat removal for 7 days. The tank is provided with connections for both on-site makeup water addition and for addition of water from off-site sources.

Once again it is possible to split costs in two different parts: materials end labor costs.

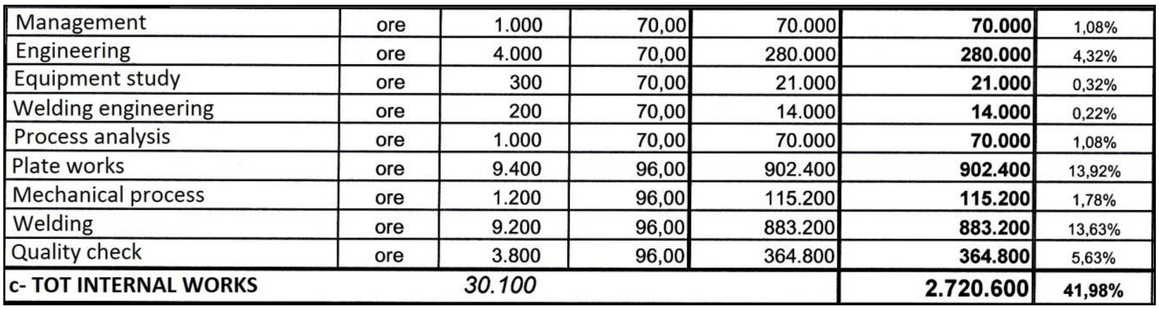
In this case materials covers only the 43% of the total cost.

This is possible because of the complexity of the project that needs more labor than usual.

In fact the most important cost drivers are: tube bending, welding, and plate works.

EHRS requires more than 30000 hours of work.

A brief summary is shown in the following chart (6-14):



Management	ore	1.000	70,00	70.000	**70.000**	1,08%
Engineering	ore	4.000	70,00	280.000	**280.000**	4,32%
Equipment study	ore	300	70,00	21.000	**21.000**	0,32%
Welding engineering	ore	200	70,00	14.000	**14.000**	0,22%
Process analysis	ore	1.000	70,00	70.000	**70.000**	1,08%
Plate works	ore	9.400	96,00	902.400	**902.400**	13,92%
Mechanical process	ore	1.200	96,00	115.200	**115.200**	1,78%
Welding	ore	9.200	96,00	883.200	**883.200**	13,63%
Quality check	ore	3.800	96,00	364.800	**364.800**	5,63%
c- TOT INTERNAL WORKS		*30.100*			**2.720.600**	**41,98%**

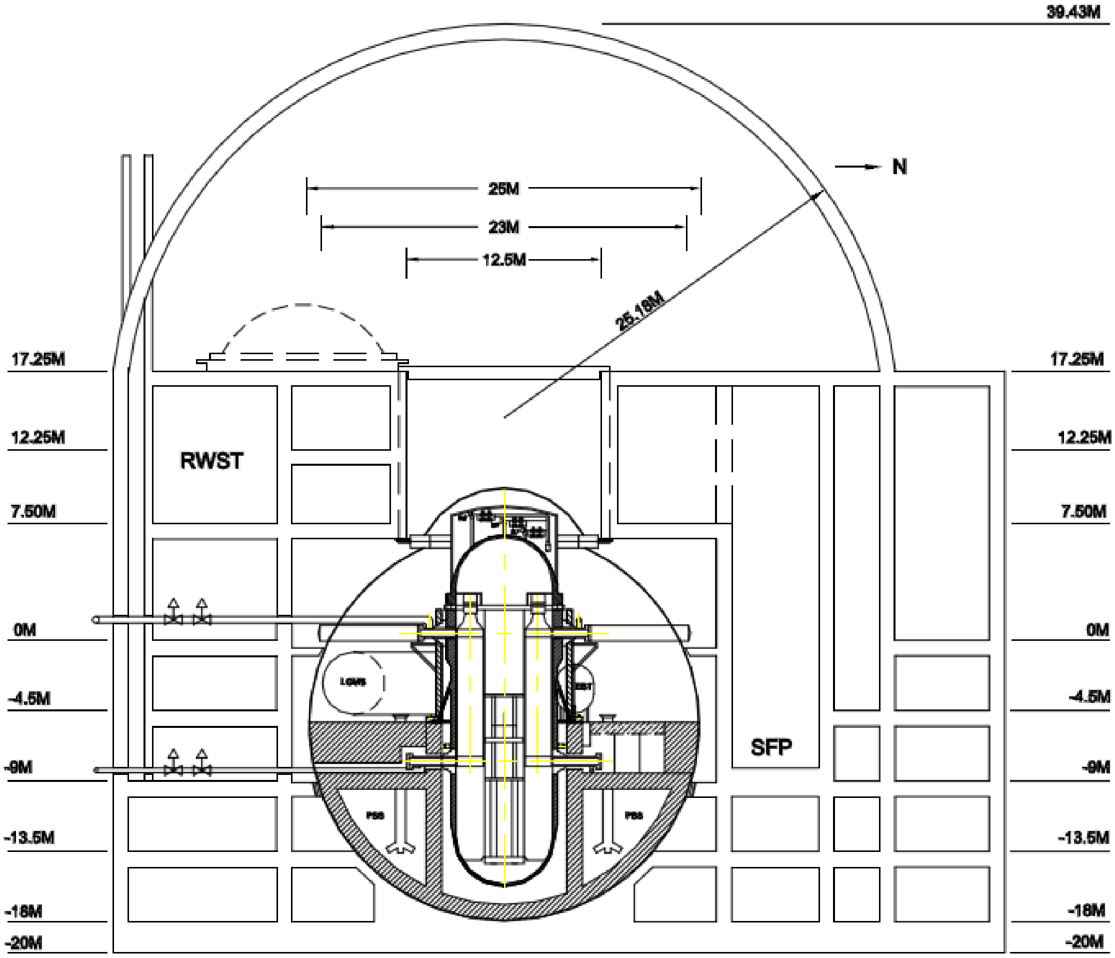
6-14 Labor works on EHRS

Percentages on the right are really useful to understand what we underlined previously concerning cost drivers.

Combining all costs shown in this chapter it is possible to find out a total cost of about **6.5M€** for the single unit, and a total of about **26M€**.

6.4 PRIMARY BUILDING

IRIS primary building houses the steel spherical containment and all safety systems.
It has a diameter of 27m and a wall thickness of 1.5m.
In the following picture the concrete containment is shown with quotes (6-15):



6-15 IRIS primary building

Optimum building configurations and properly structural designs applied to the whole plant are necessary to minimize the building volumes and bulk quantities, such as steel, concrete, rebar, structural. Obviously all these features must be consistent with safety, operational, maintenance, and structural needs.

The Nuclear Island shall be structurally designed and constructed to meet Seismic Category I requirements

The Nuclear Island is made by several components, such as: free-standing steel containment spherical structure, a concrete shield building (resistant to internal and external missiles) and several penetration areas: main steam and feedwater one, mechanical/electrical, a fuel handling area, composed by safety related mechanical or electrical components and systems.

The most suitable foundation for the nuclear island is an integral basemat, supporting the above structures. This nuclear island contains the traditional containment building, the fuel building, the auxiliary building, and the refueling water storage tank in an integrated structure.

It must be underlined, especially after Fukushima events, that the nuclear island is able to withstand the effects of a wide range of natural phenomena such as hurricanes, tornadoes, floods, tsunamis, and earthquakes without loss of capability to perform the safety functions. Design for natural phenomena shall be based on the industry standards and applicable regulatory codes.

In this evaluation process piping and mechanical equipment are not considered.

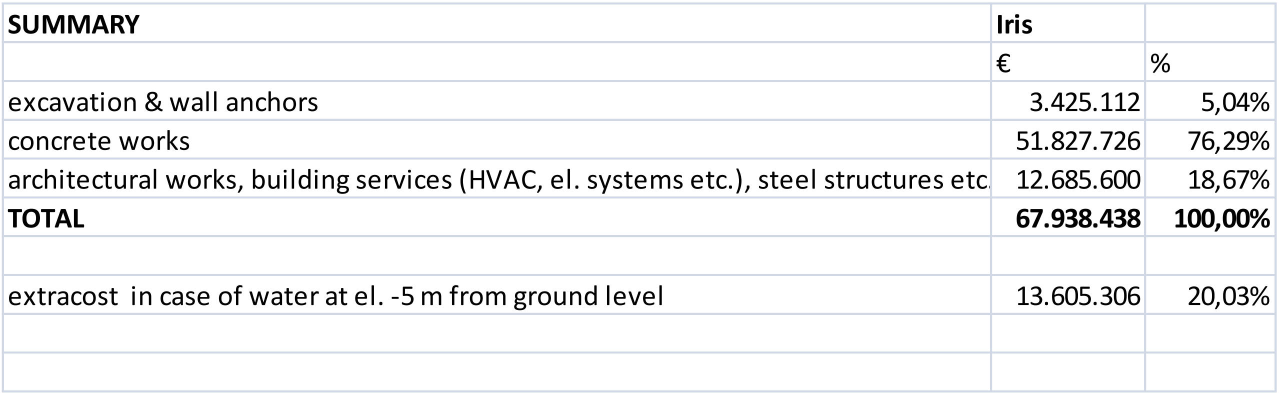
At a first time a base case is considered, in which dry soil is analyzed.

At a second stage a differential price is calculated in case of water at about 5m under the soil level.

Excavation costs are not so significant considering the total cost. In fact they account only for the 5%.

More than the 75% of the cost is represented by concrete works, such as: foundation, slabs and spherical roof.

A brief summary is presented in the following picture (6-16):



SUMMARY	**Iris**	
	€	%
excavation & wall anchors	3.425.112	5,04%
concrete works	51.827.726	76,29%
architectural works, building services (HVAC, el. systems etc.), steel structures etc.	12.685.600	18,67%
TOTAL	**67.938.438**	**100,00%**
extracost in case of water at el. -5 m from ground level	13.605.306	20,03%

6-16 IRIS primary building costs summary

All these consideration are made under the hypothesis of dry soil; in case of water 5m under the soil, as it is shown in figure (6-16), it is necessary to add about 14M€.

These costs cover for additional wall anchors, jet grounding and concrete works under 15m slabs.

This scenario may be very common because nuclear power plants usually are built near water sources.

For this reason we consider the case with the extra cost as standard, as suggested by expert’s judgment, considering a cost of about **81.6M€**.

6.5 BALANCE OF PLANT AND CIVIL STRUCTURES

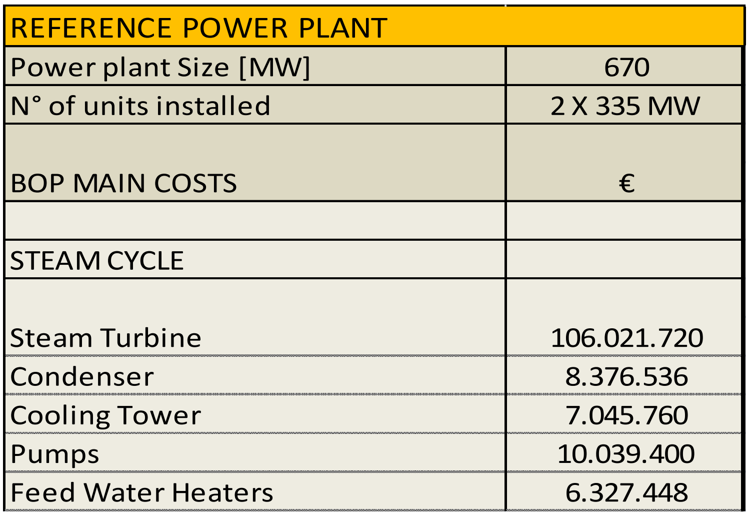
Although there are many difference looking at the primary circuit, passing from large sized reactor to small ones, the secondary systems remains standard, allowing us to make an estimation in a easier way.

Obviously also costs related to the balance of plant must be distributed on a lower power output, increasing specific costs.

Once more, cost estimation is based on expert judgment with experience in this activity.

The first thing that immediately appeared to be different: almost every structure should be built underground. IRIS primary building, as an example, needs 20m meters of excavation, resulting in a more than a half of the building built under ground level.

Under the hypothesis to couple each reactor to one BOP, knowing thermodynamics of the secondary circuit, we draw the following information (6-17):



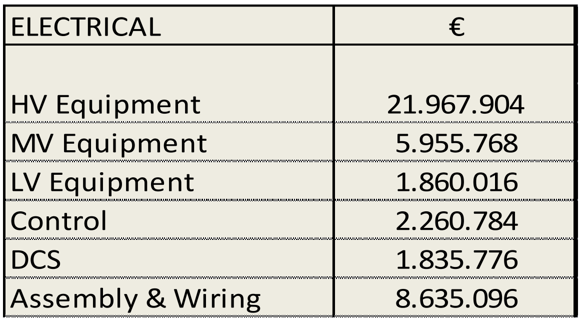
REFERENCE POWER PLANT	
Power plant Size [MW]	670
N° of units installed	2 X 335 MW
BOP MAIN COSTS	€
STEAM CYCLE	
Steam Turbine	106.021.720
Condenser	8.376.536
Cooling Tower	7.045.760
Pumps	10.039.400
Feed Water Heaters	6.327.448

6-17 Main Steam System Elements and Costs

As we can see from the chart, the steam turbine is the main cost driver, affecting the steam cycle cost area for more than the 75%. This percentage reduces to about 70% if a twin layout were introduced.

With a total cost of 106.021M€ it is the main cost driver of the BOP area, affecting total cost for about 37%.

After that we find out the electrical equipment detailed costs (6-18):

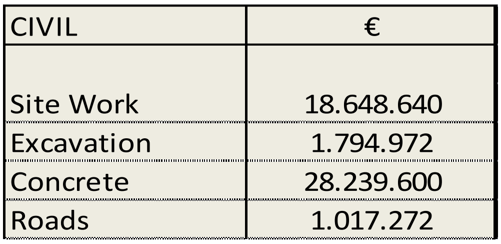


ELECTRICAL	€
HV Equipment	21.967.904
MV Equipment	5.955.768
LV Equipment	1.860.016
Control	2.260.784
DCS	1.835.776
Assembly & Wiring	8.635.096

6-18 Electrical Equipment Cost Detail

Once again it is possible to find out the main cost driver of this section that is the high voltage equipment represent the more than the 50% of the total cost.

Another significant area is the one related to civil structure, that include site preparation and the particular excavation work typical of these projects. All these costs are summarized in the chart below (6-19):

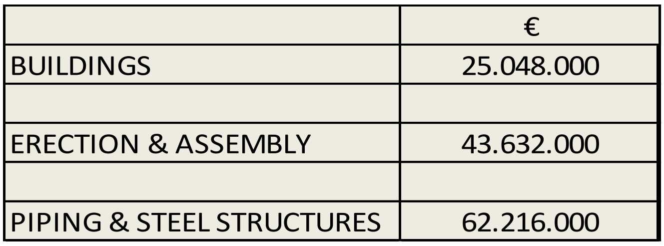


CIVIL	€
Site Work	18.648.640
Excavation	1.794.972
Concrete	28.239.600
Roads	1.017.272

6-19 Civil Structures Cost Detail

Despite the excavation work needed the most important cost drivers are concrete cost and site preparation.

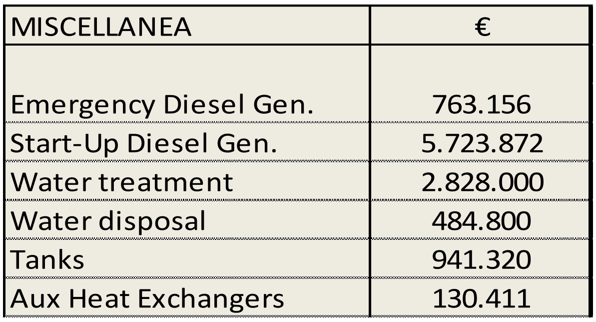
Another important cost driver is represented by piping and the steel structures that joint with the cost of other buildings and the work necessary for constructions takes around the 35% of all BOP construction expenses; all data are presented in the following chart (6-20):



	€
BUILDINGS	25.048.000
ERECTION & ASSEMBLY	43.632.000
PIPING & STEEL STRUCTURES	62.216.000

6-20 Buildings, Work and Piping Costs

Eventually we present a section including minor cost entries, such as emergency diesel and tanks (6-21):



MISCELLANEA	€
Emergency Diesel Gen.	763.156
Start-Up Diesel Gen.	5.723.872
Water treatment	2.828.000
Water disposal	484.800
Tanks	941.320
Aux Heat Exchangers	130.411

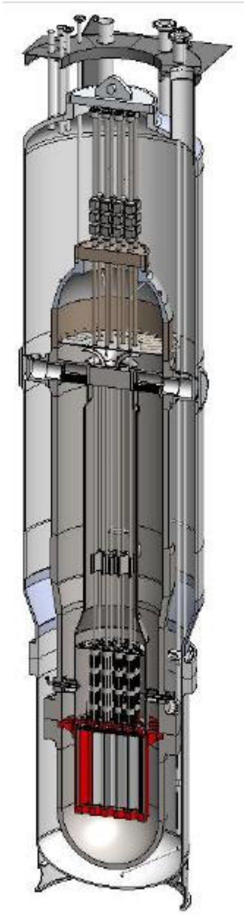
6-21 BOP Minor Cost Drivers

All these consideration lead us to determine the total cost of an IRIS balance of plant at about **372M€**.

7 NUSCALE

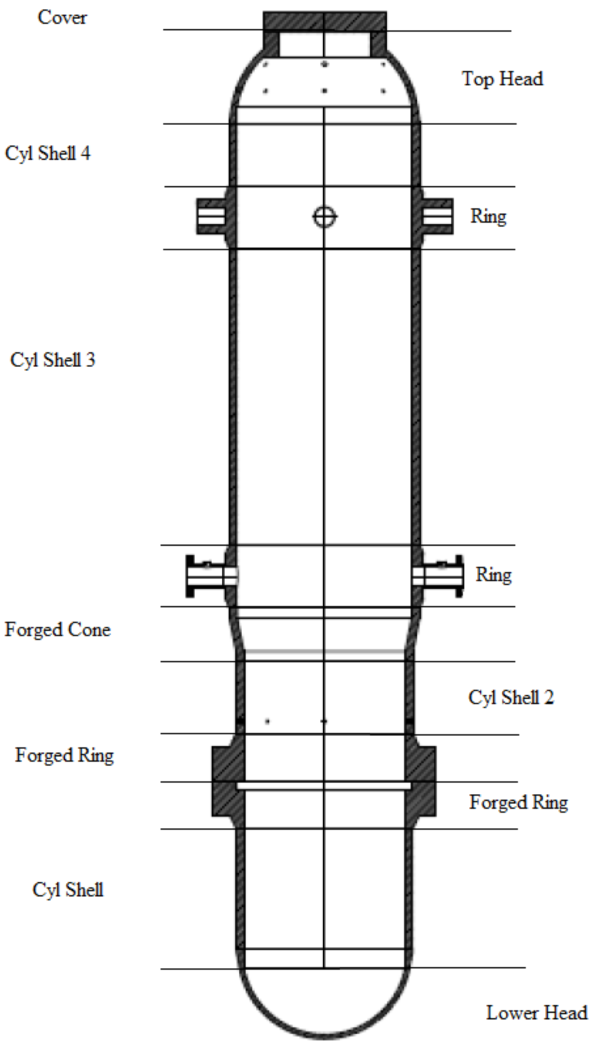
7.1 FABRICATION

Nuscale reactor vessel is significantly different from IRIS one.
Its reactor design is based on fabrication simplification. This is fundamental looking at SMR's fabrication philosophy; the number of industries that can participate in nuclear reactor construction can increase thanks to this design simplification.
The vessel is divided into 12 parts produced separately and then welded together. The lower section houses the core, with fuel, internals and control systems, while, in the upper part steam generators are located as shown in the following picture (7-1):(Reyes, 2011)



7-1 Nuscale Vessel and Steel Containment

Each different section has been analyzed by comparing actual parts to previously fabricated ones.
The following picture (7-2) helps us to understand such subdivision:



7-2 Nuscale Vessel Components Subdivision

This approach lead to the following chart (7-3):

	Diam max (m)	Diam min (m)	Height (m)	Diam Noz (m)	Thickness (m)
Lower head	2,6607	2,4448			0,0635
Cyl Shell	2,6607	2,4448	1,8034		0,108
Forged Ring	3,3592	2,4448	0,7239		0,3556
Forged Ring	3,3592	2,4448	0,7239		0,4572
Cyl Shell 2	2,6734	2,4448	1,0922		0,1143
Forged Cone	2,8767	2,4448	0,7969		0,1143
Ring	3,0541	2,648	0,9525	0,4	0,1715
Cyl Shell 3	2,8767	2,648	4,4704		0,1144
Ring	2,991	2,648	0,9525		0,1715
Cyl Shell 4	2,8767	2,648	0,9144		0,1144
Top Head	1,8352	1,378			0,0794
Cover	1,8352				0,3048

7-3 Vessel Sub-components dimensions

Once obtained these dimensions, it is possible to find weight and volume of single pieces of the vessel, as previously done with IRIS vessel:

	Vol (m^3)	Weight (kg)	Spec Cost (€/kg)	Cost (€)
Lower head	0,74	5781,70	39,85	230400,00
Cyl Shell	1,56	12271,20	5,87	72000,00
Forged Ring	2,04	16054,93	6,88	110400,00
Forged Ring	2,04	16054,93	6,88	110400,00
Cyl Shell 2	1,00	7880,14	6,28	49500,00
Forged Cone	0,76	5985,93	10,42	62400,00
Ring	1,45	11424,29	24,51	280000,00
Cyl Shell 3	4,44	34867,90	7,64	266500,00
Ring	1,59	12469,25	3,81	47500,00
Cyl Shell 4	0,91	7132,07	6,94	49500,00
Top Head	1,19	9380,99	22,39	210000,00
Cover	0,76	6009,05	5,24	31500,00

7-4 Nuscale Vessel Sub-components cost estimation

As it can be seen from partial results this vessel results lighter and cheaper than IRIS one, due to obvious design differences, introduced by lower power output and lower operating pressure at first.

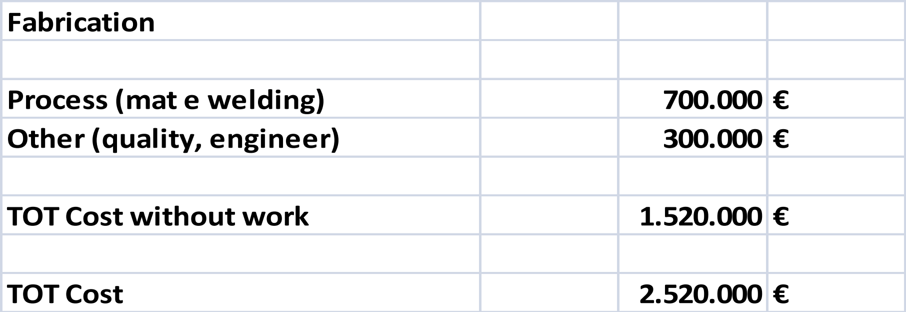
These results can be drawn by partial costs, resulting in a total cost of 1.520M€ and a total weight of only 145.312t.

It is possible to estimate costs of further works necessary for vessel fabrication, such as welding engineering etc.

Welding process includes materials and work. This is a very ticklish and important process that must undergo to several quality check.

Nuscale vessel has been designed with two liner coating, one internal and one external to the vessel. This is necessary due the presence of primary water inside the vessel itself, but also because water can be used on the external surface of the vessel as an emergency cooling system.

All these operations increased significantly the cost of the RPV leading to an additional cost of 1M€, as shown in the following picture (7-5):

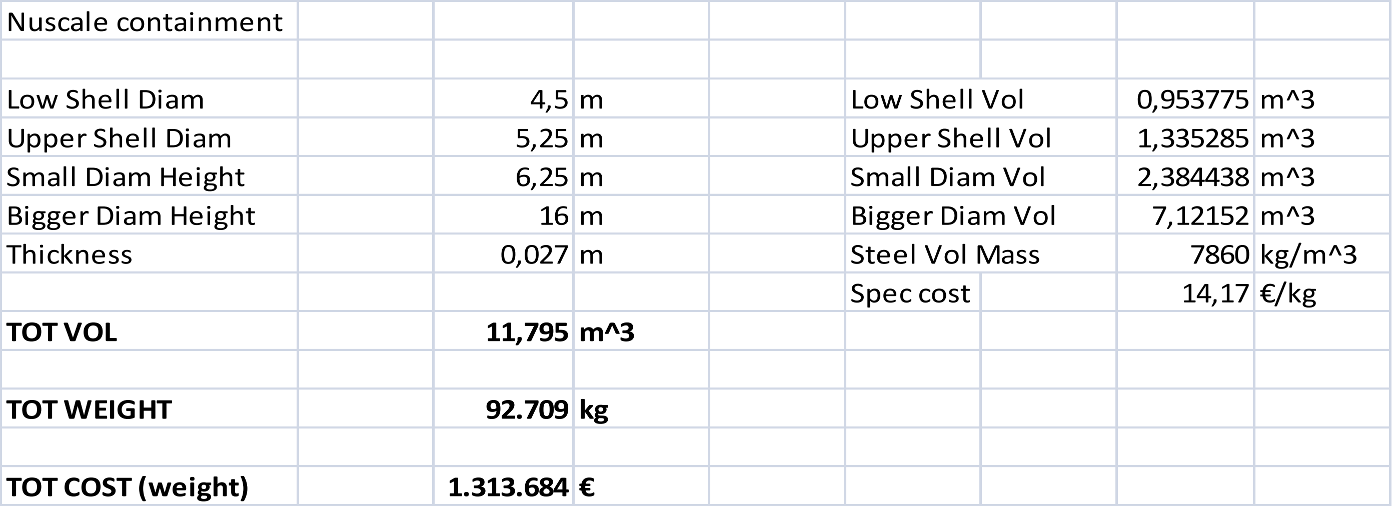


Fabrication			
Process (mat e welding)		**700.000**	**€**
Other (quality, engineer)		**300.000**	**€**
TOT Cost without work		**1.520.000**	**€**
TOT Cost		**2.520.000**	**€**

7-5 Additional Vessel Costs

Every reactor is housed in a metal containment, that grants higher safety standards, as it represent a barrier against leakage in case of emergency.

From literature it is possible to estimate its dimensions and weight as follows:



Nuscale containment								
Low Shell Diam		4,5	m		Low Shell Vol		0,953775	m^3
Upper Shell Diam		5,25	m		Upper Shell Vol		1,335285	m^3
Small Diam Height		6,25	m		Small Diam Vol		2,384438	m^3
Bigger Diam Height		16	m		Bigger Diam Vol		7,12152	m^3
Thickness		0,027	m		Steel Vol Mass		7860	kg/m^3
					Spec cost		14,17	€/kg
TOT VOL		**11,795**	**m^3**					
TOT WEIGHT		**92.709**	**kg**					
TOT COST (weight)		**1.313.684**	**€**					

7-6 Nuscale containment cost estimate

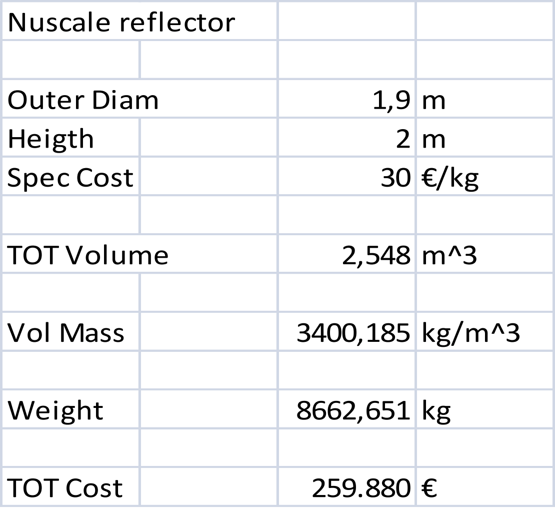
Large part of the total price is represented by the materials costs (about 45%); that’s because designers chose to produce the containment in Stainless steel. This material costs 2.5 times more than carbon steel, usually used in metal containment.

These costs include work needed in factory and on site.

In order to estimate containment volume we assumed lower and upper shell as hemispherical and a thickness of 0.0184m needed to withstand a design pressure of 3.4MPa.

These considerations lead to a cost of about **1.3M€**, and a total cost of **3.8M€**.

We proceed now evaluating Nuscale reflector, following the path introduced for IRIS reactor:



Nuscale reflector			
Outer Diam		1,9	m
Heigth		2	m
Spec Cost		30	€/kg
TOT Volume		2,548	m^3
Vol Mass		3400,185	kg/m^3
Weight		8662,651	kg
TOT Cost		259.880	€

7-7 Nuscale reflector cost

This component has a low impact on total costs, arising them to **4.1M€**.

7.2 STEAM GENERATOR

It is very difficult to estimate precisely Nuscale SG data.

From literature it is possible to obtain some general data: it has an helical coil layout with an height of about 5.5m and an ring shape, housed in the upper part of the vessel.

We must consider some hypothesis to perform a complete analysis, such as diameter and thickness of tubes.

We chose to set follow a standard steam generator configuration: 19.05mm of outer diameter and 1.83mm of thickness.

From Nuscale sketches we consider steam generator outer diameter of 2.6m and an inner one of 1.3m.

Thanks to the following formula it is possible to obtain the medium length of a SG tube (7-8):

$$2\pi\sqrt{R^2 + \left(\frac{P}{2\pi}\right)^2}$$

7-8 Coil length formula

Imposing a pass of 0.36m we obtain a medium length of 24.5m. Obviously outer coils would be longer (about 30m) and inner ones shorter (about 19m).

Considering similarities with IRIS design it is possible to draw information about Nuscale SG costs.

The most important cost driver is the one related to materials and it is basically proportional to tubes weight.

Calculating the volume of all the 1476 tubes it is possible to estimate a total weight of about 30t.

From IRIS estimate we obtained a value of 110€/kg for INCONEL tubes.

This lead to a cost of about 3.3M€.

Expert's judgment suggest to consider cost of material (not tube related) and work as 4.5M€.

Another cost driver is represented by SG connectors that have been evaluated in 850k€.

All these hypothesis and considerations lead to a total cost of about **8.6M€**.

Following once again IRIS SG evaluation costs, we can suppose to double tubes weight to find out the total bundle weight as **60t**.

Although its layout is similar to IRIS steam generator one, position and length of tubes are really different.

This differences lead to a design and fabrication simplification that is the basis of SMRs philosophy. In fact thermal treatments, for example, are easier if applied on 24.5m tubes and the positioning of internal components allows a lower vessel diameter, compared to IRIS project, enhancing fabrication possibilities.

7.3 SAFETY SYSTEM

There are no specific data available on Nuscale safety systems

All public data refers to these systems as standard ones.

This layout creates a closed loop, enhancing safety standard.

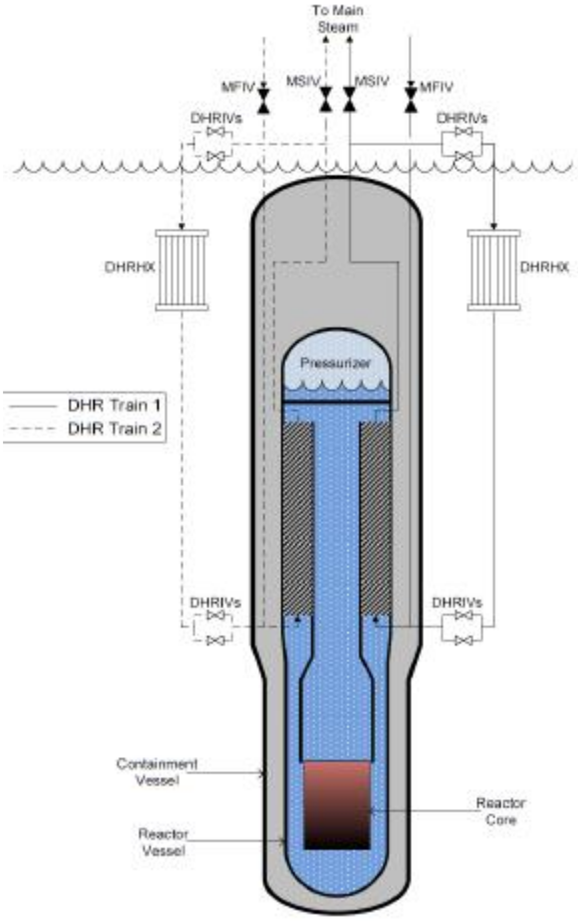
Natural circulation should be granted for 3 days in a two phase recirculation process.

So it is particularly difficult to perform a sensitive cost analysis. It is necessary to refer to manufacturers expertise.

Expert’s judgment suggests that it is possible to scale Nuscale EHRS starting from IRIS one, holding the same structure and layout, but reducing tube length.

Obviously it is not strictly size related, due to important factors, such as fixed and process costs.

It has been supposed to reduce this system cost to the 35% (compared to IRIS), leading to a cost of about **2.6M€** per unit, and a total cost of **10.4M€**.



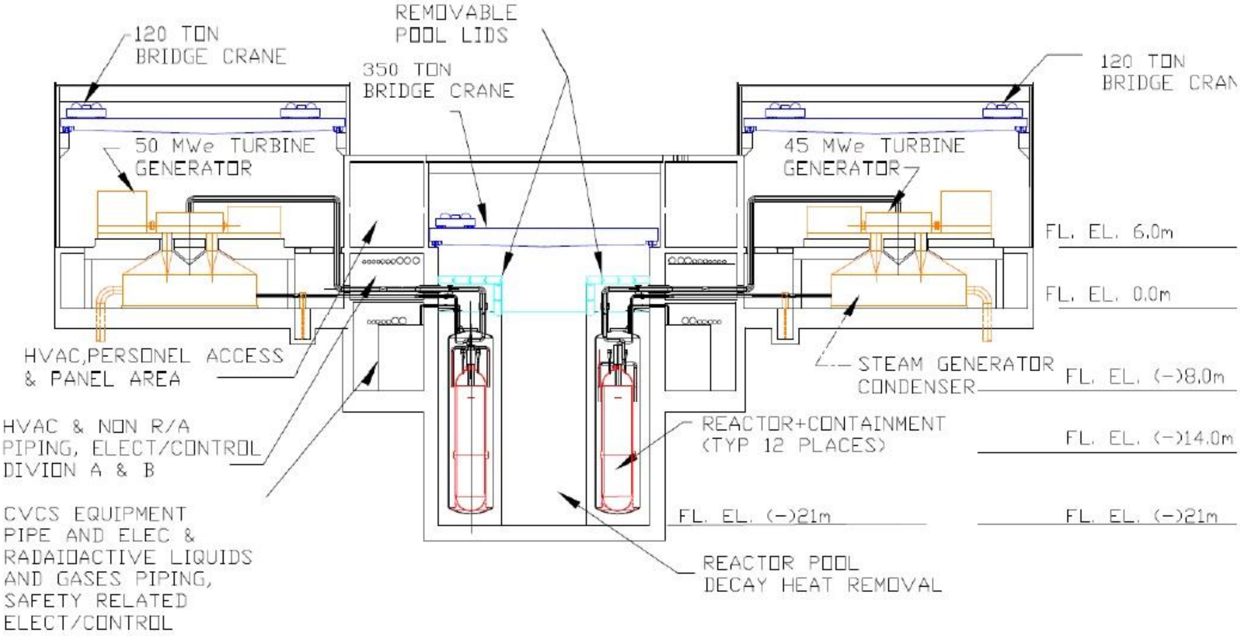
7-9 Nuscale safety system sketch

Steel containment should act as another safety system both transferring decay heat from the core to the pool and venting steam into the steel containment, creating a two phase recirculation system.

7.4 PRIMARY BUILDING

As it is possible to understand from literature, Nuscale excavation depth is about 21-23m.

A sketch may provide these information about structures dimensions more precisely:



7-10 Nuscale sketch with dimensions

As we can see the lower component in the primary reactor building is the pool.

This depth can be reached thanks to particular excavation techniques: metal slabs are used to create a section in the ground where excavation take place.

Thanks to these sectioning it is possible to control better the presence of water.

Obviously, once the entire structure has been built, we must deal with issues related to hydrostatic force pushing the entire building upwards.

One more issues may be represented by water infiltration in concrete structure. This can be solved thanks to a liner covering the most exposed areas.

As prescribed by regulatory commission, the nuclear island must be designed to withstand the effects of natural phenomena and possible terrorism acts.

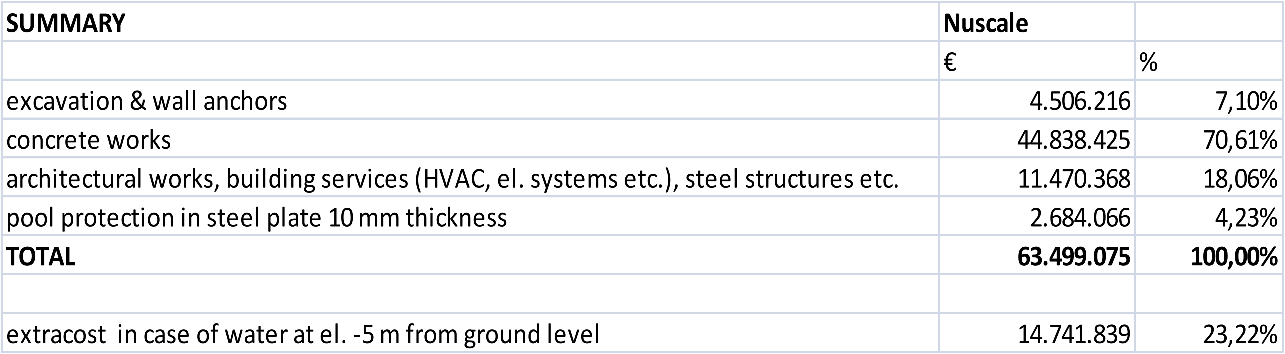
As for IRIS case we consider two scenarios: a dry soil case and a wet ground one.

It is possible to consider extra cost to be added to a base case.

The most important cost driver is concrete works for Nuscale power plant too.

It represent more than the 70% of the total cost, while excavation work, in the dry case, accounts for only the 7%.

A brief summary is shown in the chart below (7-11):



SUMMARY	Nuscale	
	€	%
excavation & wall anchors	4.506.216	7,10%
concrete works	44.838.425	70,61%
architectural works, building services (HVAC, el. systems etc.), steel structures etc.	11.470.368	18,06%
pool protection in steel plate 10 mm thickness	2.684.066	4,23%
TOTAL	**63.499.075**	**100,00%**
extracost in case of water at el. -5 m from ground level	14.741.839	23,22%

7-11 Nuscale primary building costs summary

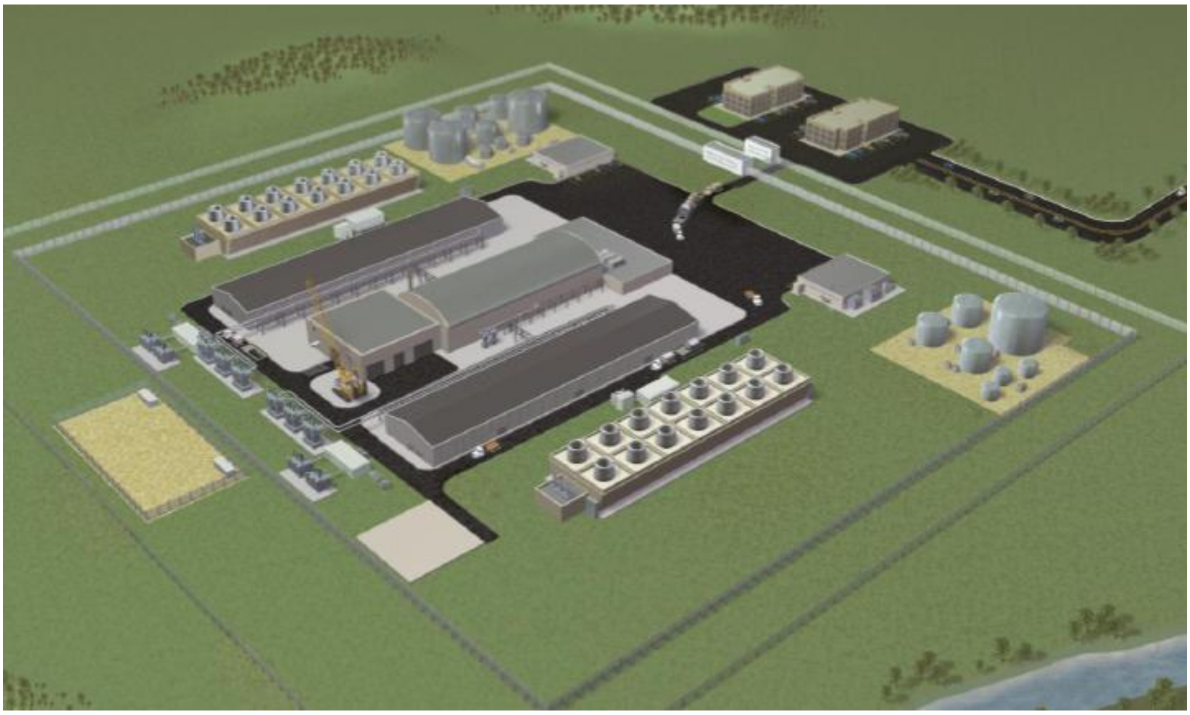
Extra costs are very similar to IRIS ones, they affect the total cost for about 23%.

Obviously we consider the wet case as the most common, because of the location chosen for nuclear power plants, usually near water.

This lead to total cost of about **78.2M€**.

7.5 BALANCE OF PLANT AND CIVIL STRUCTURES

Nuscale power plant is design to be operated in a 12 reactor layout. Each reactor feeds its own standard steam system. The 12 module layout can be represented as follows (7-12):



7-12 Nuscale Plant Layout

In order to achieve a significant comparison between the three reactors presented we decided to consider the standard 12 modules layout, producing 540MW of power. (Welter, 2010)
These data and the steam cycle area are summarized as follows (7-13):

REFERENCE POWER PLANT	NUSCALE
Power plant Size [MW]	540
N° of units installed	12 X 45MW
BOP MAIN COSTS	€
STEAM CYCLE	
Steam Turbine	146.753.808
Condenser	10.100.000
Cooling Tower	8.917.088
Pumps	5.382.896
Feed Water Heaters	4.390.672

7-13 Main Steam Systems Elements and Costs

Turbine has a greater influence of steam cycle area cost, affecting it for over the 80%.

This comes from the use of 12 different turbines, increasing costs of that kind of equipment of about 40%.

Another big difference comes from the reduced secondary water flow, that provide Nuscale a saving of about 45% concerning the pumps cost driver.

Condenser and cooling towers cost drivers result more expensive compared to other reactors because of the 12 modules layout, operated pairing each reactor with a single turbine.

As underlined in section 6.2 steam cycle cost area is the main area affecting final BOP cost.

In fact it influences total cost for about 43%, and it's the highest value among the three concepts evaluated in this work.

Electrical equipment data are shown in the following chart (7-14):

ELECTRICAL	€
HV Equipment	21.412.000
MV Equipment	2.007.072
LV Equipment	4.400.368
Control	1.612.768
DCS	5.226.144
Assembly & Wiring	7.388.352

7-14 Electrical Equipment Cost Detail

There are no big differences between Nuscale electrical cost drivers and the other reactor ones, except for a significant saving in MV equipment.

Civil structures cost driver are reported in the following chart (7-15):

CIVIL	€
Site Work	10.457.136
Excavation	4.040.000
Concrete	41.717.040
Roads	1.140.896

7-15 Civil Structures Cost Detail

They result to be the highest among all projects considered, although a sensitive saving concerning the site work cost driver (44% less than IRIS).
On the other hand side massive excavation work, due to the presence of the pool, and the concrete cost driver rises total civil costs up to 57M€ (15% more than IRIS project).
Looking at the following cost drivers great influence is provided by the 12 turbine buildings needed to house the 12 BOP. This fact greatly influences the buildings cost driver:

	€
BUILDINGS	42.581.600
ERECTION & ASSEMBLY	27.472.000
PIPING & STEEL STRUCTURES	54.944.000

7-16 Buildings, Work and Piping Costs

Building cost driver increases of the 70% compared to the same IRIS cost driver, while erection&assembly and piping costs decrease of the 37% and 12% respectively.
A collection of minor costs is reported in the following chart (7-17):

MISCELLANEA	€
Emergency Diesel Gen.	293.062
Start-Up Diesel Gen.	1.526.312
Water treatment	2.747.200
Water disposal	468.640
Tanks	1.934.352
Aux Heat Exchangers	40.497

7-17 BOP Minor Cost Drivers

The only noticeable values are start-up diesel generators that allows Nuscale to save 73% compared to IRIS. On the other hand side a 50% of expense is needed for tanks.

All these results lead to a total cost of **407M€**, as expected the highest of the three plant presented. In fact Nuscale BOP results to be 10% more expensive than IRIS one.

Economic performance decreases if we consider specific costs, due to the lower power output: in fact, compared to IRIS the results lead to 754€/kW concerning Nuscale against IRIS' 554€/kW.

Nuscale is designed to be cooled by an air cooled condenser.

This option lead to a lower efficiency of the entire cycle but allows the plant to operate in difficult areas, where a heat sink may not be present.

Considering these factors we need an estimate of the new balance of plant costs. In fact we suppose that, with air cooling, costs should increase.

All these topics are summarized in the following chart (7-18):

COST ESTIMATION [€]		Equipment	Construction	Civil (concrete)	Civil (excavation)
POWER PLANT NUSCALE					
Water cooled	Cooling Tower	8.917.088	8.080.000	4.686.400	533.280
	Water Cooled Condenser	10.100.000	1.292.800	2.585.600	290.880
	Make up, waste water treatment	3.215.840	1.050.400	404.000	242.400
Air cooled	Air Cooled Condenser	42.824.000	17.776.000	3.474.400	1.292.800

7-18 Costs concerning different cooling systems

As we anticipated plant costs increase significantly. To quantify this increase we refer to the following chart (7-19):

COST ESTIMATION [€]		Sub total	TOTAL	Delta Cost	Delta USD / kW
POWER PLANT NUSCALE					
Water cooled	Cooling Tower	22.216.768	41.398.688	23.968.512	44,39
	Water Cooled Condenser	14.269.280			
	Make up & waste water treatment	4.912.640			
Air cooled	Air Cooled Condenser	65.367.200	65.367.200		

7-19 Total and differential costs between air cooled and water cooled solution

So the total balance of plant cost turns out to be about **531M€**, and the specific cost about **798€/kW.**

8 MPOWER

8.1 FABRICATION

mPower vessel has a design closer to Nuscale one: it is obviously bigger and ticker, due to higher power output and operating pressure, but, as Nuscale’s RPV, houses the core in the lower part, leaving the upper part to steam generators. Its dimensions are 4.5m in diameter and 22m tall.(Lee, 2011)

Power’s vessel has been divided in to easily fabricating pieces, as we did for previous projects. Thanks to that we are able to determine in a more precisely way the cost of the entire vessel.

Once again, thanks to previous experience, we obtain this set of data (8-1):

	Diam max (m)	Diam min (m)	Height (m)	Thick (m)
Lower Head	4,6	4,4		0,1
Low shell 1	4,6	4,2	2,882	0,2
Low shell 2	4,6	4,2	2,882	0,2
Low shell 3	4,6	4,2	2,882	0,2
Ring	4,716	4,2	0,8515	0,258
Ring 2	4,716	4,2	0,8515	0,258
Joint	4,716	4,2	1,441	0,2
Shell Nozzle	4,2	3,8	2,096	0,2
Nozzle				
Joint 2	3,8	3,4	0,917	0,2
Upper Shell	3,8	3,4	2,1615	0,2
Upper shell 2	3,8	3,4	2,1615	0,2
Ring	3,9	3,4	1,179	0,25
Ring sub pressur	4,716	4,216	0,524	0,25

8-1Vessel Sub-components dimensions 1

	Diam max (m)	Diam min (m)	Height (m)	Thick (m)
Shell press	4,716	4,216	1,31	0,25
Cover	4,716			0,25
Pumps Ins	0,393		0,524	
Shell press	2,489	2,089	3,93	0,2
Press Head	2,489	2,289		0,1

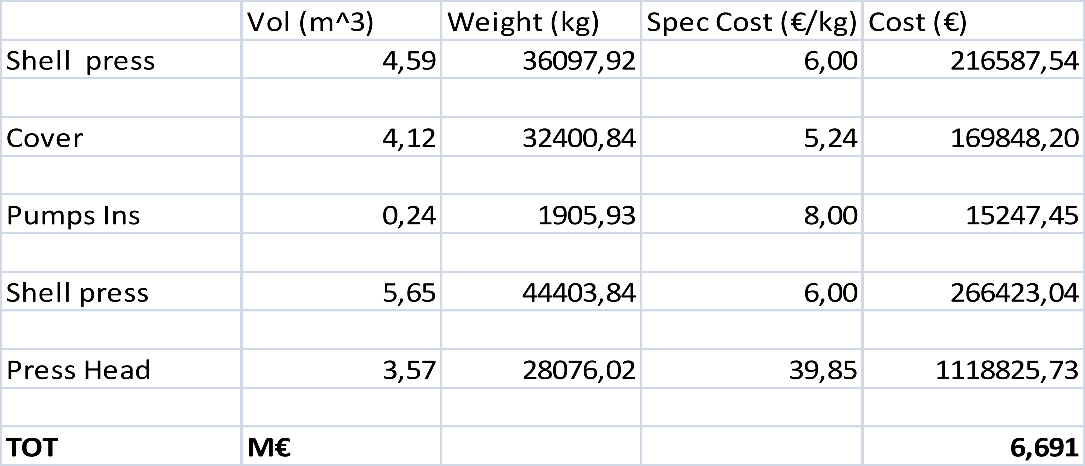
8-2Vessel Sub-components dimensions 2

This sectioning has been made under the hypothesis that none of the components could exceed the limits of weight and dimensions previously described in 6.1.

Thanks to this data set it is possible to obtain weight and volume data:

	Vol (m^3)	Weight (kg)	Spec Cost (€/kg)	Cost (€)
Lower Head	6,46	50760,18	39,85	2022786,58
Low shell 1	7,96	62593,44	6,00	375560,66
Low shell 2	7,96	62593,44	6,00	375560,66
Low shell 3	7,96	62593,44	6,00	375560,66
Ring	2,61	20545,44	6,88	141270,48
Ring 2	2,61	20545,44	6,88	141270,48
Joint	3,43	26952,88	10,42	280968,81
Shell Nozzle	1,89	14846,54	6,00	89079,26
Nozzle	2,59	20329,94	8,00	162639,49
Joint 2	1,76	13850,74	10,42	144386,27
Upper Shell	4,89	38409,61	6,00	230457,68
Upper shell 2	4,89	38409,61	6,00	230457,68
Ring	2,87	22569,28	10,42	235272,28
Ring sub pressur	1,84	14439,17	6,88	99283,73

8-3 Mpower Vessel Sub-components cost estimation



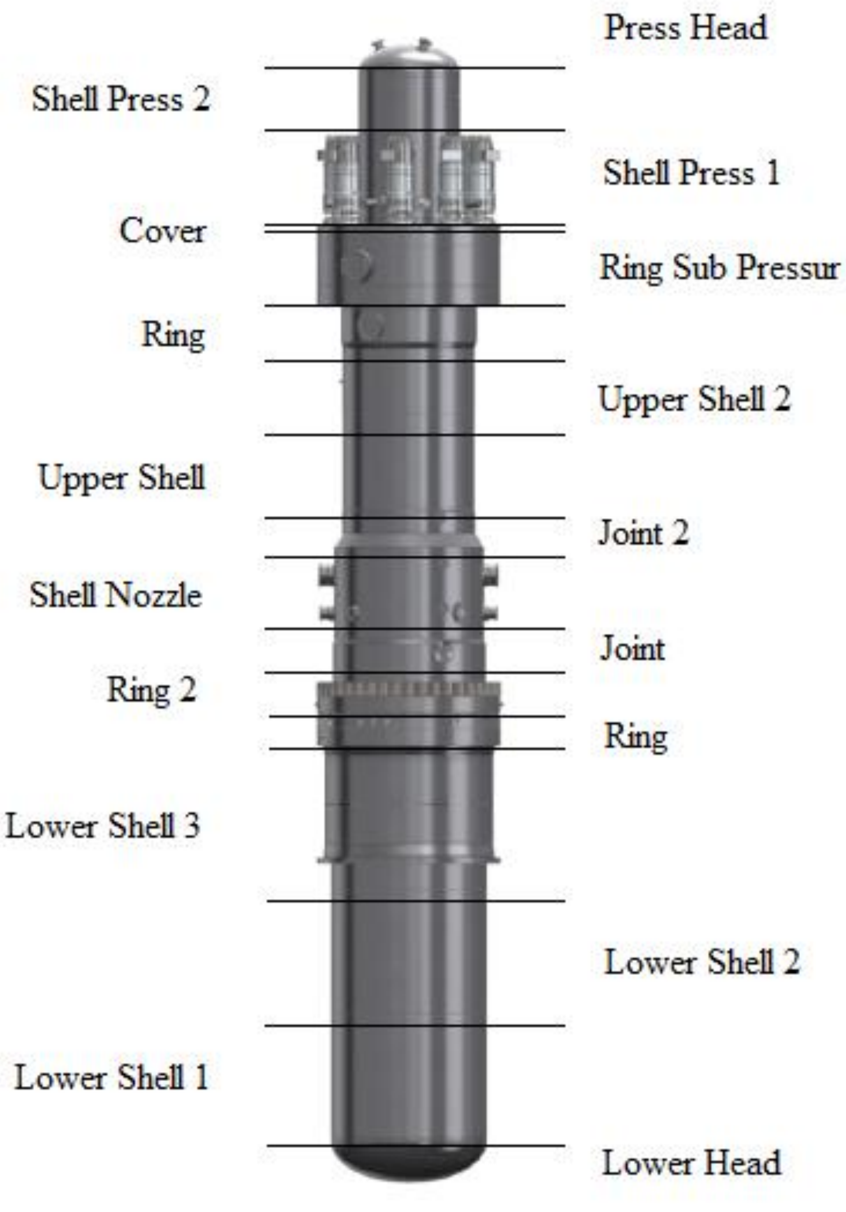
	Vol (m^3)	Weight (kg)	Spec Cost (€/kg)	Cost (€)
Shell press	4,59	36097,92	6,00	216587,54
Cover	4,12	32400,84	5,24	169848,20
Pumps Ins	0,24	1905,93	8,00	15247,45
Shell press	5,65	44403,84	6,00	266423,04
Press Head	3,57	28076,02	39,85	1118825,73
TOT	**M€**			**6,691**

8-4 Mpower Vessel Sub-components cost estimation

These data lead to a total cost of 6.691M€ and a total weight of 612.324t.

This is a rougher estimation compared to the previous ones because of the lack of precise data concerning vessel structure.

We were compelled to draw information from scaled design schemes and to propose an appropriate subdivision of the RPV under the restraint conditions of dimensions and weight as shown in the following picture (8-5):



8-5 Mpower Vessel Subsections

We assume that Mpower reactor vessel is coated with a standard steel layer of 3cm.

Thanks to previous experiences this operation has an estimated cost of about 1.449M€, raising the total vessel price to **8.14M€**.

mPower reactor has been designed with a metal containment, that houses the entire RPV fuel handling systems and some of the safety systems.

From data available in literature we are able to estimate dimensions and costs as follows:

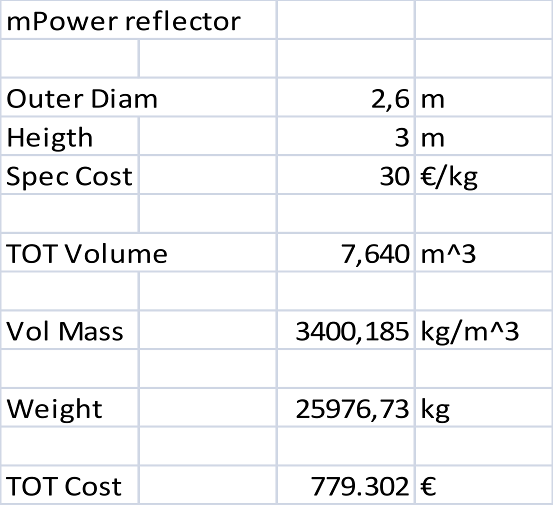
mPower containment								
Diam		33	m		Vol Mass		7860	kg/m^3
Height		30	m		Spec costs		10,14	€/kg
Height Sphere		35	m					
Thickness		0,059	m					
Surf		**4277,465**	**m^2**					
Vol		**238,914**	**m^3**					
TOT WEIGHT		**1.877.864**	**kg**					
TOT COST (weight)		**19.041.542**	**€**					

8-6 mPower containment cost estimate

These data are calculated under the hypothesis of a carbon steel containment, with a cylindrical shape and a hemispherical head.

These considerations lead to a total cost of about **19M€**, that, added to previous ones returns a cost of **27.14M€**.

Once again we present the evaluation of the reflector, that is not going to affect total cost significantly.



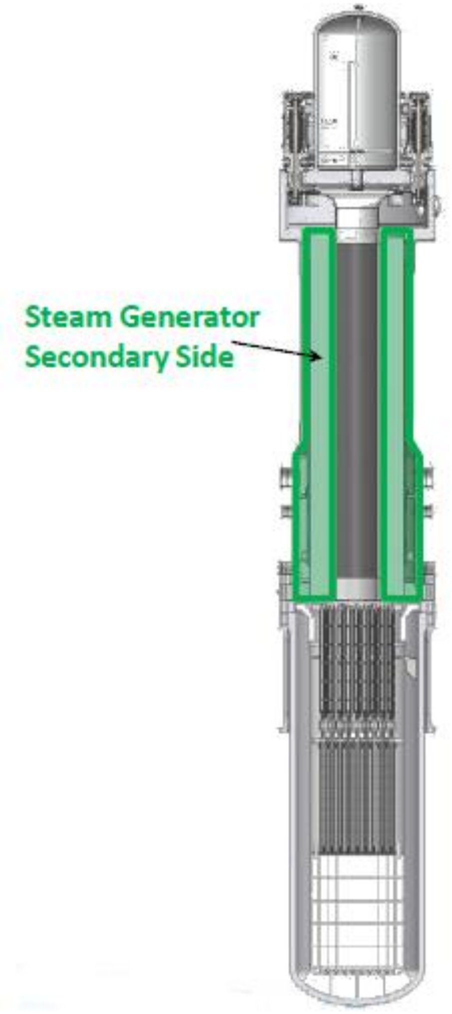
mPower reflector			
Outer Diam		2,6	m
Heigth		3	m
Spec Cost		30	€/kg
TOT Volume		7,640	m^3
Vol Mass		3400,185	kg/m^3
Weight		25976,73	kg
TOT Cost		779.302	€

8-7 mPower reflector cost

Finally, total costs rise to about **28M€**.

8.2 STEAM GENERATOR

mPower steam generator data are obtained from sketches available in literature.



8-8 Mpower secondary circuit

It has a ring shape, housed in the upper part of the vessel.

It has been evaluated an outer diameter of 3.5m and an inner one of 2.6m. it is made of straight tubes with a length of 10.7m.

A triangular path has been supposed to estimate the number of tubes involved in mPower SG fabrication.

This analysis results in a 7400 tubes. It is a very high number, especially compared to other project SGs. We must consider that mPower relies on straight tubes that provide less exchange surface than helical ones, resulting in shorter tubes. In fact the medium length estimated for mPower tubes are 10.7m against 32m of IRIS ones.

Further hypothesis must be considered to evaluate SG cost properly, such as the presence of at least 12 grid to avoid vibration and maintain the correct positioning of tubes.

We consider INCONEL 690 tubes with an outer diameter of 19.05mm and 2.11mm thick, considering these parameters as standard

All these considerations lead to a total cost of **9.1M€.** A wide part of this cost comes from materials cost that results in about 6.5M€.

All data can be summarized in the following chart:

TOTAL COST		**€**	**9.100.000**
TOTAL FABR HOURS		**h**	**29750**
TOTAL FABR COST		**€**	**920.000**
TOTAL METERIAL COST		**€**	**6.488.000**

8-9 Total mPower SG costs

8.3 SAFETY SYSTEM

Once again information available on the mPower design are not precise.

All its safety systems are defined as standard as well as Nuscale ones.

Low power density reduces fuel and clad temperature during accident and small penetration at high elevation enhance safety standard.

Emergency heat removal systems may be considered similar to IRIS and Nuscale reactor ones.

In fact it is difficult to perform a precise cost analysis due to the lack of information and the analysis may not be completely significant.

We must follow the path built for Nuscale estimation.

Thanks expert's judgment it has been evaluated that EHRS costs may be about **4.5M€** concerning the single unit and a total cost of about **18M€**.

This represent around 60% of IRIS EHRSs.

From literature we know that no diesel generators are needed thanks to safety enhancements.

8.4 PRIMARY BUILDING

mPower primary building, following the original project, is almost entirely built underground.

This solution arises several technical issues because of the difficulties in performing a 50m excavation.

A simple conceptual sketch may provide information about the layout (8-10):

8-10 mPower nuclear island (Twin configuration)

In fact usually it is possible to reach depths of about 23-25 meters with no particular issues even if in presence of water.

50m although seems to be a depth very difficult to reach.

One of the possible solution could be to change pillars disposition during excavation, trying to avoid pillars ruptures due to the excessive weight of the surrounding ground.

This must be done with particular pillars, 60m long.

The presence of water though, seems to be the biggest challenge.

The most common technique used in these cases is to isolate the bottom ground with jet grouting techniques, and the "walls" with standard techniques.

Another option, less frequently used, is to isolate small portion of ground during excavation, and perform ground work sector by sector.

These techniques though introduce higher costs. In particular costs concerning anchors, almost quadrupled, and pillars, almost doubled.

Usually foundation costs counts for the 30% of total cost of civil work; in case of 50m excavation this percentage clearly arises over 50%.

Thanks to these considerations it is possible to perform a cost analysis on mPower primary building, leading to the following results:

SUMMARY	**Nuscale**	
	€	%
excavation & wall anchors	59.085.000	51,32%
concrete works	44.253.756	38,44%
architectural works, building services (HVAC, el. systems etc.), steel structures etc.	11.796.800	10,25%
TOTAL	**115.135.556**	**100,00%**
extracost in case of water at el. -5 m from ground level	41.707.182	36,22%

8-11 mPower primary building costs summary

Extra costs concerning presence of water are significantly higher compared to Nuscale ones, because of the deeper excavation needed.

This lead to a total cost of about **156.8M€**, in fact, despite all these ad-hoc techniques, this remains a challenging civil work.

We need to face the problem of hydrostatic force provided on the entire structure that is floating on the water on the bottom of the excavation.

It is possible to use different solutions such as limiting depth to 25 m and provide a sort of underground coverage by surrounding the building with ground reported from nearby to form a sort of bunker.

This seems to be a very effective technique but it introduces several issues.

The first one is the capability of the ground to sustain the new weight.

It is in fact possible to experience some subsidings that could compromise the integrity of the structure. We must underline that building must be completed before the ground is reported and every little movement of its foundations can compromise its integrity.

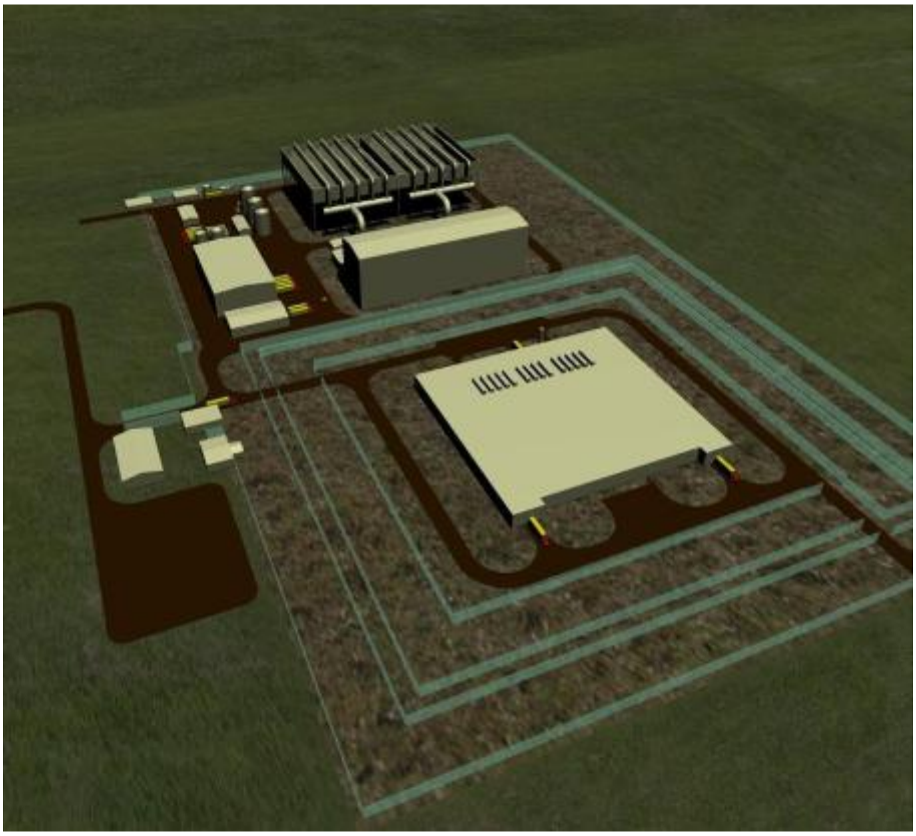
So it could be only possible to perform such a technique only on rocky grounds that can sustain further weight more easily.

All these issues lead to a project really complex, clearly contrasting SMR simplification philosophy.

The final project will more likely have a primary building built underground only for a half, with the hemispherical dome and part of the sustain structure built above ground.

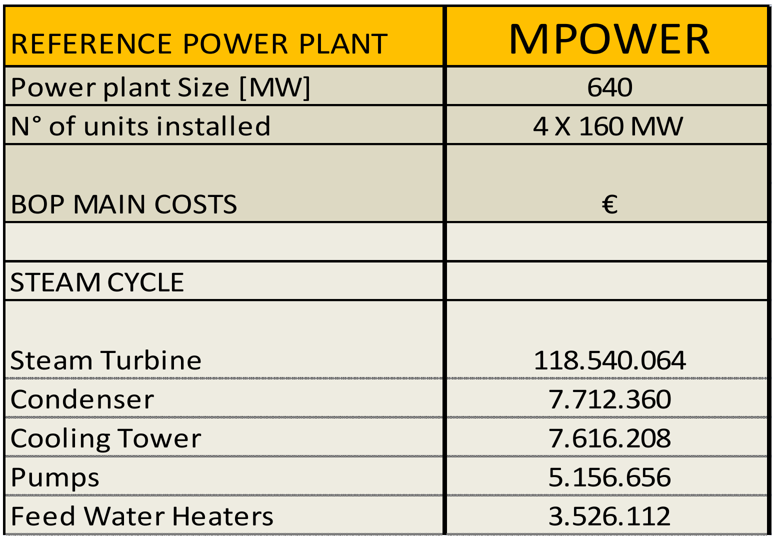
8.5 BALANCE OF PLANT AND CIVIL STRUCTURES

mPower reactor can operate both with air cooling systems and water cooling standard ones.
In the picture above the less efficient air cooled layout is shown (8-12):



8-12 Mpower plant Layout

Economic analysis has been made considering both the standard water cooled system, to be comparable to IRIS and Nuscale ones, and the air cooling.
As the picture shows all the nuclear island is almost entirely built underground to enhance safety standards level, mainly against external attacks. In order to achieve a significant and comparable cost estimation we have to consider a 4 unit layout with a total power of 640MW.(Lee, 2011)
As considered before, each nuclear reactor feeds only one steam system.
In the following chart (8-13) we find a brief summary of all the elements reported:



REFERENCE POWER PLANT	MPOWER
Power plant Size [MW]	640
N° of units installed	4 X 160 MW
BOP MAIN COSTS	€
STEAM CYCLE	
Steam Turbine	118.540.064
Condenser	7.712.360
Cooling Tower	7.616.208
Pumps	5.156.656
Feed Water Heaters	3.526.112

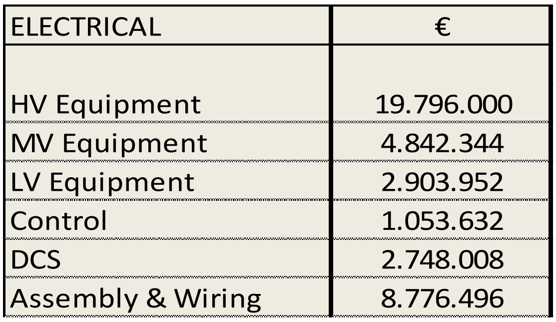
8-13 Steam Systems Elements and Costs

Once again the most relevant element of the steam cycle area is the turbine. This time it affects the cost of his area for more than the 80%, the same amount estimated for Nuscale project.

This difference is due to different cost of pumps , 9.6M€ for IRIS reactor against 4.8M€ needed for mPower. This is a consequence of the big difference in the water flow needed in the secondary system, 502kg/s and 204kg/s for mPower.

Steam cycle cost area covers about the 40% of the total BOP cost, very close to IRIS ratio.

A brief summary of mPower electrical equipment:



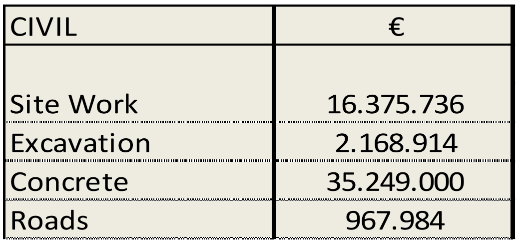
ELECTRICAL	€
HV Equipment	19.796.000
MV Equipment	4.842.344
LV Equipment	2.903.952
Control	1.053.632
DCS	2.748.008
Assembly & Wiring	8.776.496

8-14 Electrical Equipment Cost Detail

Once again there are no big differences between the three reactor designs in this section.

The total cost is around 40M€ as the previous ones.

A summary of civil work is available in the following chart (8-15):

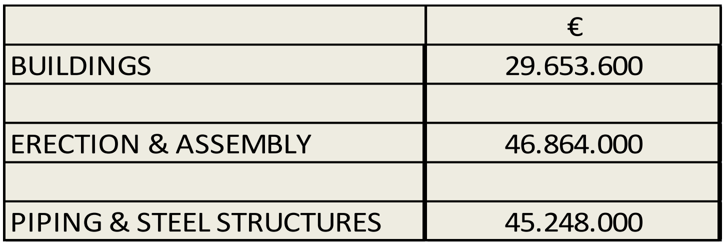


CIVIL	€
Site Work	16.375.736
Excavation	2.168.914
Concrete	35.249.000
Roads	967.984

8-15 Civil Structures Cost Detail

These values are very similar to IRIS ones except for the concrete cost driver resulting significantly higher. As already spotted in the previous scenarios site work and concrete covers almost entirely the civil structure cost area.

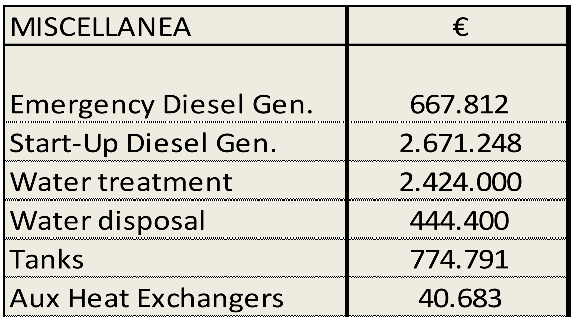
mPower building and erection&assembly costs are very close to IRIS values except for the last cost driver. In fact mPower introduces a massive saving in piping and steel structure of about the 25%. These results are reported in the following chart (8-16):



	€
BUILDINGS	29.653.600
ERECTION & ASSEMBLY	46.864.000
PIPING & STEEL STRUCTURES	45.248.000

8-16 Buildings, Work and Piping Costs

As previously done finally we present a brief summary of all minor cost related to mPower balance of plant:



MISCELLANEA	€
Emergency Diesel Gen.	667.812
Start-Up Diesel Gen.	2.671.248
Water treatment	2.424.000
Water disposal	444.400
Tanks	774.791
Aux Heat Exchangers	40.683

8-17 BOP Minor Cost Drivers

Significant difference between this design and the others is represented by the start-up emergency diesel.

All these partial results lead to a total balance of plant cost of about **366M€**, very similar to IRIS one.

If we want to use a more significant estimator we should look at specific cost. In this case IRIS shows higher economic performance: 554€/kW against mPower's 572€/kW.

As Nuscale reactor, also mPower can be designed air cooled.

Once again this fact allows its use in critical areas, with no rivers available or far from the sea.

Obviously the air cooled layout is once again more space demanding and more expensive.

It is possible to summarize the costs in the following chart (8-18):

COST ESTIMATION **[€]**		Equipment	Construction	Civil (concrete)	Civil (excavation)
POWER PLANT MPOWER					
Water cooled	Cooling Tower	7.616.208	6.464.000	4.524.800	496.920
	Water Cooled Condenser	7.712.360	1.018.080	2.424.000	242.400
	Make up & waste water treatment	2.868.400	1.050.400	404.000	242.400
Air cooled	Air Cooled Condenser	39.592.000	16.160.000	3.232.000	1.212.000

8-18 Costs concerning different cooling systems

A complete comparison between the two solutions can be made thanks to the following chart (8-19), where all data are summarized:

COST ESTIMATION **[€]**		Sub total	TOTAL	Delta cost	Delta USD / kW
POWER PLANT MPOWER					
Water cooled	Cooling Tower	19.101.928	35.063.968	25.132.032	39,3
	Water Cooled Condenser	11.396.840			
	Make up & waste water treatment	4.565.200			
Air cooled	Air Cooled Condenser	60.196.000	60.196.000		

8-19 Total and differential costs between air cooled and water cooled solution

Once again it is possible to identify a sensible increase in the plant cost, due to the air cooled solution

This lead to a total cost of about **391M€** and a new specific cost of about **611€/kW**

9 LOCATION

Choosing appropriate location for a nuclear power plant could be difficult.

Different factors must be considered, such as: reactor design and its operation, population density, distance from population centers, seismology and hydrology and so on.

We would like to analyze transport on site costs, so the base for this analysis is to find proper locations in different part of the world, representative of the whole area they belong to.

It's been decided to study 3 different locations, one for each continent: USA, East Europe and China.

To test SMR performance and flexibility these site must have specific characteristics; they should be challenging from the point of view of energy production and transportation and in the meantime be realistic.

This means location far from the sea or river, useful for transportation as well as water sink, with poor infrastructures or low quality ones.

For what concerns USA, it is possible to select Clinch River as a site.

In fact it is a former nuclear location, because of the fast breeder reactor built there in 1972, in operation till October 26 1983.

It is about 6 square kilometers wide and it's owned by Tennessee Valley Authority (TVA) that has recently taken contact with Babcock&Wilcox group to discuss the possibility of building a mPower plant.

Western Russia could be identified as a significant location, representative of all Eastern Europe.

Is it possible to choose Ryazanskaya GRES CHP Power Plant's site as a possible location for the installation of a SMR reactor. In fact small nuclear reactor could be built to replace old coal plants.

This is true not only in eastern Europe, but it is one of the key of SMR strategy in USA too.

Material transportation on site could be challenging because of the absence of a high quality infrastructures grid. Components could easily arrive by sea till Ukraine's shore. It could be transported by rail or by truck till Novomičurinsk. Russian railways are often a good means of transport but they are not always well distributed.

Highways, on the other side could be able to stand the weight transported by trucks carrying nuclear equipment. The most difficult task is to transport components on site. This site, e.g., is located on the Pronya river, that is not navigable. The only solution is a road transportation, but at least 500km must be covered, without adequate infrastructures that can easily allow the transportation of components.

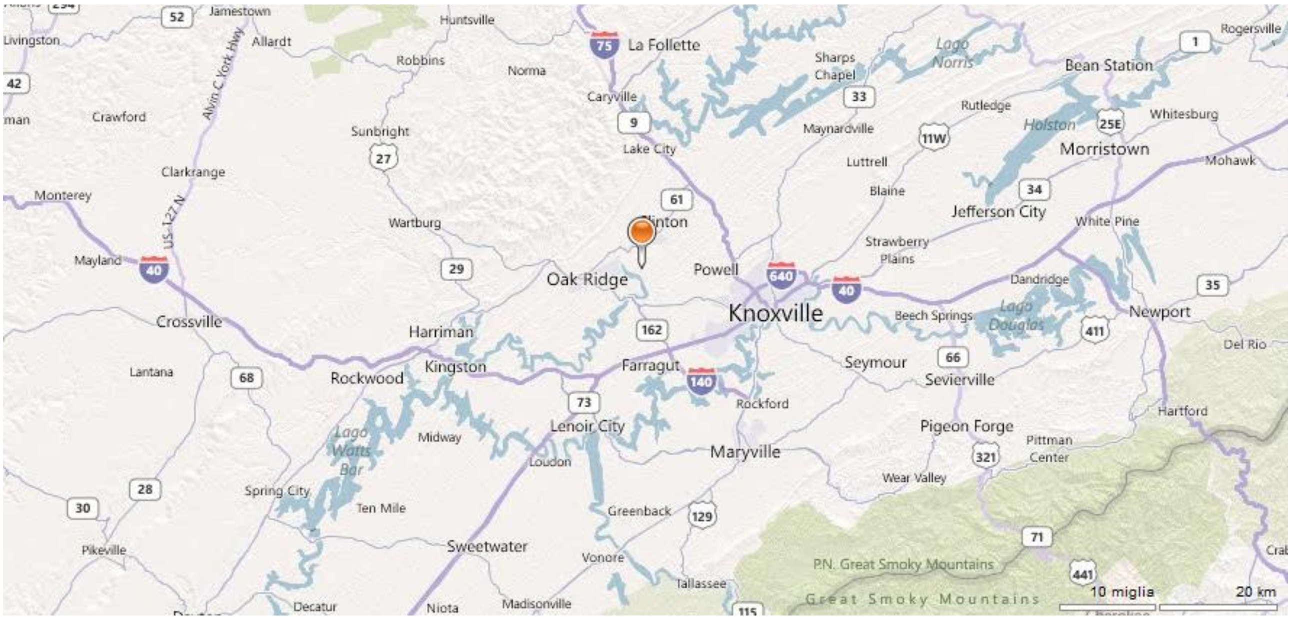
India and China areas, at first, are the most representative location for the Eastern part of the world. On the other hand, also Mongolia could be spotted as a particularly challenging area where the need for electricity stands with difficult environmental and infrastructural conditions.

The area around Sharyngol represent an hot spot for the mining industry in Mongolia. There is no presence of water, such as significant river or lake, and it is located far from the Chinese or Russian shores. This makes that location particularly challenging, both from the point of view of nuclear plant operation and of transportation.

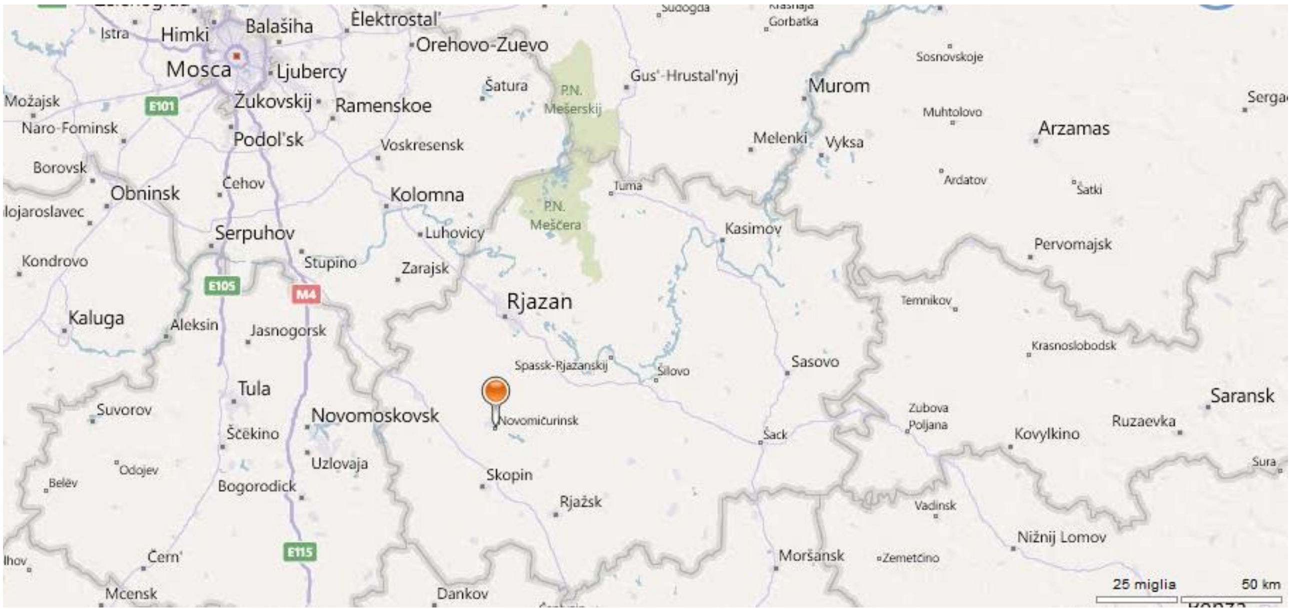
Moving industrial materials is also difficult in Mongolia due to the lack of a good infrastructural network: in fact there are only 1810km of railways and highways are not really widespread.

Mongolia anyway, aims to build a massive industrial park in Sainshand, capital of Dornogovi Province, to help transport metals and coal to customers around the world. This could help transportation of heavy materials in the most difficult territories.

Here a few images to locate SMR hypothetical sites:



9-1 Clinch River site-map



9-2 Ryazanskaya site-map

9-3 Sharyngol site-map

A complete and generalized evaluation of transport costs is basically impossible to perform.

Sea transport doesn’t introduce big difficulties and usually it is not particularly expensive.

On the other hand side, inland transportation requires a detailed route, structural bridges, obstacles and roads) survey, method assessment and study.

This means that every transportation has its peculiarity and it is not possible to perform a generalized cost analysis.

The main issue concerning sea transportation may be represented by the lack of proper structure to handle such heavy equipments.

In this case it is usually necessary to build proper docks, able to withstand the weight of the structures carried by boats or barges. These structure are not very expensive and should not affect costs sensibly.

A total different scenario concerns inland transportation. In fact there are lots of variables that can affect total costs. First of all the presence of proper infrastructure and their conditions.

Usually it is not a big issue in developed countries, but it can be an important one in developing countries, such as the ones that may be interested in SMRs construction (e.g. Mongolia in our case study).

The necessity of building roads ad-hoc, dismantling obstacles (such as bridges, overpasses, traffic lights) may arise costs significantly.

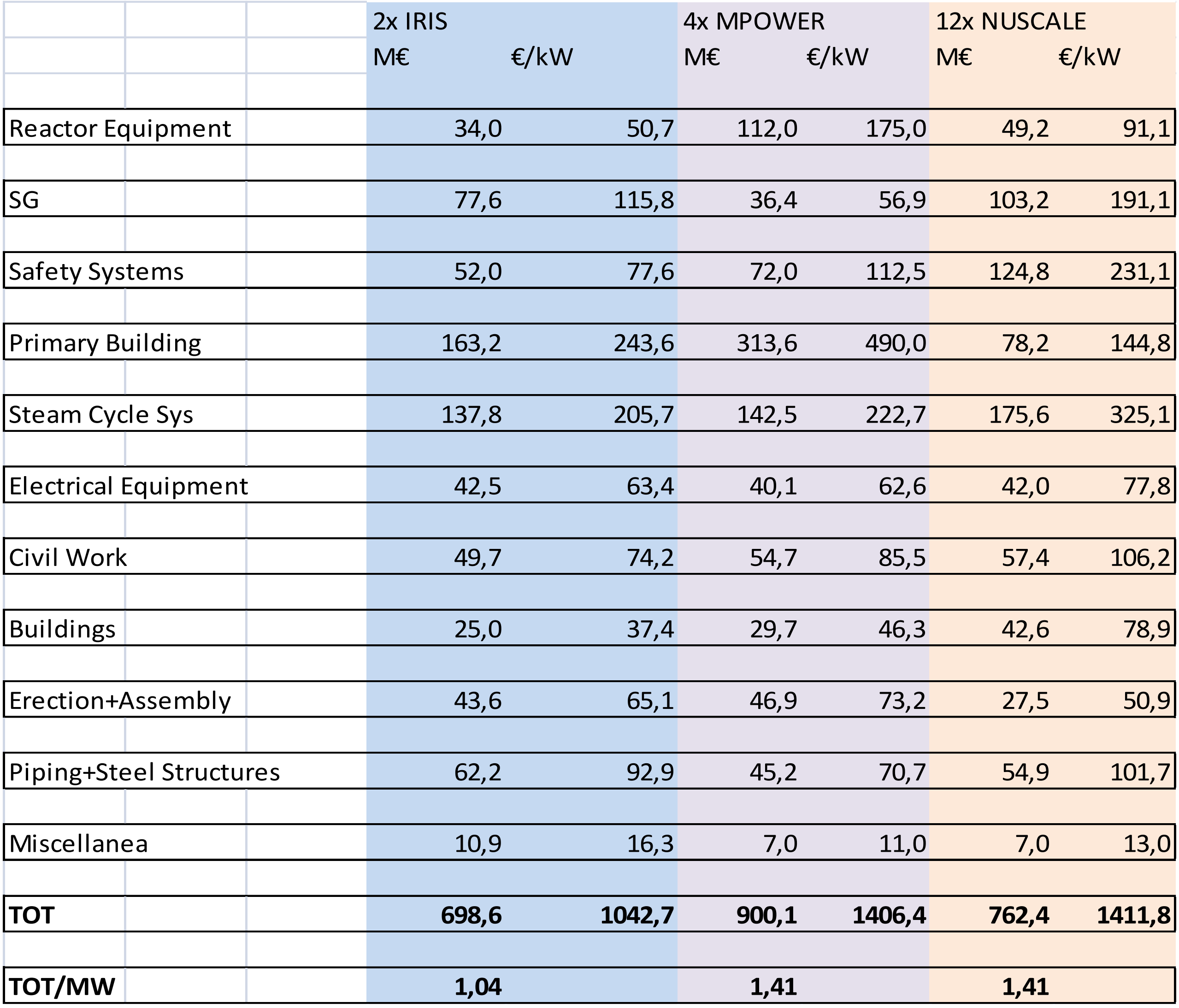
Thanks to expert’s judgment it has been evaluated that transportation should not affect costs in a crucial way.

10 DATA ANALYSIS

In this chapter we are going to summarize all the results achieved by this work.

For each reactor we are going to show all costs, stressing the area they belong to (reactor equipment, SG, safety systems..) following the path of IAEA COA described in chapter 5.1.

All the analysis are performed considering similar power output, more precisely: 2 IRIS reactors (670MW), 4 mPower ones (640MW) and 12 Nuscale ones (540MW).



	2x IRIS		4x MPOWER		12x NUSCALE	
	M€	€/kW	M€	€/kW	M€	€/kW
Reactor Equipment	34,0	50,7	112,0	175,0	49,2	91,1
SG	77,6	115,8	36,4	56,9	103,2	191,1
Safety Systems	52,0	77,6	72,0	112,5	124,8	231,1
Primary Building	163,2	243,6	313,6	490,0	78,2	144,8
Steam Cycle Sys	137,8	205,7	142,5	222,7	175,6	325,1
Electrical Equipment	42,5	63,4	40,1	62,6	42,0	77,8
Civil Work	49,7	74,2	54,7	85,5	57,4	106,2
Buildings	25,0	37,4	29,7	46,3	42,6	78,9
Erection+Assembly	43,6	65,1	46,9	73,2	27,5	50,9
Piping+Steel Structures	62,2	92,9	45,2	70,7	54,9	101,7
Miscellanea	10,9	16,3	7,0	11,0	7,0	13,0
TOT	**698,6**	**1042,7**	**900,1**	**1406,4**	**762,4**	**1411,8**
TOT/MW	**1,04**		**1,41**		**1,41**	

10-1 Reactor costs comparison

It must be underlined that some of these data were evaluated in a rough way, so that they result in a lower bound estimate.

This is particularly true for all primary buildings.

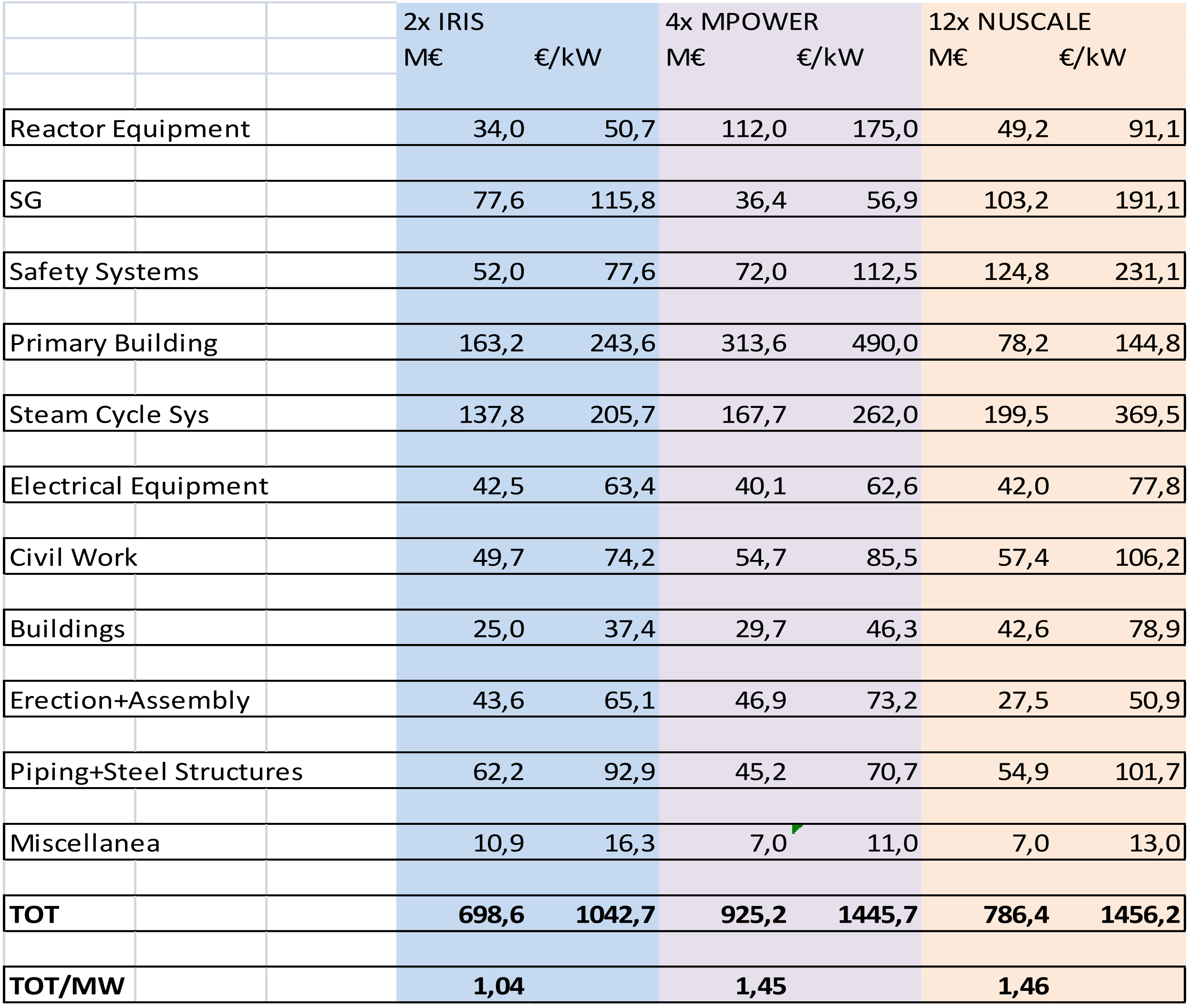
In fact it is very difficult to calculate the work needed to connect and link primary circuits and safety systems, as well as produce an exact estimate of piping dimension and weight.

It would be necessary to have precise data concerning the location of tanks and safety systems, but they are not available in literature.

Without precise data on safety systems, concerning Nuscale and mPower ones, it has been followed the expert’s judgment to scale them properly, referring to standard layout and equipment.

Nuscale and mPower can be designed with an air cooling system. This option slightly increase costs (Steam Cycle sys cost driver), but it has not taken into account in the previous chart to produce an estimate that can be comparable to IRIS one.

Considering air cooling layout this would be the result:



	2x IRIS		4x MPOWER		12x NUSCALE	
	M€	€/kW	M€	€/kW	M€	€/kW
Reactor Equipment	34,0	50,7	112,0	175,0	49,2	91,1
SG	77,6	115,8	36,4	56,9	103,2	191,1
Safety Systems	52,0	77,6	72,0	112,5	124,8	231,1
Primary Building	163,2	243,6	313,6	490,0	78,2	144,8
Steam Cycle Sys	137,8	205,7	167,7	262,0	199,5	369,5
Electrical Equipment	42,5	63,4	40,1	62,6	42,0	77,8
Civil Work	49,7	74,2	54,7	85,5	57,4	106,2
Buildings	25,0	37,4	29,7	46,3	42,6	78,9
Erection+Assembly	43,6	65,1	46,9	73,2	27,5	50,9
Piping+Steel Structures	62,2	92,9	45,2	70,7	54,9	101,7
Miscellanea	10,9	16,3	7,0	11,0	7,0	13,0
TOT	**698,6**	**1042,7**	**925,2**	**1445,7**	**786,4**	**1456,2**
TOT/MW	**1,04**		**1,45**		**1,46**	

10-2 Reactor costs comparison with air cooled systems

One of the most significant factors is the specific cost. mPower and Nuscale have similar has similar economic performance although Nuscale has a lower power output.

We must underline what Nuscale competitiveness is related to a 12 reactor layout, thanks to the possibility of distribute costs on several units. Twin layout, instead, is mPower basic configuration: that means 320MW module, that can fit better SMR philosophy.

IRIS shows the higher competitiveness with 1042.7€/kW. This is basically due to primary equipment, steam cycle and safety systems costs, less expensive compared to other projects.

11 CONCLUSION

We are going to draw conclusion starting from data available in chapter 10. It is necessary to underline that all data shown refers to almost the same power output and not to a single unit.

The first cost driver to be analyzed is the reactor equipment.

Despite a more complex design IRIS reactor equipment results to be less expensive than the others.

This happens because the primary cost driver in the reactor vessel account is the cost of materials, that results to be more competitive if the number of reactors is smaller.

This can be easily shown comparing specific costs.

Steam generator cost driver shows the economic performance of mPower SG that relies on a simpler design, with straight and shorter tubes compared to the other projects.

In fact bending tubes to produce helical coils is very expensive and results to affects costs more than dealing with an higher number of tubes, introduced in mPower design.

Specific costs express clearly this topic: mPower's 56.9€/kW compared to Nuscale's 191.1€/kW; we must underline that helical coil design grants a better use of space, reducing volumes. On the other hand side one of the biggest issues related IRIS SG is tube length. In fact it is really difficult to produce 32m (on average) tubes, first of all in terms of thermal treatment ovens.

It must be stressed the value of 77.6€/kW of IRIS safety system results significantly lower than the others, particularly if compared to Nuscale one, that must consider safety systems for all 12 reactors.

Nuscale primary building costs result to be affected by the presence of the reactor pool, that introduces design complications, especially concerning steel liner. This effect is mitigated by lower excavation depth needed.

mPower primary building cost driver results the highest because of excavation depth, that makes all civil work extremely challenging, arising costs till 490€/kW.

Electrical equipment doesn't represent a differential in the analysis, as well as the miscellanea account.

Steam cycle system account shows a particularly high specific costs concerning Nuscale reactor. This fact relies on the choice of coupling every reactor to a single BOP. Using a 12 BOP layout introduces higher costs but, on the other hand side, it allows to shorten construction time, due to an easier assembling work.

The economic performance of mPower and Nuscale reactors decreases if an air cooling system is considered.

Civil work cost driver shows higher specific cost related to Nuscale project.

This in the effect of the reduced excavation depth (and consequently cost) that cannot balance costs deriving from the wider plant footprint, requiring more “concrete work”. Once again this effect is produced by the 12 BOPs.

This choice influences also the Buildings account that results in a double specific costs compared to IRIS one. The presence of the pool increase building costs too, increasing primary building dimensions.

Erection and assembly code stresses the competitiveness of Nuscale power plant. In fact assembling 12 small units results easier than deal with less but bigger unit, because of the complexity and dimensions of the equipment.

Simpler plant layout enhances mPower competitiveness concerning piping and steel structures. Once again Nuscale results to be less competitive due to the 12 BOPs layout, that requires redundant structures.

These considerations stress the higher competitiveness of mPower enhanced by its simple layout.

Nuscale design and its 12 BOPs layout introduce higher safety standards but increase construction costs, especially considering reactor pool and the 12 BOP buildings.

We must introduce other considerations about costs; it is very important to consider time and location of construction.

Time is crucial because of materials prices. In fact, as we can see in the following picture, large differences exist between, e.g., nickel price in the years:

11-1 Nickel price from 12/07/2008 till nowadays

This fact is considered during estimation introducing formula to correct raw materials costs.

Other considerations must be expressed concerning location, not only looking at transportation issues, as we did in chapter 9.

In fact labor costs and fabrication may be very different from a country to another.

China, e.g., can rely on a very cheap labor cost: this could lead to significant cost reduction, as well as material characteristics requirement (chemical composition, higher standard concerning tubes, etc).

In fact it must be underlined that the analysis performed in this work are significant only if compare reactors made in the same time window and in the same place.

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13 FIGURES INDEX

14 ANNEX 1

DATA REFERENCES

In order to analyze the origin of the data used in the first steps of the cost analysis it is useful to organize the data in the different areas concerning a nuclear power plant, such as Reactor Civil Structures, Safety Systems, Heat Transport Systems, Fuel Handling Systems and so on.
It is also useful to have an immediate comparison between different reactor designs, so, the characteristics of every area are immediately analyzed and described accordingly to each reactor design scheme.

14.1 REACTOR CIVIL STRUCTURES AND EQUIPMENT

					IRIS	NUSCALE	MPOWER
212	Reactor Island Civil Structures	(Primary process facility) Includes installation, labor, and materials for concrete and metalwork for the building surrounding and supporting the nuclear island, including the		reactor containment	25m diam 4.4 thick steel (air attack prrof)	4,5m D x 22m H 7,6cm thick carbon steel cont+ liner pressure 3,4 MPa	28m diam x46H concrete 1,5m thick
				foundation (scavo)	20m	21m (390x350 footprint MASLWR)	ca 47m
				reactor building	50mDx39,4 mH	260x250 (pool+ contol)	100x73mx15H
				pool (if any)		91x78mx28H 1,5 thick concrete	
221	Reactor Equipment	Includes the reactor vessel and accessories, reactor supports, reactor vessel internals (non-fuel), transport to the site, in-core reactor		reactor vessel	6,2x22,2m 25cm thick	2,7Sx13,7m 7,6cm 10,76 Mpa	4.6mD X 29,6m H, 13,1MPa, 16c, thick (Mariotte)
				reactor supports			
				reactor vessel internals			
				control rod system	Ag-In-Cd or B4C outer diam 10,26mm	16 contr rod cluster	AlC , B4C, Gd2O3 control rods

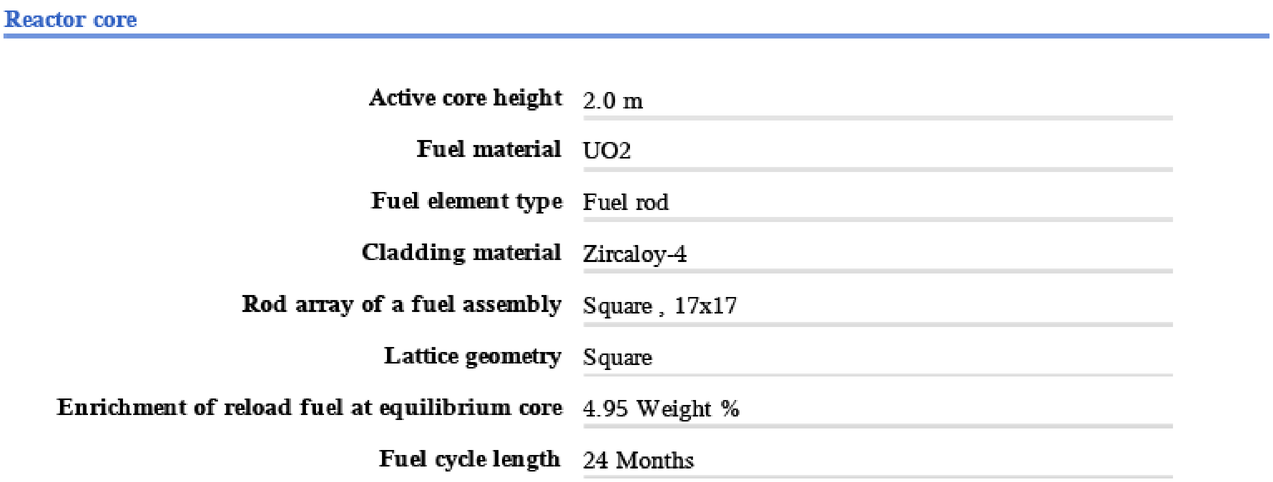
It has been decided to divide code of account 212 and 221 in sub-categories, in order to describe cost distribution in a better way. These are very sensitive information and not easy to obtain. They can be drawn analyzing nuclear reactor publications by the owners, when they are available. Sometimes it’s not possible to obtain all dimensions data necessary to a complete plant description. In that situations we assume data as hypothesis and we try to extrapolate measures of interest. It is also possible to look at schemes or sketches and compare known dimensions elements with unknown ones. Obviously this gives us approximated data, but they are useful anyway because our interest is to evaluate the order of magnitude of costs, using a high grade of approximation.

14.1.1 NUSCALE

Nuscale reactor data can be obtained thanks to the document:

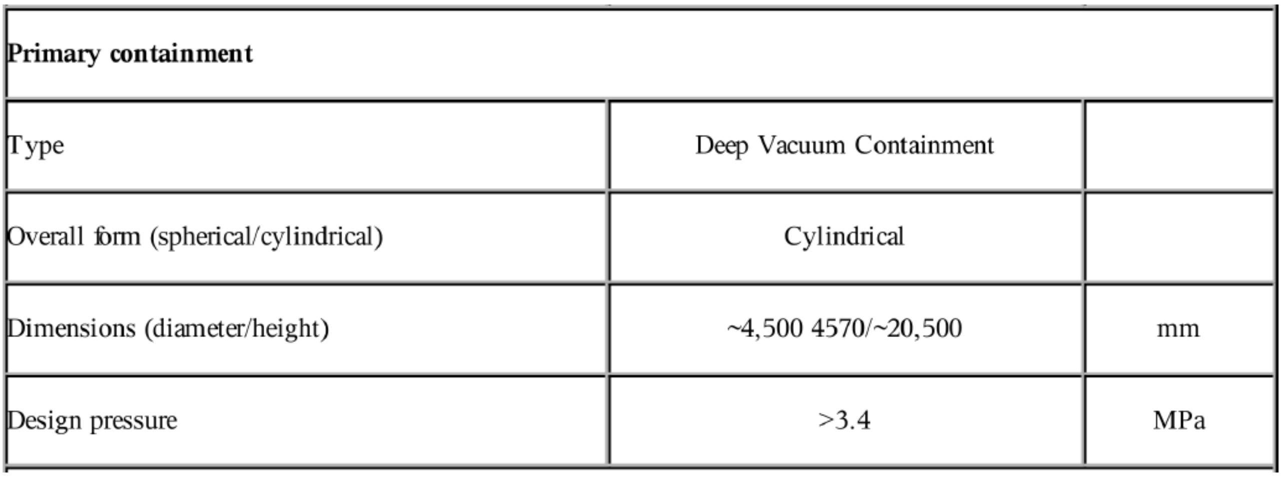
Status report 106 - Nuscale Power Modular and Scalable Reactor (Nuscale) – 01-08-2011 published by IAEA website.

Information contained in this document are very precise and they concern data layouts measures and safety systems.



Reactor core

Active core height	2.0 m
Fuel material	UO2
Fuel element type	Fuel rod
Cladding material	Zircaloy-4
Rod array of a fuel assembly	Square , 17x17
Lattice geometry	Square
Enrichment of reload fuel at equilibrium core	4.95 Weight %
Fuel cycle length	24 Months



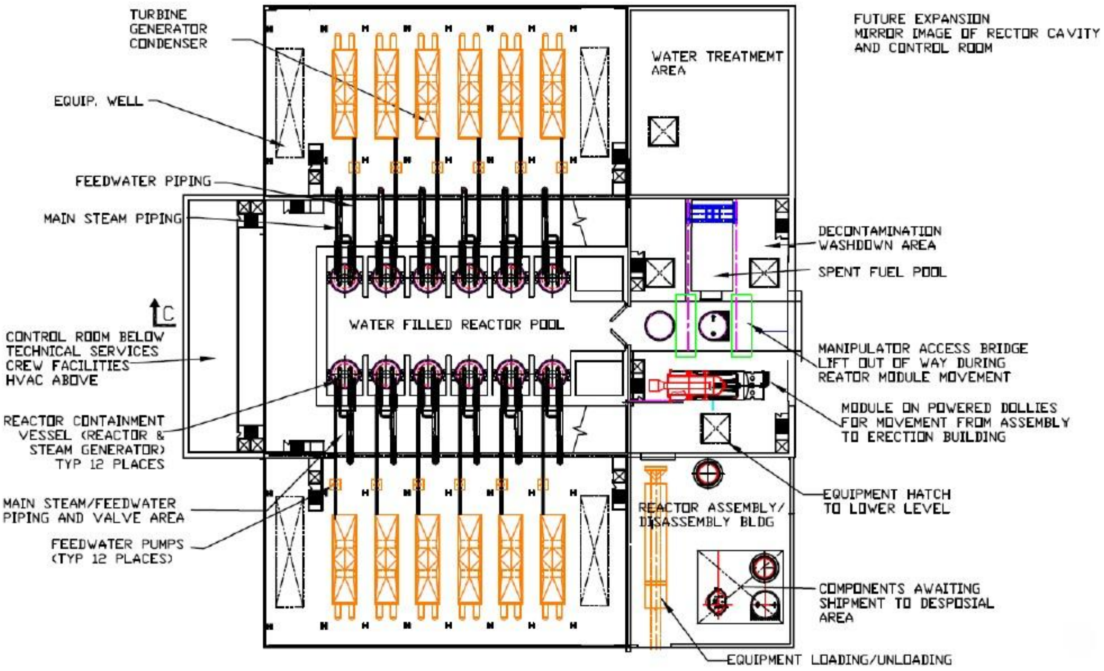
Primary containment		
Type	Deep Vacuum Containment	
Overall form (spherical/cylindrical)	Cylindrical	
Dimensions (diameter/height)	~4,500 4570/~20,500	mm
Design pressure	>3.4	MPa

Dr K. Welter and Dr J.N.Reyes Jr in 2010 and 2008 respectively, summarized Nuscale project in these documents:

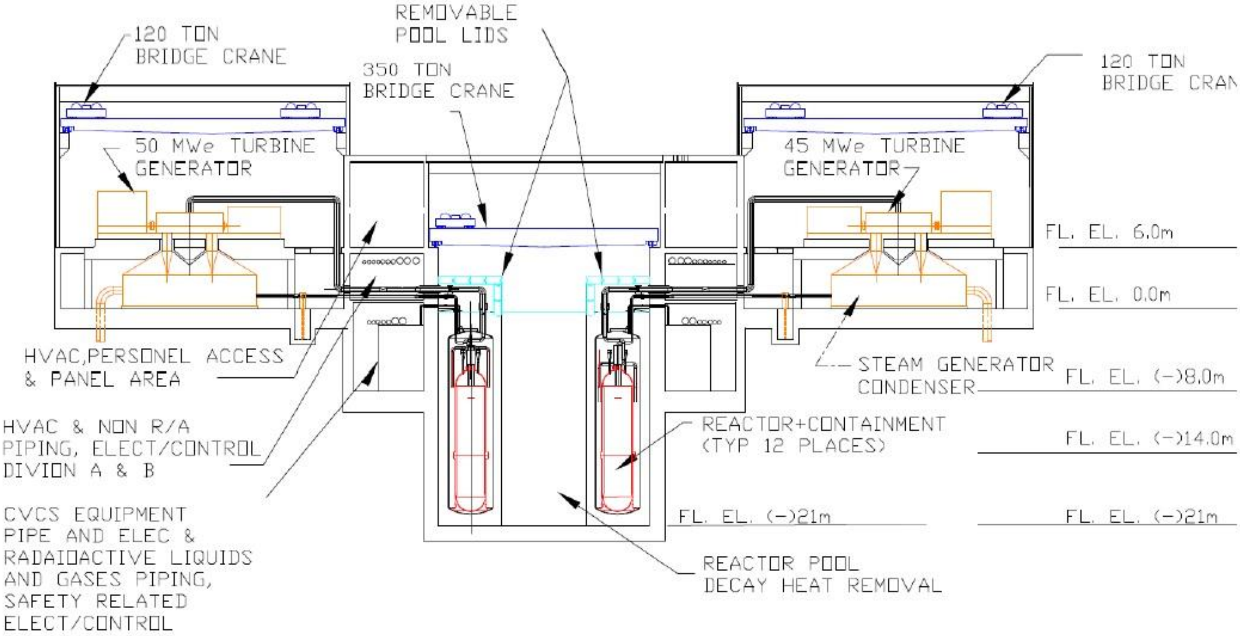
Introduction to Nuscale Design , Dr. José N. Reyes, Jr. Chief Technical Officer, July 24, 2008 and

Nuscale Technology Overview , Dr. Kent Welter, Senior Safety Analysis Manager December 13 2010

Very precise scheme and plant layouts allow us to calculate the 12 modules layout footprint, comparing unknown dimensions to known ones, such as Reactor Containment and BOP Buildings. The scheme is presented in the following picture:



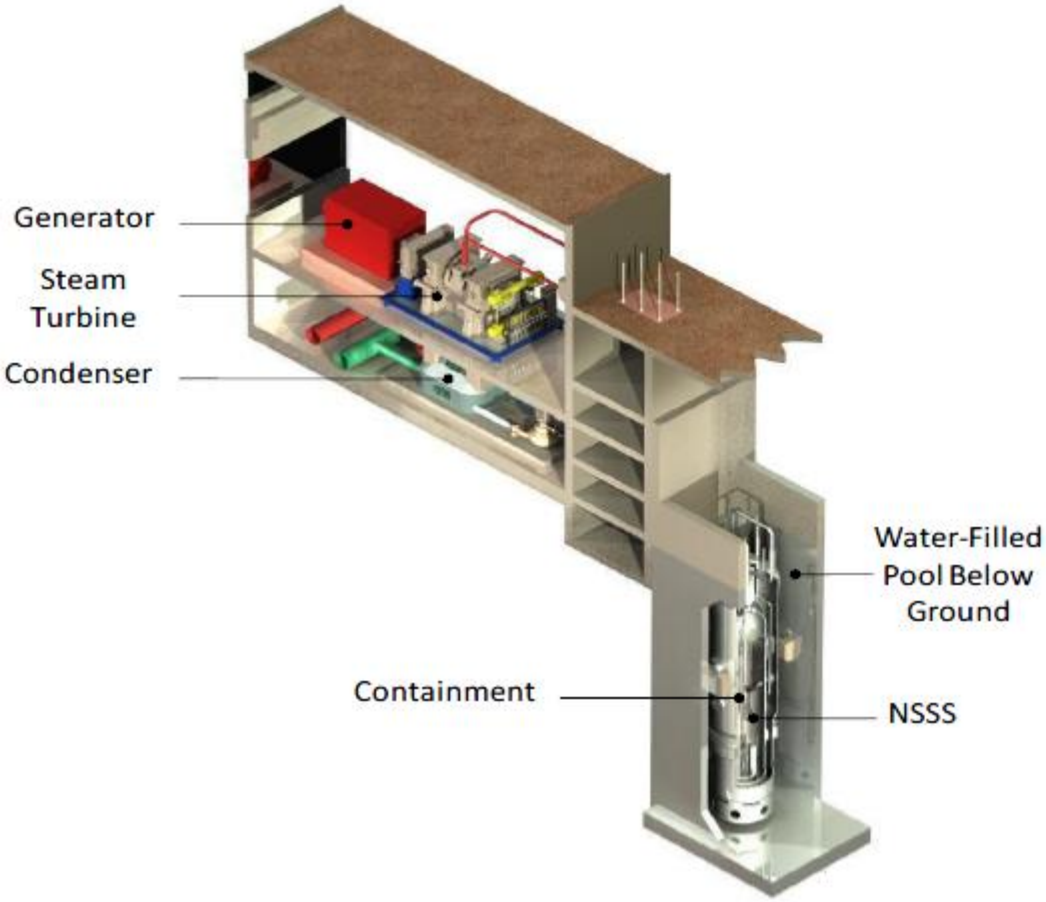
14-1 Nuscale plant layout (12 modules)



14-2 Nuscale plant section

It has been possible to obtain further information through Nuscale project website from which this image is taken.

It shows a single reactor module and its own BOP (Balance Of Plant), stressing the modular reactor configuration.



14-3 Nuscale reactor and BOP

From this image it has been possible to obtain rough information about dimensions of a single Reactor&BOP unit. It must be stressed that, as in all other cases, each reactor in coupled with a single BOP.

14.1.2 MPOWER

All data concerning mPower reactor come from presentations of B&W members, like John Ferrara in this document:

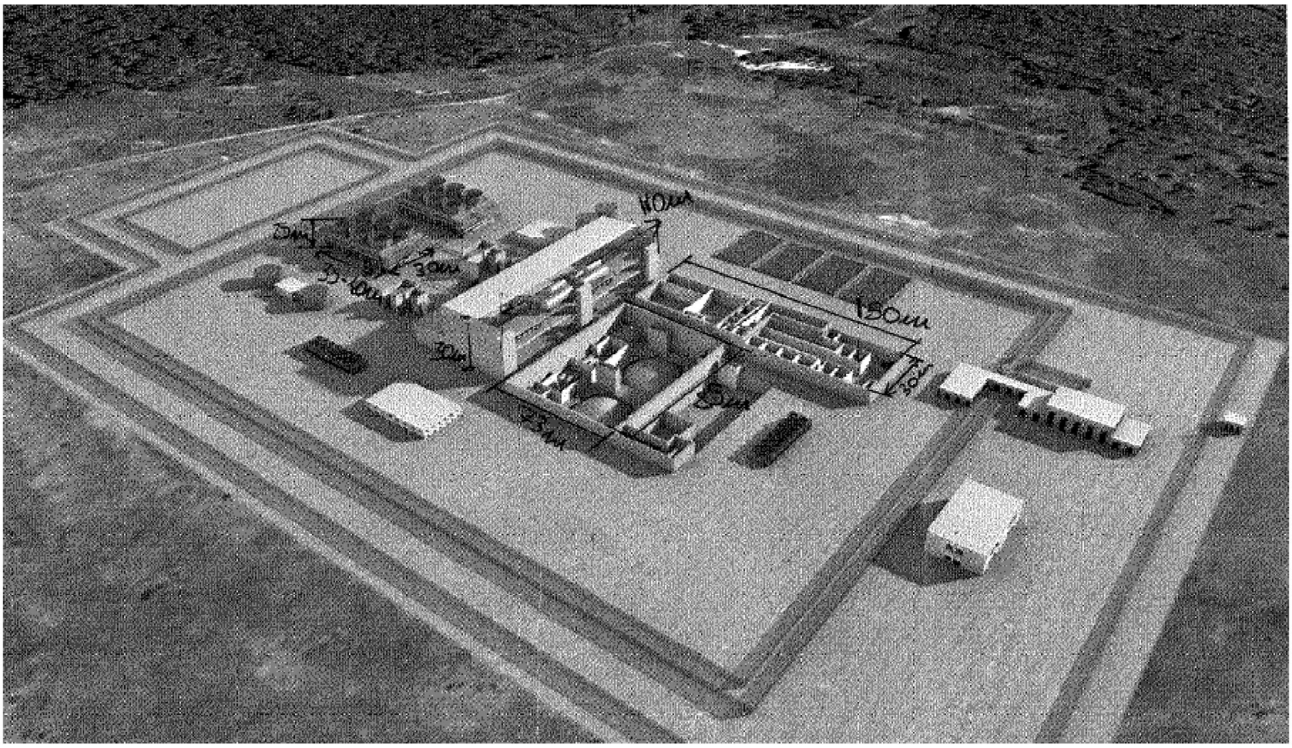
A Novel Approach to Small Modular Light Water Reactors , John Ferrara, Nuclear Power Europe June 8, 2011

In these documents usually there are no precise data regarding dimensions or thermodynamic cycle, but they are focused on providing information about fuel cycle and modularization.

The only known dimensions are the ones of the core and its containment. So a comparison between reactor containment and reactor building let us know plant dimension, especially BOP and reactor buildings ones.

Ferrara’s document estimate the plant footprint, air cooled, to be about 42 acre. Obviously these dimensions should be different in case of water cooling.

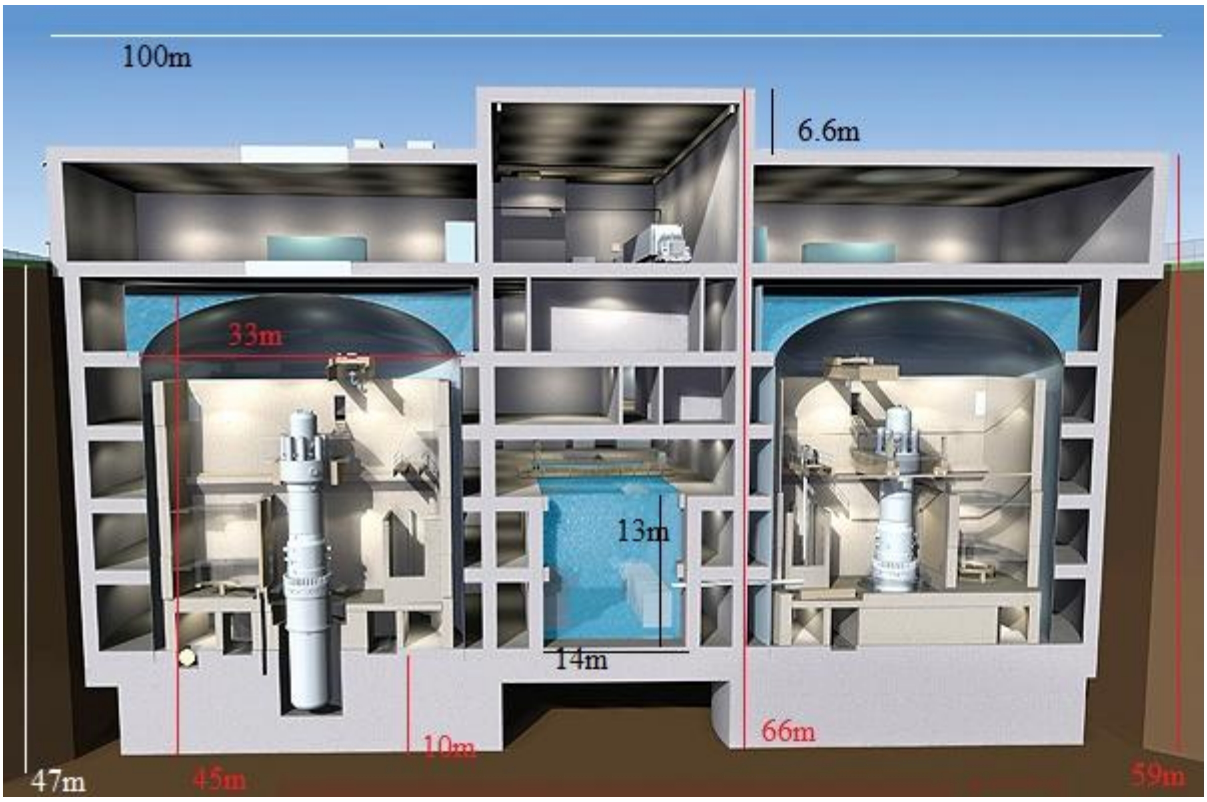
A quoted picture can help us visualizing the situation previously described:



14-4 mPower plant layout showing approximated dimensions

As the reactor is almost entirely built below ground level it is important to evaluate groundwork needed. So, looking at reactor vessel dimensions, we can evaluate necessary excavation depth.

Once again it is important to stress the objective of the work, that is to establish rough dimensions to obtain an order of magnitude of costs and not the exact amount. The following quoted picture shows primary building approximated dimensions:



14-5 mPower twin plant layout approximated dimensions

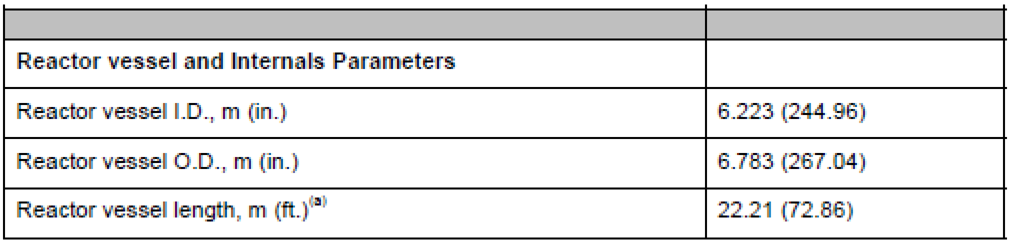
14.1.3 IRIS

We’ve got a lot of information about IRIS plant, thanks to the document:

IRIS Plant Description Document march 21, 2003

Main data are all summarized in this document, from primary to secondary steam cycle.

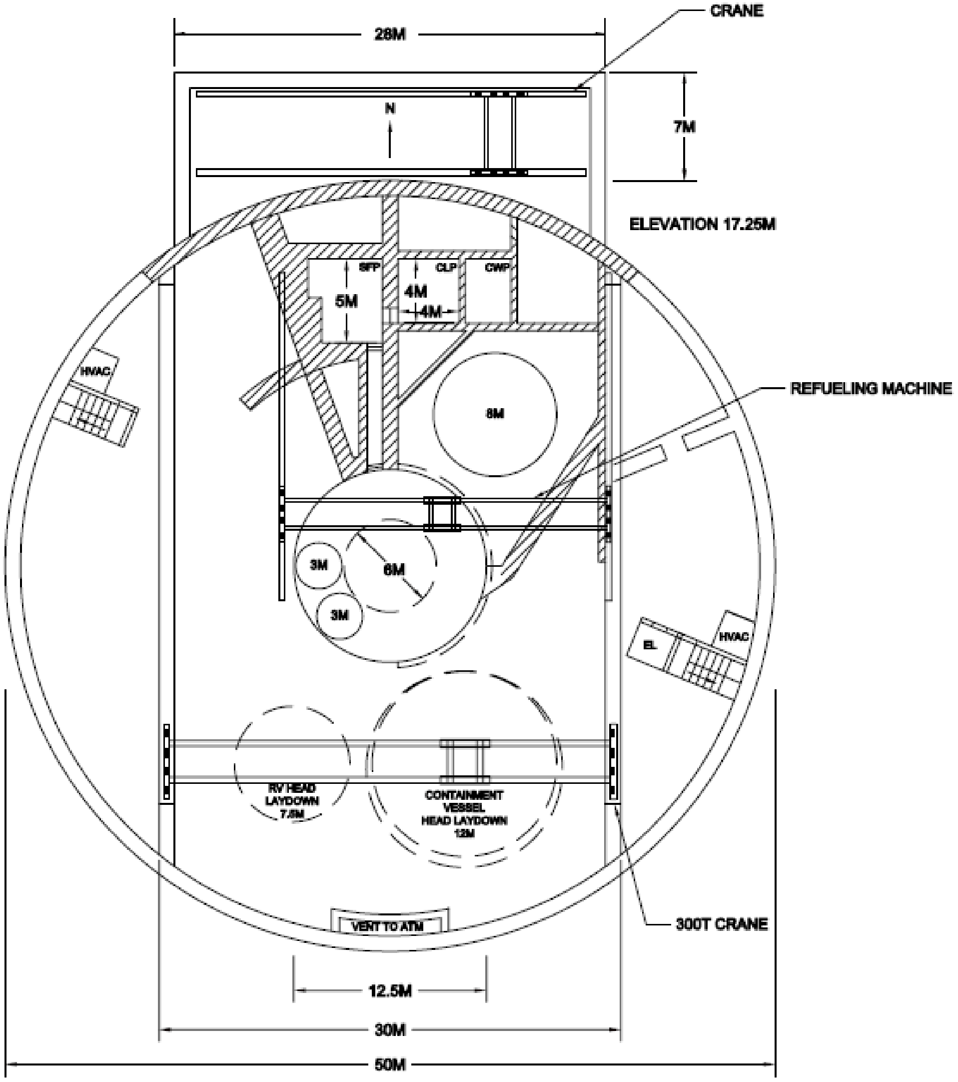
Looking at technical data charts we can obtain core dimension data:



Reactor vessel and Internals Parameters	
Reactor vessel I.D., m (in.)	6.223 (244.96)
Reactor vessel O.D., m (in.)	6.783 (267.04)
Reactor vessel length, m (ft.)[a]	22.21 (72.86)

14-6 Core dimension data

Plant layout sketches give us the possibility to obtain footprint and the location and dimensions of principal buildings, as shown as follows:



14-7 IRIS reactor island plant layout

14.2 MAIN HEAT TRASNPORT SYSTEMS

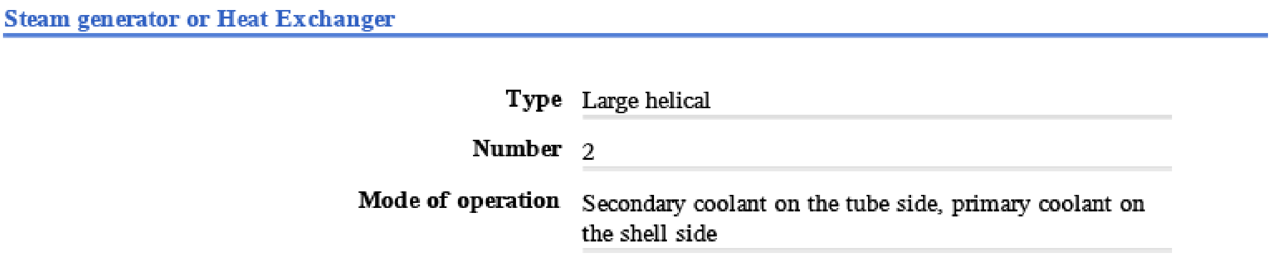
				IRIS	NUSCALE
222	Main Heat Transport System	Includes the initial reactor coolant load, the pressurizing or cover gas system, steam generators (if applicable), the reactor coolant piping system, the fluid drive circulation system (including pumps), heat exchangers, and	SG	5240 tubes, 17,4mm diam, 2,11mm thickness 32m; 1149m^2*8 units 8,5m height	layout porcospino 22,3m height (Two independent tube bundles, secondary coolant in tubes)
			other heat exchanger		
			pumps (valocità)	1600kg,1800rpm,4500kg/s	primary natural circ
			piping & valves	12"-16" lines per SG	

14.2.1 NUSCALE

Once again we can obtain basic information checking the IAEA document:

Status report 106 - NuScale Power Modular and Scalable Reactor (NuScale) – 01-08-2011

SG details are summarized in the following table:



Steam generator or Heat Exchanger

Type	Large helical
Number	2
Mode of operation	Secondary coolant on the tube side, primary coolant on the shell side

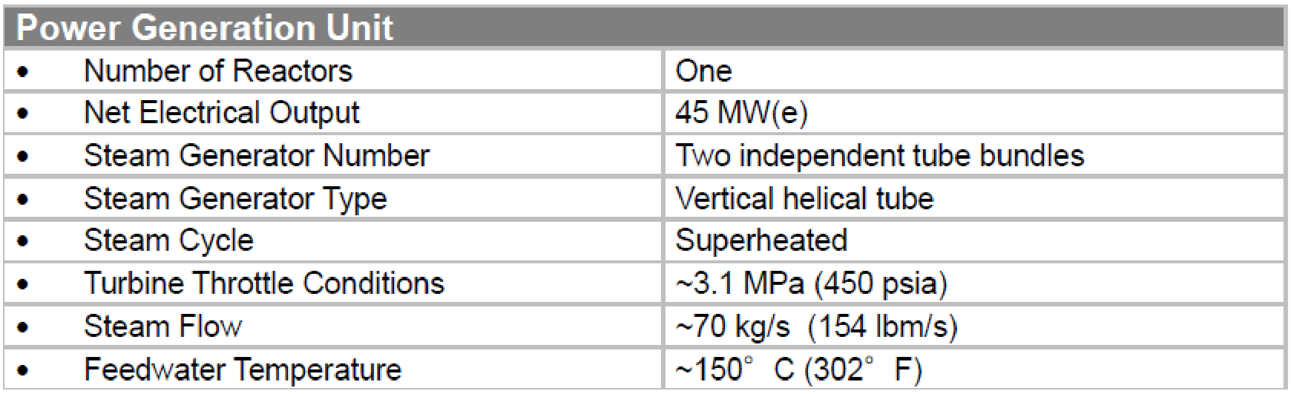
14-8 Nuscale SG data

Thanks to ATB expertise we can suppose a particular SG layout, called “porcupine”, that involves tubes with a spiral layout with different coil diameters, and particular supports.

A brief description of the secondary circuit comes from:

NuScale Technology Overview , Dr. Kent Welter, Senior Safety Analysis Manager December 13 2010

The summarizing chart gives us the following data:



Power Generation Unit	
• Number of Reactors	One
• Net Electrical Output	45 MW(e)
• Steam Generator Number	Two independent tube bundles
• Steam Generator Type	Vertical helical tube
• Steam Cycle	Superheated
• Turbine Throttle Conditions	~3.1 MPa (450 psia)
• Steam Flow	~70 kg/s (154 lbm/s)
• Feedwater Temperature	~150° C (302° F)

14-9 Nuscale secondary side data summary

We just need main data as pressure flow rate and temperature. This is enough to simulate a secondary steam cycle with little overheating, about 30°C, obtaining all data we’re looking for to describe the steam cycle.

14.2.2 MPOWER

All mPower data available about the new B&W project come from these documents:

A Novel Approach to Small Modular Light Water Reactors , John Ferrara, Nuclear Power Europe June 8, 2011

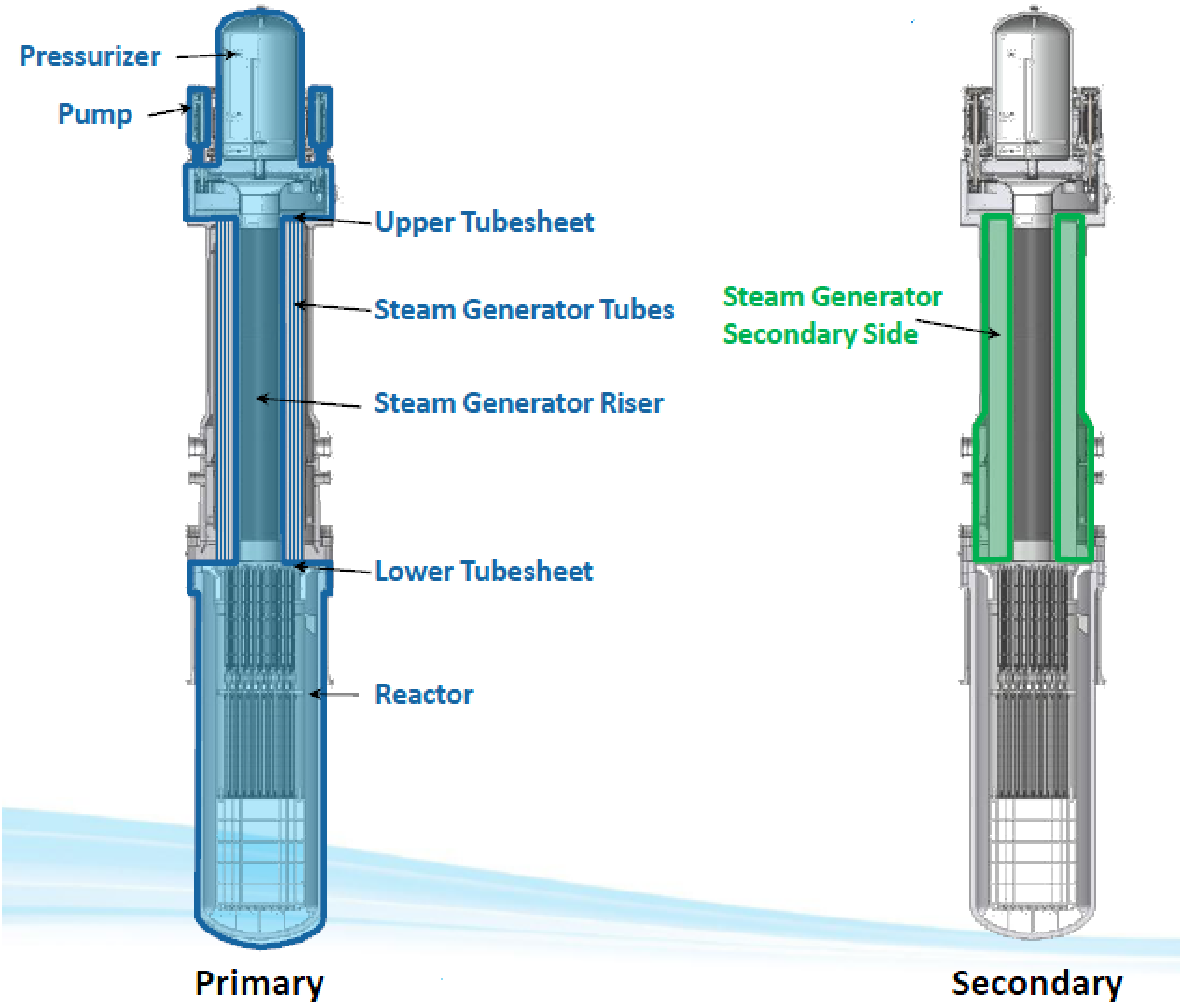
And

Introduction to B&W mPower™ Program, Doug Lee, IAEA Interregional Workshop Vienna, Austria July 7, 2011

These documents contain plant designs that let us obtain SG info thanks to dimension comparison with known elements.

14-10 mPower reactor

A more detailed description of mater and steam flows in mPower reactor can be provided by the following picture:

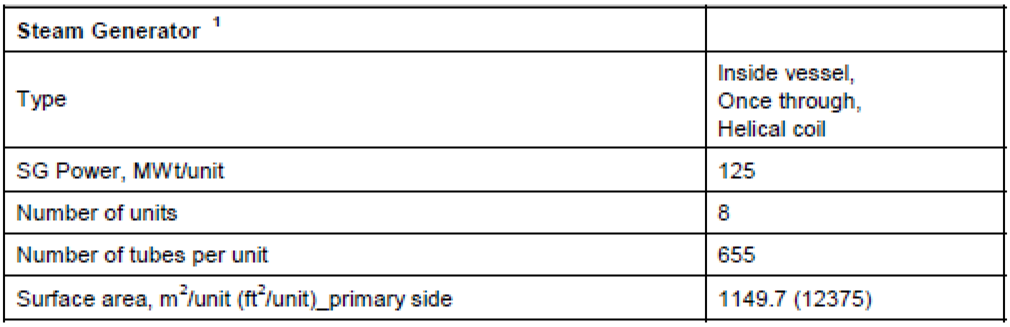


14-11 View of mPower SG and mater and steam flows in the reactor vessel

14.2.3 IRIS

A brief chart summarize the complete heat transport description given in this document:

IRIS Plant Description Document march 21, 2003



Steam Generator [1]	
Type	Inside vessel, Once through, Helical coil
SG Power, MWt/unit	125
Number of units	8
Number of tubes per unit	655
Surface area, m^2/unit (ft^2/unit)_primary side	1149.7 (12375)

14-12 IRIS heat transport system

14.3 SAFETY SYSTEMS

					IRIS	NUSCALE	MPOWER
223	**Safety Systems**	Includes the residual heat removal system, the safety injection system, any containment spray system, the combustible gas control system, and any associated heat exchangers, valves, pumps,					
				Pool	SG make-up tank (58bar), 6 suppression tank+1 for uncondensible (10bar), 2 boron tank 155bar	91x78mx28 H 1,5 thick concrete, 1 atm	
				Heat exch			
				piping	8" 58 bar		
				valves	2x4" motor valves	2 sump+2 vent valves	

14.3.1 NUSCALE

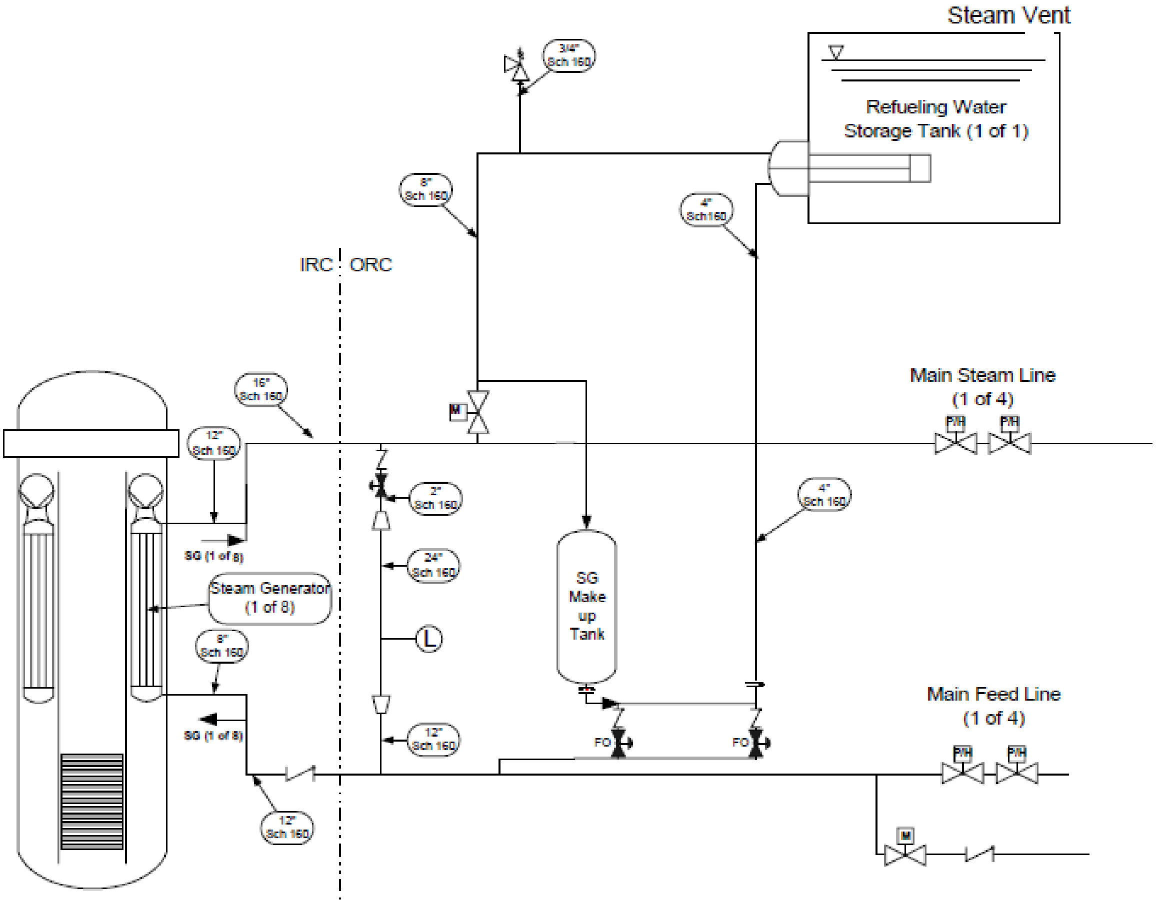
As reported above Nuscale pool data are obtained from a comparison with other design elements, and it appears also as a safety system because of the possibility to use that water as a further cold sink, in case of emergency. It must contain 12 reactors, according to engineers' designs, at atmospheric pressure.

14.3.2 MPOWER

All documents published by Babckock&Wilcox company just report the existence of safety system, passive and active, but without an accurate description. We can at least suppose devices and procedures referring to standard safety measures.

14.3.3 IRIS

The following picture extracted from the document **IRIS Plant Description Document march 21, 2003** describes the IRIS Emergency Heat Removal System:



14-13 Simplified EHRS sketch

Further data (pressure e.g) can be obtained studying the circuit they belong to. For example for a primary injection system we assume pressure equal to the primary one, 15.5MPa.

Piping size is also expressed in the sketch. It is possible to obtain more data thanks to manufacturer expertise, that could provide us further information (piping thickness) starting from operation pressure.

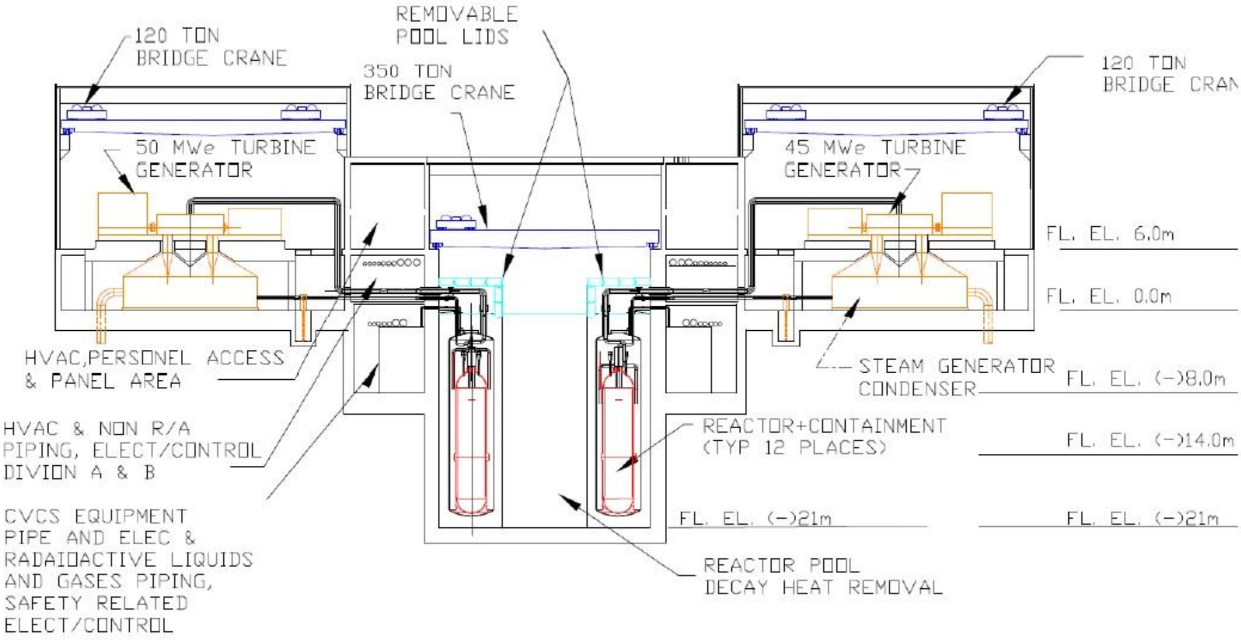
Another important parameter is the total length of that piping, but it is difficult to estimate. Once again manufacturer experience can help us determining this value, even if in a rough way.

14.4 FUEL HANDLING SYSTEMS

				IRIS	NUSCALE	MPOWER
Fuel Handling Systems	Includes fuel handling and storage equipment, such as cranes, fuel handling tools, service platforms, and fuel cleaning and inspection					
			Fuel crane	20m scartam	350 ton (scart ca45m)	25m scart
Other Reactor Plant Equipment	Includes the inert gas system, make-up coolant systems, coolant treatment system, the auxiliary cooling system, maintenance equipment, and sampling equipment.					
			Make up coolant sys	max flow rate 8,52 m^3/s		

14.4.1 NUSCALE

Fuel crane characteristics comes from some design analysis included in the documents quoted above in the passages:



14-14 Nuscale sketch showing cranes characteristics

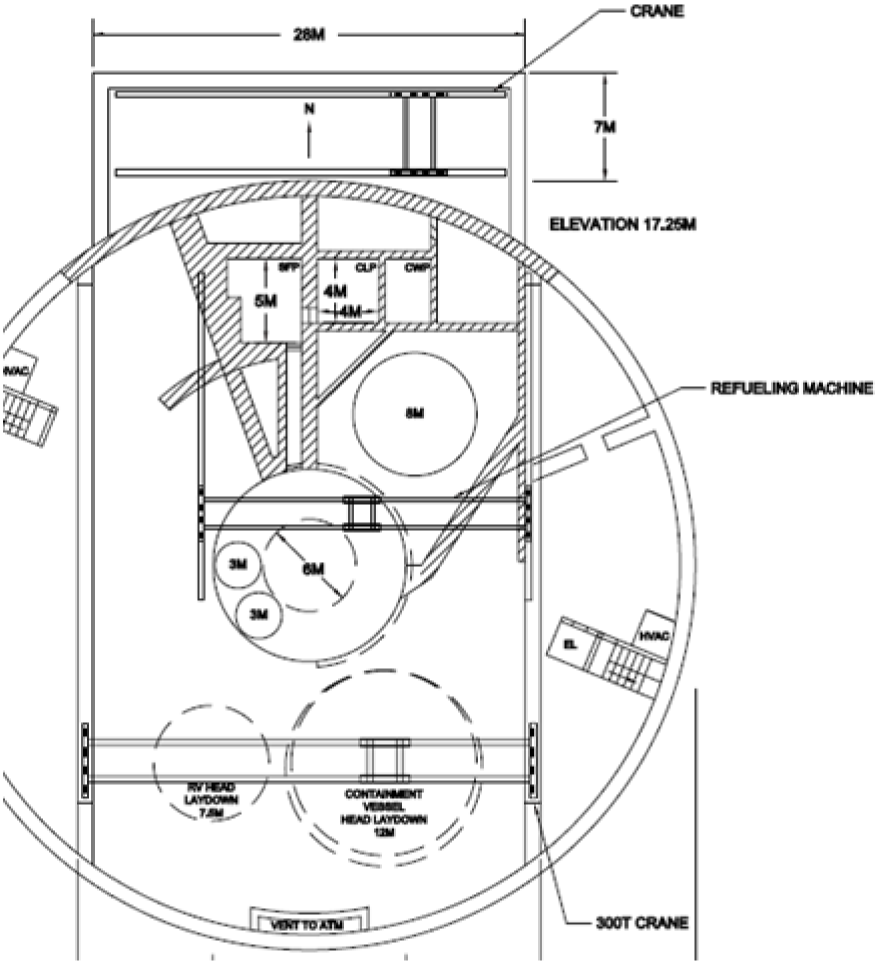
14.4.2 MPOWER

14-15 Cranes in mPower reactor building

This mPower underground containment picture (taken from B&W web-site) let us know crane dimensions (Equal to the internal diameter of the structure). Once again this is a rough evaluation of crane characteristics.

14.4.3 IRIS

Once again from the document quoted above it is possible to extract information about IRIS cranes:



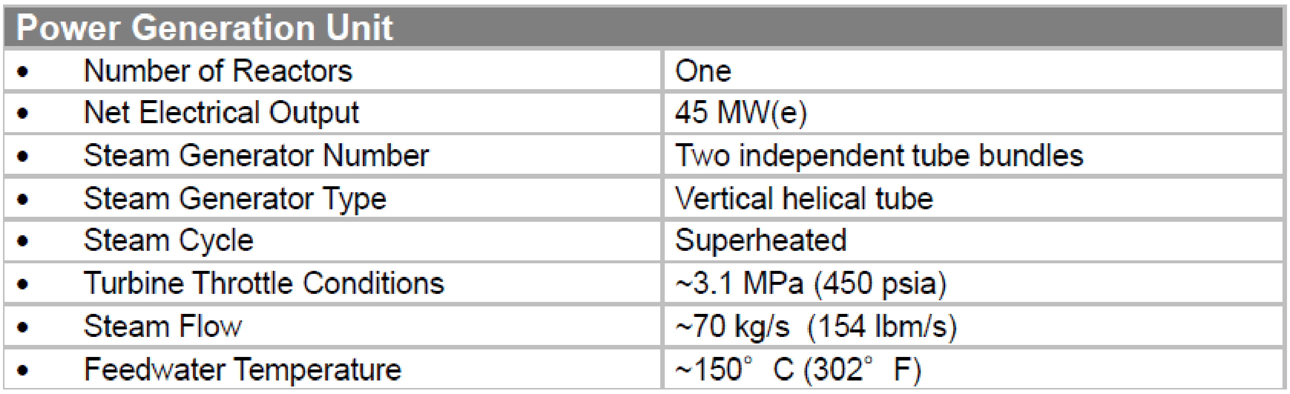
14-16 Sketch showing cranes needed for IRIS project

It is possible to know from this section (Ansaldo-Camozzi tables) fuel crane characteristics (other 2 cranes are visible, but related to material and not fuel handling).

14.5 TURBINE GENERATOR AND CONDENSING SYSTEMS

				IRIS	NUSCALE	MPOWER
231	Turbine Generator	Includes turbine generator plus associated mountings, main steam control and isolation valves, lubrication system, gas systems, moisture separator, and drain system, excitation system, and controls. Main				
			Turbine+valves	300MWe (502kg/s)	45MWe(71,3kg/s; 3,1MPa)	160MWe, 204 kg/s, 5,7 Mpa
233	Condensing	Includes condenser equipment, the				
			Condenser	0,005MPa	about 0,005MPA	about 0,005MPA

14.5.1 NUSCALE



Power Generation Unit	
• Number of Reactors	One
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• Steam Generator Type	Vertical helical tube
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• Turbine Throttle Conditions	~3.1 MPa (450 psia)
• Steam Flow	~70 kg/s (154 lbm/s)
• Feedwater Temperature	~150° C (302° F)

14-17 Summary of steam cycle characteristics

Some secondary circuit characteristics can be found in the Nuscale documents quoted before. All data are precise except for condensing pressure that is supposed equal to one of a standard secondary steam cycle.

14.5.2 MPOWER

Steam condition are determined by a cycle analysis supposing secondary pressure of 5.7 MPa.. This cycle description is simulated in excel format, using TPX add-on.

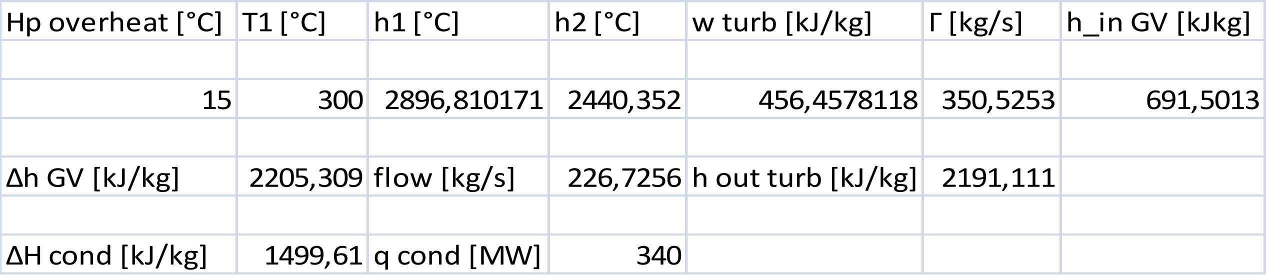
Thanks to these tools we are able to simulate a standard steam cycle, based on a heat source of 500MWth.

Anyway it is necessary to consider different hypothesis about overheating and analyze different steam cycle.

This has been made thanks to a tool providing water and steam properties at given conditions.

It is necessary to impose steam generator inlet and outlet conditions: in a standard steam cycle these can be considered as 160°C as inlet conditions and 300°C as outlet ones while pressure can be considered 5.7MPa.

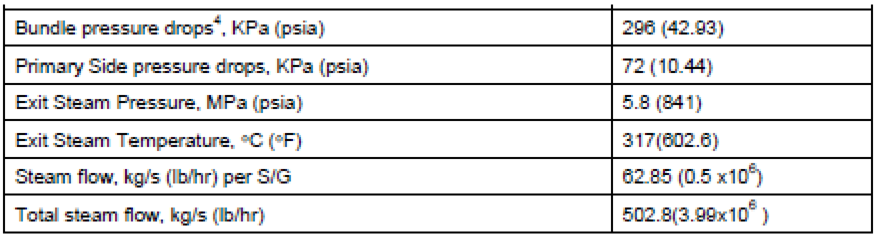
These assumptions provide us the following data:



Hp overheat [°C]	T1 [°C]	h1 [°C]	h2 [°C]	w turb [kJ/kg]	Γ [kg/s]	h_in GV [kJkg]
15	300	2896,810171	2440,352	456,4578118	350,5253	691,5013
Δh GV [kJ/kg]	2205,309	flow [kg/s]	226,7256	h out turb [kJ/kg]	2191,111	
ΔH cond [kJ/kg]	1499,61	q cond [MW]	340			

14-18 mPower steam cycle analysis

14.5.3 IRIS



Bundle pressure drops[4], KPa (psia)	296 (42.93)
Primary Side pressure drops, KPa (psia)	72 (10.44)
Exit Steam Pressure, MPa (psia)	5.8 (841)
Exit Steam Temperature, °C (°F)	317(602.6)
Steam flow, kg/s (lb/hr) per S/G	62.85 (0.5 x10^6)
Total steam flow, kg/s (lb/hr)	502.8(3.99x10^6)

14-19 Summary of steam cycle characteristics concerning IRIS reactor

From this table, included in the document quoted in the paragraph above, we know all secondary circuit data, especially pressure and flow data.