LAPPEENRANTA – LAHTI UNIVERSITY OF TECHNOLOGY

SCHOOL OF ENERGY SYSTEMS

DEGREE PROGRAM IN NUCLEAR ENERGY ENGINEERING

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Data on water cooled small modular reactor and incorporating the benefits of SMRs over conventional large reactor

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ABSTRACT

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Master's Thesis

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Key words : Small modular reactor, Pressurized water reactor, Loss of coolant accident, Emergency planning zone, Desalination, District heating

Goal of this thesis report is to combining data on water cooled SMR design technology and under which condition SMR could be a valid choice over traditional type large reactors. This report consists of 2 parts, where part 1 comprises the literature review on the beneficiary use of SMR by comparing them with large reactor based on economical and other data, part 2 is related to the compilation of design based data of different water cooled advanced reactors those are under construction and in order to the near term deployment. In the literature review part (part 1) NuScale SMR has been taken as identical while comparing the SMRs with the large reactor. In the compilation of the data part CAREM, SMART and ACP100 has been chosen.

ACKNOWLEDGEMENT

It was difficult at the beginning to find the topic, although a lots of reading made me to reach to the goal. Thanks to professor Juhani Hyvärinen and Juhani Vihavainen for their valuable comments while writing my thesis. And last but not the least, thanks to my friend Emad for encouraging me to finish the thesis.

Md Mahadi Hasan

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LIST OF ABBREVIATIONS

COA	Code of account
CRDM	Control rod drive mechanism
CDF	Core damage frequency
CMT	Core make up tank
DOE	Department of energy
DBA	Design basis accident
ESF	Engineered safety features
EPZ	Emergency planning zone
ET	Event tree
ELSMOR	European licensing of Small Modular Reactor
FTA	Fault tree analysis
FOAK	First-Of-A-Kind
GCFR	Gas cooled fast reactor
HLMC	Heavy liquid metal cooled
HTGR	High temperature gas-cooled rector
IAEA	International atomic energy association
LCOE	Levelized cost of electricity
LOCA	Loss of coolant accident
MED	Multi-effect distillation (MED)
MSF	Multi-stage flash distillation (MSF)
NOAK	Nth-Of-A-Kind
PRA	Probabilistic risk assessment
PDHRS	Passive decay heat removal system
RPV	Reactor pressure vessel
RO	Reverse Osmosis (RO)
REA	Rod ejection accident
SMR	Small modular reactor
SIT	Safety injection tank

1. INTRODUCTION

With the increasing number of global population, as all the basic needs are rising, the demand for clean energy supply is also sky rocketing, because the mitigation of the basic needs are somehow correlated with the energy supply. 7 billion of the world current population is expected to rise by more 2 billion within next 30 years, which might result in doubling the electricity consumption (Vujić et al, 2012). In order to supply such a growing energy demand we need to look forward to all the different energy resources we have besides fossil fuels. But at the same time we can not compromise the climate change due to carbon emission through industrial process. Exactly where the nuclear energy comes into place and plays a vital role.

During the past decades nuclear energy has been used as a clean source to produce electricity. Although different sized of power reactors are used to fulfill the current 11% of total global electricity demand (World Nuclear Association, 2019). , this paper has been written particularly focusing on small modular reactor (SMR). Considering the current state of global environment change due to carbon and other green house gas emission SMR can be the most promising technology. Even though there is renewable energy, it can not compete with the growing electricity demand. Whereas, uranium being the main compound of nuclear electric power is more abundant and enough to power up the world for the next two hundred years if all of them are mined (Fetter, 2019)

Reactors those are of 300 MWe equivalent or less is called SMR. So, generally, SMRs can be of different power shaped between 60 mega watt output to 300 mega watt output, although very few reactors are powered less than 50 MWe (World Nuclear Association, 2019). After the range of SMR reactors, from 300 MWe to 700 MWe are known as medium sized reactors. And eventually bigger than 700 mega watt output power are categorized as large reactors (Locatelli et al, 2014). Compared to medium and large sized reactors SMRs are more compact in design, advanced technology, reliable to safety system and environment friendly. Moreover, SMRs are more economically viable requiring little investment cost and it can be carried from one place to another depending on the size of the reactor. More than one unit can be deployed in one site in order to meet the requirements. Currently a good number of SMRs are under development and on near term deployment stage, which will be discussed in the later part of the report.

The later part of the report, in a nutshell, consists of different parts where classification of different SMR design technology, importance of SMRs beside conventional nuclear power plant is discussed. Moreover, the economic viability of SMRs, some specific use of SMRs has been noted in the report.

2. CLASSIFICATION OF SMALL MODULAR REACTOR

Fifty different designs of SMRs have been proposed so far, where some of them are under construction, some are under development in recent years. Among them three major designs bear the advanced technology, acquainted as CAREM in Argentina, HTR-PM in China and KLT40s in Russia, importantly all of these three design are under construction and in immediate deployable situation as shown in figure 1. Also in the USA some designs are on the improvement stage, named as B&W mPower, NuScale, Westinghouse SMR and SMR-160 . All these fifty designs lie as a sub category under four main categories, such as Water cooled SMRs, High temperature gas cooled SMRs, Fast neutron spectrum SMRs and Molten salt SMRs.

Table 1 : Classification of SMRs (IAEA,2018).

Design	Output MW(e)	Type	Designers	Country	Status
PART 1: WATER COOLED SMALL MODULAR REACTORS (LAND BASED)					
CAREM	30	PWR	CNEA	Argentina	Under construction
ACP100	100	PWR	CNNC	China	Basic Design
CAP200	150/200	PWR	CGNPC	China	Conceptual Design
DHR400	(District Heating)	LWR(pool type)	CNNC	China	Basic Design
IRIS	335	PWR	IRIS Consortium	Multiple Countries	Conceptual Design
DMS	300	BWR	Hitachi GE	Japan	Basic Design
IMR	350	PWR	MHI	Japan	Conceptual Design
SMART	100	PWR	KAERI	Republic of Korea	Certified Design
ELENA	68 kW(e)	PWR	National Research Centre "Kurchatov Institute"	Russian Federation	Conceptual Design
KARAT-45/100	45/100	BWR	NIKIET	Russian Federation	Conceptual Design
RITM-200	50 × 2	PWR	OKBM Afrikantov	Russian Federation	Under Development
RUTA-70	70 MW(t)	PWR	NIKIET	Russian Federation	Conceptual Design
UNITHERM	6.6	PWR	NIKIET	Russian Federation	Conceptual Design
VK-300	250	BWR	NIKIET	Russian Federation	Detailed Design
UK-SMR	443	PWR	Rolls-Royce and Partners	United Kingdom	Mature Concept
mPower	195 × 2	PWR	BWX Technologies	United States of America	Under Development
NuScale	50 × 12	PWR	NuScale Power	United States of America	Under Development
SMR-160	160	PWR	Holtec International	United States of America	Preliminary Design
W-SMR	225	PWR	Westinghouse	United States of America	Conceptual Design

PART 2: WATER COOLED SMALL MODULAR REACTORS (MARINE BASED)					
ACPR50S	60	PWR	CGNPC	China	Preliminary Design
ABV-6E	6-9	Floating PWR	OKBM Afrikantov	Russian Federation	Final design
KLT-40S	70	Floating PWR	OKBM Afrikantov	Russian Federation	Under construction
RITM-200M	50 × 2	Floating PWR	OKBM Afrikantov	Russian Federation	Under Development
SHELF	6.4	Immersed NPP	NIKIET	Russian Federation	Detailed Design
VBER-300	325	Floating NPP	OKBM Afrikantov	Russian Federation	Licensing Stage

PART 3: HIGH TEMPERATURE GAS COOLED SMALL MODULAR REACTORS					
HTR-PM	210	HTGR	INET, Tsinghua University	China	Under Construction
GTHTR300	300	HTGR	JAEA	Japan	Basic Design
GT-MHR	285	HTGR	OKBM Afrikantov	Russian Federation	Preliminary Design
MHR-T	205.5x4	HTGR	OKBM Afrikantov	Russian Federation	Conceptual Design
MHR-100	25 – 87	HTGR	OKBM Afrikantov	Russian Federation	Conceptual Design
A-HTR-100	50	HTGR	Eskom Holdings SOC Ltd.	South Africa	Conceptual Design
HTMR-100	35	HTGR	Steenkampskraal Thorium Limited	South Africa	Conceptual Design
PBMR-400	165	HTGR	PBMR SOC Ltd	South Africa	Preliminary Design
SC-HTGR	272	HTGR	AREVA	United States of America	Conceptual Design
Xe-100	35	HTGR	X-energy LLC	United States of America	Conceptual Design

PART 4: FAST NEUTRON SPECTRUM SMALL MODULAR REACTORS					
4S	10	LMFR	Toshiba Corporation	Japan	Detailed Design
LFR-AS-200	200	LMFR	Hydromine Nuclear Energy	Luxembourg	Preliminary Design
LFR-TL-X	5~20	LMFR	Hydromine Nuclear Energy	Luxembourg	Conceptual Design
BREST-OD-300	300	LMFR	NIKIET	Russian Federation	Detailed Design
SVBR-100	100	LMFR	JSC AKME Engineering	Russian Federation	Detailed Design
SEALER	3	Small Lead Cooled	LeadCold	Sweden	Conceptual Design
EM^2	265	GMFR	General Atomics	United States of America	Conceptual Design
SUPERSTAR	120	LMFR	Argonne National Laboratory	United States of America	Conceptual Design
WLFR	450	LFR	Westinghouse	United States of America	Conceptual Design
PART 5: MOLTEN SALT SMALL MODULAR REACTORS					
IMSR	190	MSR	Terrestrial Energy	Canada	Basic Design
CMSR	100-115	MSR	Seaborg Technologies	Denmark	Conceptual Design
CA Waste Burner	20	MSR	Copenhagen Atomics	Denmark	Conceptual Design
ThorCon	250	MSR	Martingale	International Consortium	Basic Design
FUJI	200	MSR	International Thorium Molten-Salt Forum: ITMSF	Japan	Experimental Phase
Stable Salt Reactor	37.5×8	MSR	Moltex Energy	United Kingdom	Conceptual Design
Stable Salt Reactor	300~900	MSR	Moltex Energy	United Kingdom	Pre-Conceptual Design
LFTR	250	MSR	Flibe Energy	United States of America	Conceptual Design
Mk1 PB-FHR	100	MSR	University of California, Berkeley	United States of America	Pre-Conceptual Design
MCSFR	50	MSR	Elysium Industries	USA and Canada	Conceptual Design

Land based water cooled SMRs are the most common type of nuclear reactor presenting integral pressurized water reactor (iPWR). There is also similar integral pressurized water reactor which can be used as a submarine. High temperature gas cooled SMRs written as HTGR as an abbreviated form. HTGR generates high temperature heat (>750°C), useful in electricity production, several industrial applications as well as in CHP plant. Fast neutron spectrum reactors are named differently according to their coolant. Coolant those are used are sodium cooled fast reactor (SFR), heavy liquid metal cooled (HLMC), gas- cooled fast reactor (GCFR) . Molten salt reactors are advanced reactor technology, where liquid stable salt and uranium mixture is used as fuel.

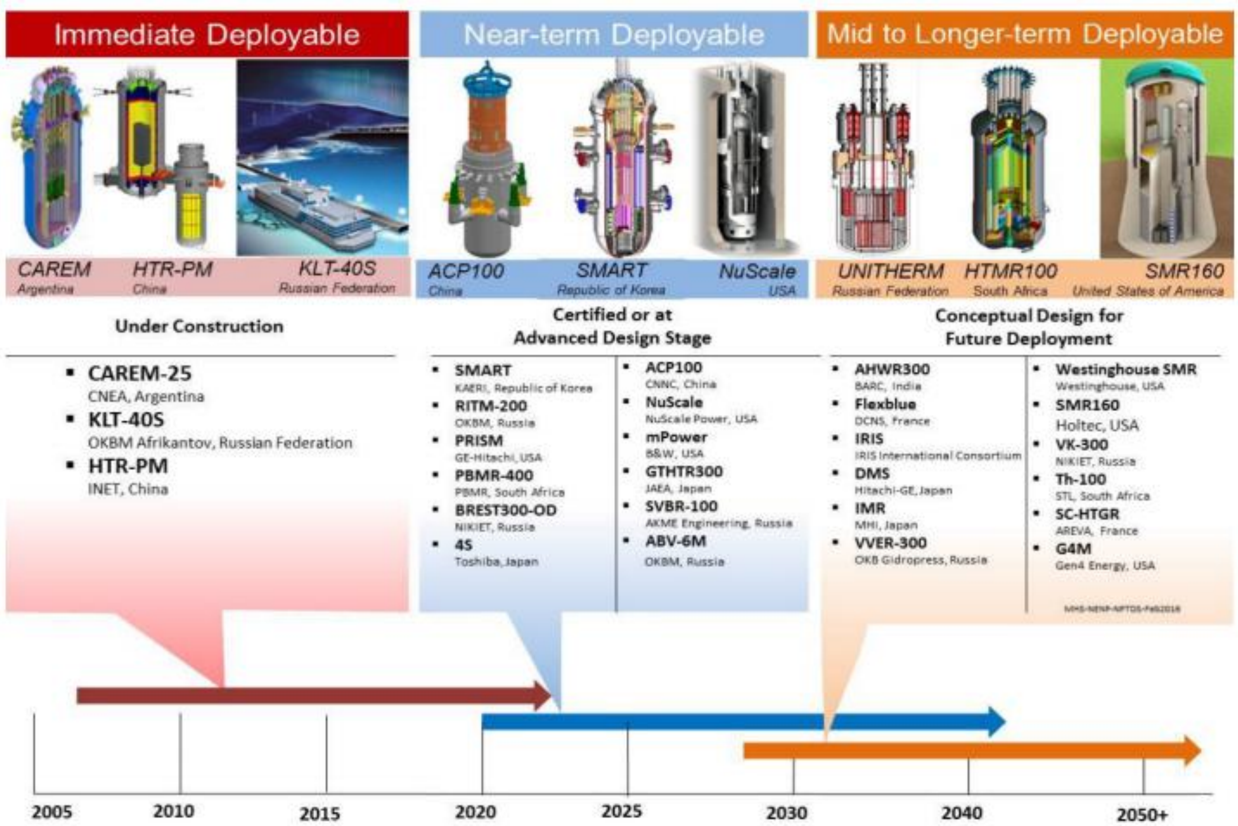

Figure 1 : Estimated timetable for the deployment of SMRs by IAEA

3. IMPORTANCE OF SMR OVER LARGE REACTOR

SMR can mitigate some significant demand over conventional nuclear power plant because of their relatively small size, modular concept, enhanced safety, economic viability and low construction time. Below some details have been provided.

3.1 COMPACT DESIGN AND EASY TRANSPORTATION

Besides being small in size, main design difference between conventional rector and SMRs are the piping system between the core and steam generator, as well as between the core and pressurizer. Such long piping systems of large reactors are eliminated in SMRs, as the modularity by itself means compact design, where the main components will be build in a factory and assembled on the site. (Carelli et al, 2005). Below a figure describing the design difference between a general PWR and IRIS (SMR) has been given.

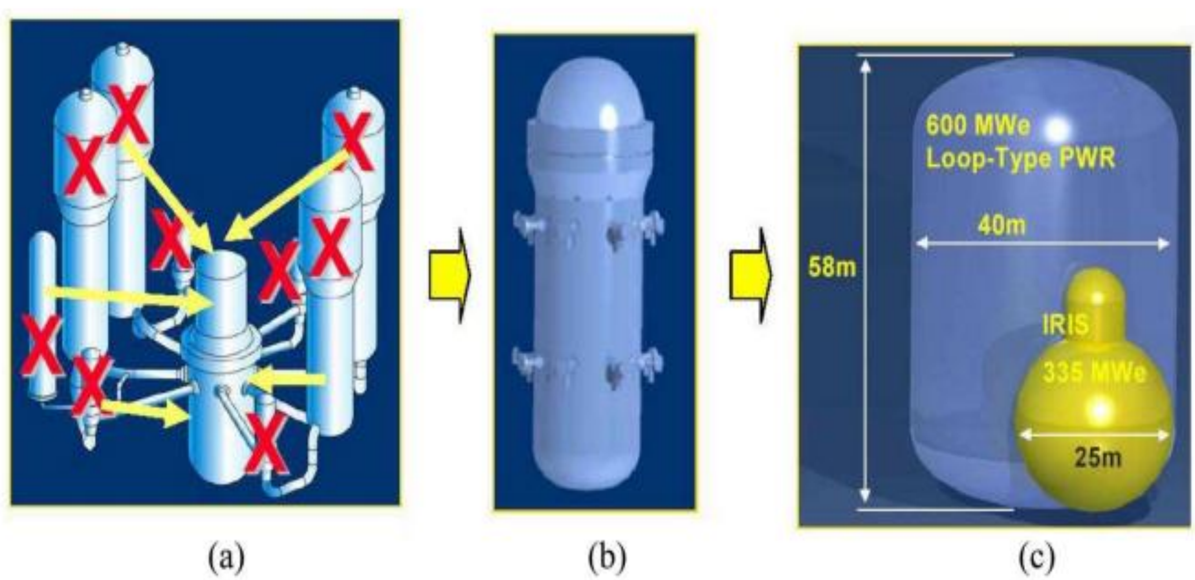

Figure 2 : Design comparison between large PWR and small PWR (SMR) (Carelli et al, 2005).

In the above figure, option (a) depicts that all the piping systems of PWR can be eliminated by integrating the primary components (steam generator, pressurizer) into one single vessel. And that one particular vessel of SMR is showed in option (b). Option (c) has shown the total containment size.

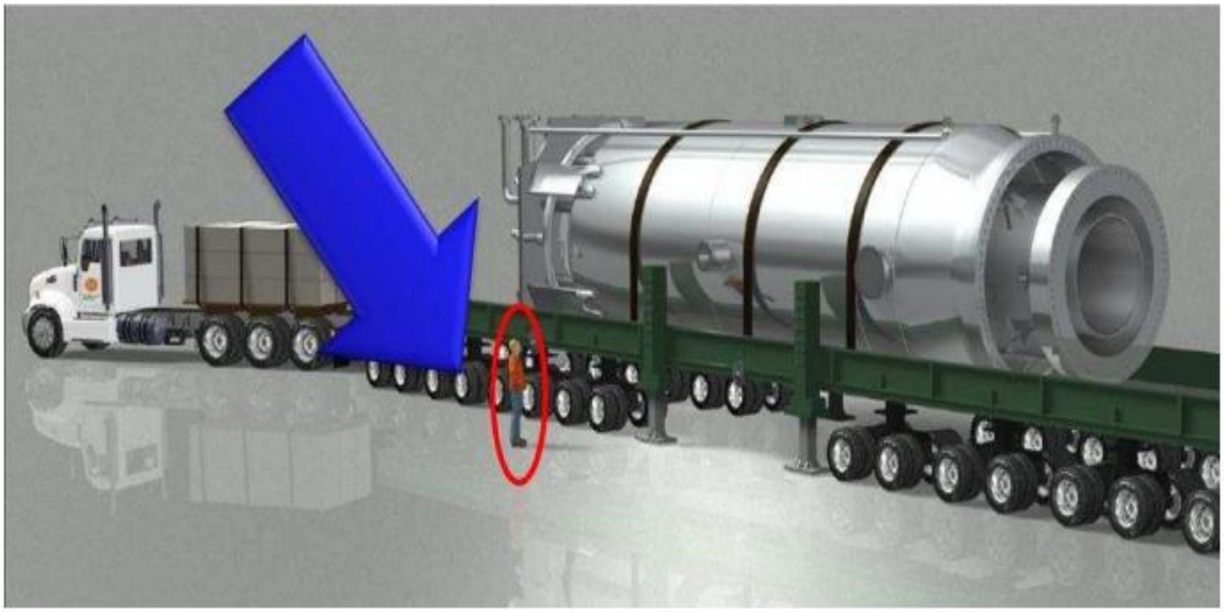

Figure 3: Transportation of NuScale (45 MWe) SMR reactor vessel (Locatelli et al, 2014).

Figure 3 shows transportation facility of an SMR reactor vessel from factory to site with a large truck.

3.2 ELIMINATION OF ROD EJECTION ACCIDENT (REA)

After reactor has been operated in one fuel cycle it is needed to shut down safely in order to change the fuel elements. Safety Shut down is also needed in any kind of emergency situation. This shut down process is carried out by inserting the control rods which is made of neutron absorbing material such as boron. Mechanism that plays the role during insertion of control rods is called control rod drive mechanism (CRDM). In conventional nuclear power plant this CRDM is placed outside the pressure vessel, either on top (PWR) or bottom (BWR) of the reactor. This kind of CRDM is prone to face rod ejection accident (REA) because of rupture of the pressure housing supporting the shaft of the control rods, which results in small break LOCA. In SMRs CRDM is placed inside the reactor pressure vessel which will prevent REA (Ishida et al, 2001).

3.3 LOW CONSTRUCTION TIME AND LOW COST

Forbes magazine has nicely pointed out the necessity of SMRs against traditional nuclear power plants, where they focused particularly on lengthy construction time of the traditional one which may take up to several years to decades (Cohen, 2019). In various cases the construction time is delayed due to technical difficulties which may results in more cost penalty. For example, third reactor in Olkiluoto nuclear power plant in Finland postponed it's operation since 2009 and as a result construction cost has now risen up by three times more than the estimated (Koistinen, 2019).

In case of SMRs, construction difficulties of conventional nuclear power plant can be eliminated, and the reason is similar to above as discussed of simpler design.

3.4 ACCIDENT MITIGATION SYSTEM

3.4.1 Reducing the risk of LOCA event

Safety gets the utmost priority in almost any kind of industrial work, and when it's about the field of energy, specially nuclear energy, safety is the first and foremost thing that is taken into consideration. Three accident scenarios in the past known as Three Mile Island (TMI 1979), Chernobyl 1986 and Fukushima Daiichi 2011 brought this term to a further step forward to concern. Design oriented accident in large water reactor (LWR) known as LOCA can be eliminated in SMR, specially in an integral pressurized water reactor (iPWR), since the pipelines associated with LOCA have been removed (Black et al, 2019). Considering LOCA event two types of cooling safety system is incorporated in a nuclear power plant, such as active safety system and passive safety system, although none of them came to work at the time of Fukushima Daiichi accident in March, 2011 in Japan. That accident was not a result of LOCA but natural calamities called earthquake and tsunami took over the active safety system and gradually disabled the passive safety system. Such an accident brought a concern to rethink about the safety issue and to develop an advance modular design of nuclear reactor (IAEA, 2016).

3.4.2 Small emergency planning zone (EPZ)

Emergency planning zone (EPZ) correspondence to the area under which immediate action is taken due to any emergency situation such as an accident. Generally, two types of EPZ is taken into consideration while planning a plant site, namely as Plume Exposure Pathway and Ingestion Exposure pathway (Nuscalepower, 2019). Plume Exposure Pathway take care of any release of radioactive material from the plant so that is can be minimized within the boundary of 10 miles for the conventional reactor. Necessary action those are taken care of within that boundary includes sheltering, evacuation and use of potassium iodide if necessary. On the other hand Ingestion Exposure pathway measures the area within which the contamination of food or any natural substances can be reduced due to exposure from the plant and put a restriction from eating or drinking within that area. For a traditional nuclear reactor Ingestion Exposure pathway is measured as 50 miles (Nuscalepower, 2019). Figure 4 shows describes the phenomena more clearly.

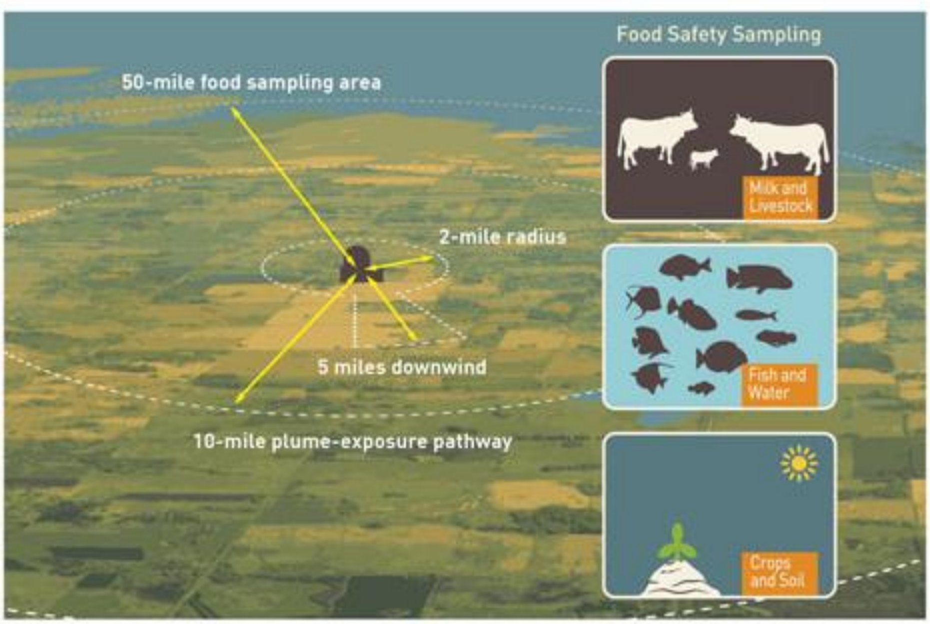

Figure 4 : EPZ of a conventional nuclear power plant (Nrc, 2019).

Smaller EPZ might be beneficiary to an unavoidable event that happened in Fukushima Daiichi accident. Obviously, SMRs have smaller EPZ compared to large conventional nuclear reactor

(Zabielski, 2018). As shown in figure 5 below, emergency planning area of a NuScale SMR is 40 acres, which is much smaller than the conventional nuclear power plant.

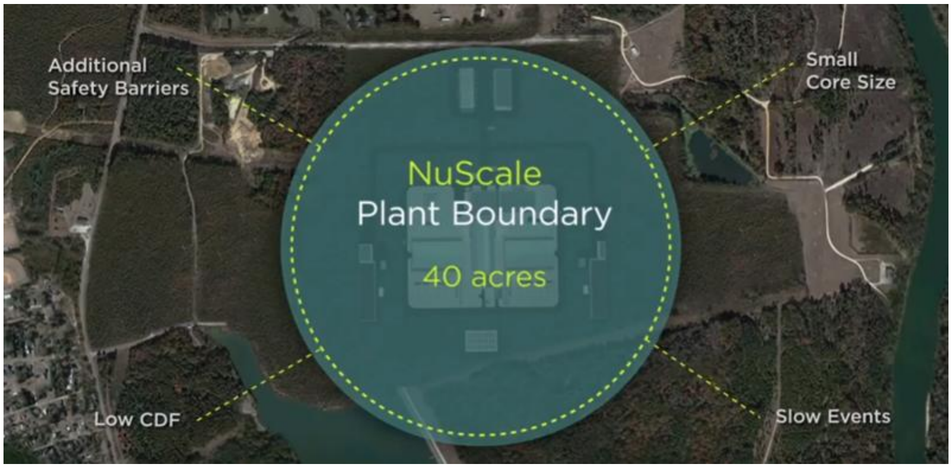

Figure 5 : Emergency planning area of a NuScale comprising of small core size, low CDF (Nrc, 2019).

3.4.2 Low core damage frequency (CDF)

All the safety features of a nuclear reactor is established on a mission to keep the reactor core cooled that prevents any melt down of the fuel material, which in result prevents any release of the radioactive material. Probabilistic risk assessment (PRA) is the term that measures any probable risk that may cause damage to the reactor core by calculating core damage frequency (CDF). A lower core damage frequency is always expected since a lower CDF means lower chance of core damage in the future. Definitely, an SMR has lower core damage frequency than a traditional large reactor. As an example of lower CDF of SMR is given on the above figure 5 for NuScale, which is one occurrence per module in every three billion years (*Nrc, 2019).*

Several steps are followed in order to calculate seismic PRA. All the steps related to PRA is given as follows as a step by step and also as a flow chart on figure 6,

- Gathering data on earthquakes and previous accident events
- Seismic hazard evaluation

- Fragility evaluation
- Accident sequence evaluation
- Documentation

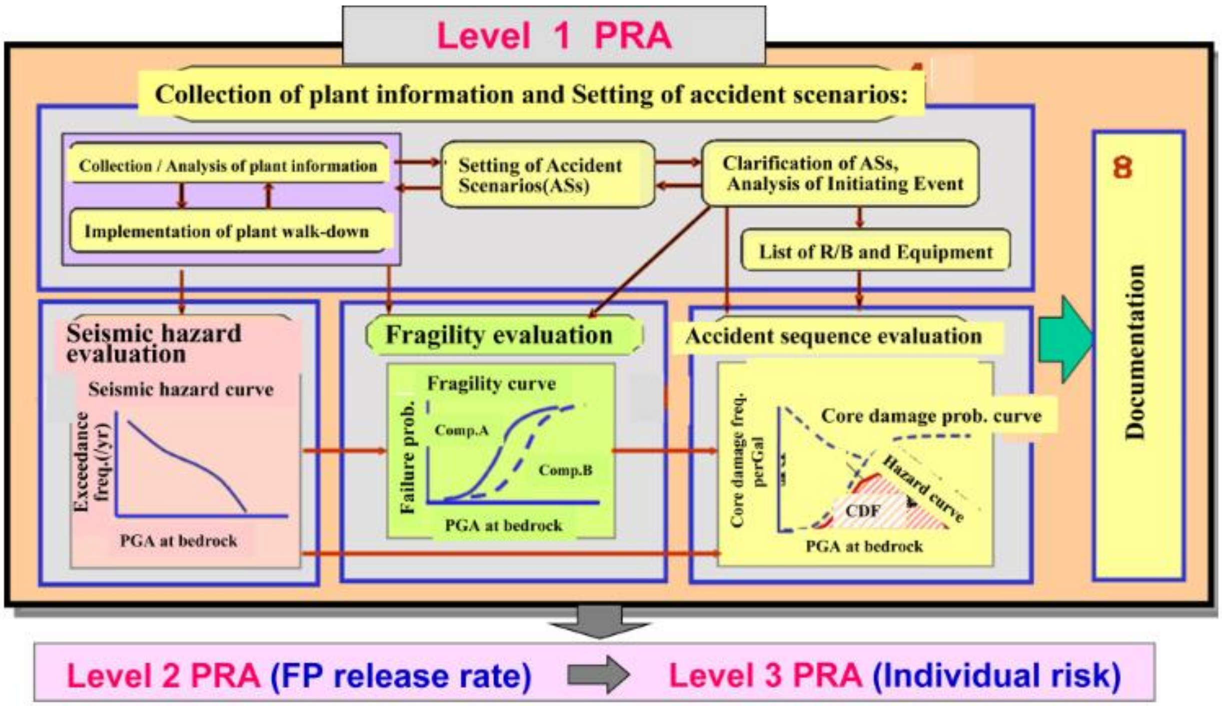

Figure 6 : Flow chart of seismic probabilistic risk assessment

4. ECONOMICAL ASPECTS OF SMR VS LARGE REACTOR

Since SMRs have not come to in commercial operation yet, economical viability of these type of reactor is still uncertain. The earliest studies show that LCOE of SMRs could be higher than the large reactor. But according to recent study SMRs could be even cheaper. Below overview of both the study has been summarized.

4.1 LEVELIZED COST OF ELECTRICITY (LCOE) ANALYSIS

Lokhov et al in their research in 2013, has nicely depicted a general overview of SMRs in terms of economy. Levelized cost of electricity (LCOE) is the key indicating factor that determines the cost of electricity production. LCOE is the ratio of total life cycle cost to the total lifetime energy production of a plant, whereas life cycle cost depends on capital cost, operation and maintaining cost, fuel cost and decommissioning. The leading factor to the LCOE is the investment/capital cost. According to Lokhov et al LCOE of SMR is higher compared to large reactor, since smaller parts are more expensive to buy.

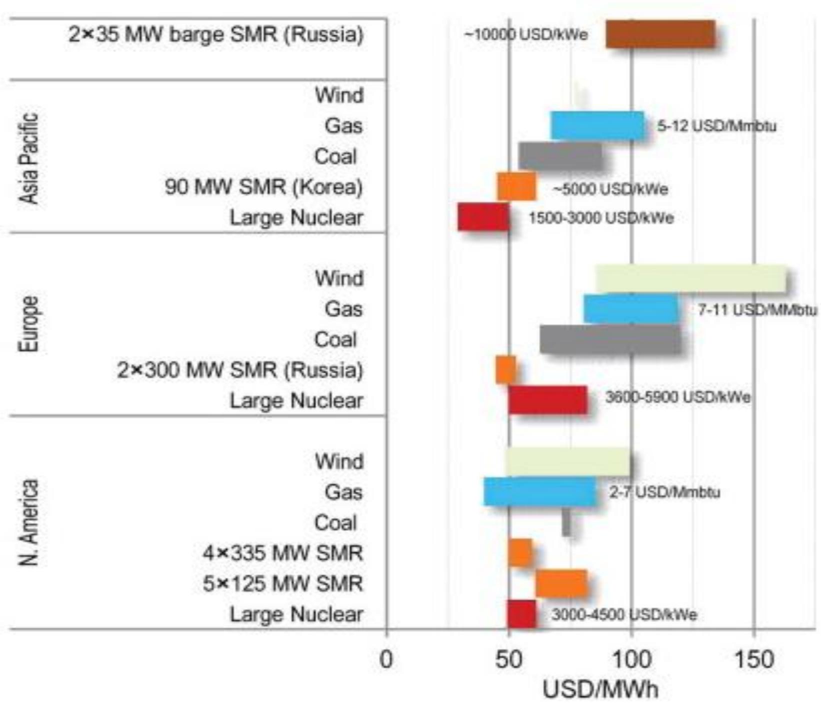

Figure 7 : Comparison of LCOE of SMRs and other energy sources (with 5% discount rate) (Lokhov et al, 2013).

From the above figure we can see that with 5% discount rate LCOE in SMRs is higher than large nuclear reactors but comparatively smaller than other energy sources. LCOE also depends on the discount rate. If the discount rate is small, LCOE is also small. And vice versa. Discount rate is used in LCOE calculation which determines the future value of something at present time. A table below will describe this discount rate phenomena more precisely.

Table 2 : LCOE according to discount rate(Lyndon G et al,2016)

	Coal[8]		Nuclear[9]		Natural Gas[10]	
Discount Rate	Median ($/MWH)	Range ($/MWH)	Median ($/MWH)	Range ($/MWH)	Median ($/MWH)	Range ($/MWH)
3%	75	65.31-94.81	55	25.59-64.38	98	60.84-133.21
7%	82	75.53-107.42	82	37.23-100.75	103	65.95-138.42
10%	95	81.57-119.25	115	48.83-135.72	108	70.62-143.07

According to table 2 LCOE is relatively low in Nuclear power while the discount rate is low (3%). As the discount rate increases future cost of electricity of Nuclear power dramatically increases than the other power options.

4.2 CODE OF ACCOUNT APPROACH (COA)

Black et al in their research in 2019 described how SMRs could be economically more viable than the large reactors. A comparison of construction cost calculation between NuScale SMR and larger reactor (PWR-12) has been carried out and it has been showed that SMRs base construction cost would actually be lower than the large reactors, although uncertainty remains due to lack of data available. PWR-12 cost data from Oak Ridge National Laboratory itself has been used for the cost estimation of SMR 12-pack module. Each module's output is accounted as 60 MWe, summing as 720 MWe and net output as 685 MWe. Several factors have been taken into account in the calculation, such as reduced pipeline connection in SMRs, mass production, which will reduce the cost. Moreover, cost goes down by proceeding from First-Of-A-Kind

(FOAK) to Nth-Of-A-Kind (NOAK). In engineering economics FOAK is the related cost for the production of first item, which is relatively much higher than the later items to be produced, namely as NOAK. Two digits and three digits mixed code of account (COA) approach has been used.

Table 3 : Cost comparison between NuScal SMR and PWR-12 (Black et al,2019)

COA	General Description	NuScale SMR Cost	PWR-12 Cost	Cost Difference
		Cost per Kilowatt		
20	**Capitalized Direct Costs**	**$2534.23**	**$2644.66**	**$110.46**
21	Structures and Improvements	$859.17	$1036.15	$176.98
22	Reactor Plant Equipment	$1220.15	$574.71	($645.44)
23	Turbine Plant Equipment	$275.26	$489.69	$214.43
24	Electric Plant Equipment	$49.10	$269.45	$220.35
25	Heat Rejection Systems	$88.33	$114.99	$26.66
26	Miscellaneous Plant Equipment	$42.22	$159.67	$117.45
30	**Capitalized Indirect Costs**	**$931.52**	**$2942.46**	**$2010.94**
31	Design Services at Home Office	$183.83	$1050.34	$866.51
34	Field Construction Management	$85.48	$71.87	($13.61)
35	Field Construction Supervision	$346.57	$846.47	$499.90
36	Field Indirect Costs	$315.64	$973.78	$658.14
	Base Construction Costs	**$3465.72**	**$5587.12**	**$2421.42**

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Total base construction cost as well as capitalized direct and indirect cost is higher in PWR-12 than the NuScale SMR. The only sector where NuScale cost is higher than the PWR-12 is the Reactor Plant Equipment, symbolizes as (Account 22).

It is needed to mention that the COA approach is much flexible and used by the US department of energy (DOE) in order to estimate the costs of different power plant to make comparison between them. Since this COA method is flexible enough because of design simplicity, it is not a good approach to estimate the cost of a complex design where multi-unit integral system is used, such as NuScale.

5. SOME NON-ELECRICAL USE OF SMR, RESULTS AND COST COMPARISON

SMRs can widely be used in non electrical purpose, desalination, district heating, textile, agro-industry etc. In all these case SMR can be more useful than any other power source option, even more beneficiary than a large reactor. The figure below shows different use of industrial process in different temperature.

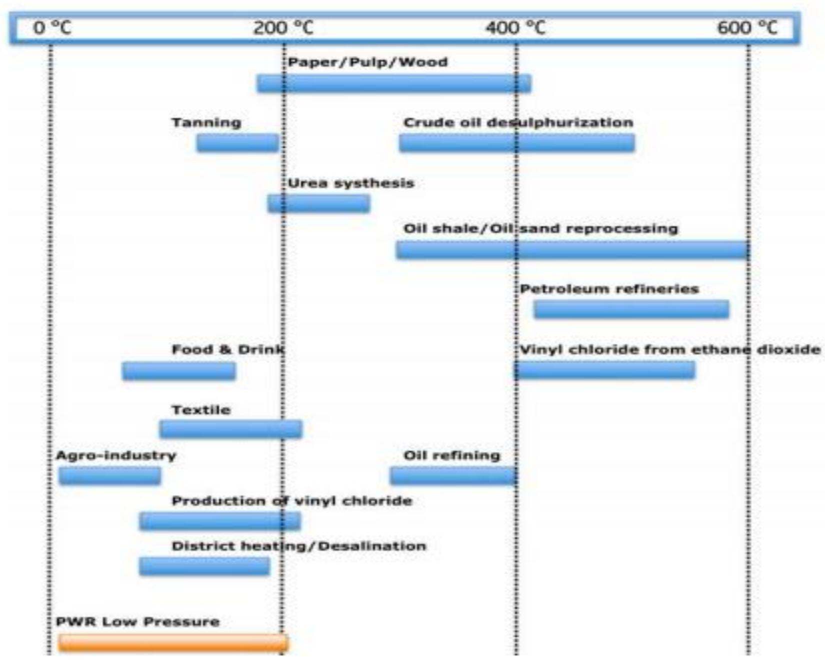

Figure 8: Industrial process in different temperature where SMR can be useful (Locatelli et al, 2014).

Below two most important process, desalination and district heating has been described.

5.1 DESALINATION OF WATER

Needless to say that the demand for clean water is gradually rising. 71% of our earth surface is water while more than 70% of human body is consists of water (Abraham, 2018). But every day we are contaminating the source of surface water by doing earthly activities. In terms of purification of water it requires electricity, on the other hand to produce electricity is requires water. Nuclear energy is a powerful option for the cogeneration of electricity and heat, where heat can be used for the desalination of water. New generation of reactor called NuScale SMR can be the best solution in this regard because of lower cost desalination approach, prolonged safety performance and easy set up affordability (Ingersoll et al, 2014).

The world runs on mainly three different technologies to purify sea water, namely as multi-effect distillation (MED), multi-stage flash distillation (MSF) and Reverse Osmosis (RO). MED and MSF are distillation based technology and RO is membrane-based technology. The method which one should be used depends on the source of water, also depends on how much purified the water needs to be for the end users . MED and MSF is suitable distillation process if the water is dirty or salty, because too dirty water can damage the membrane of reverse osmosis (RO) (Ingersoll et al, 2014).

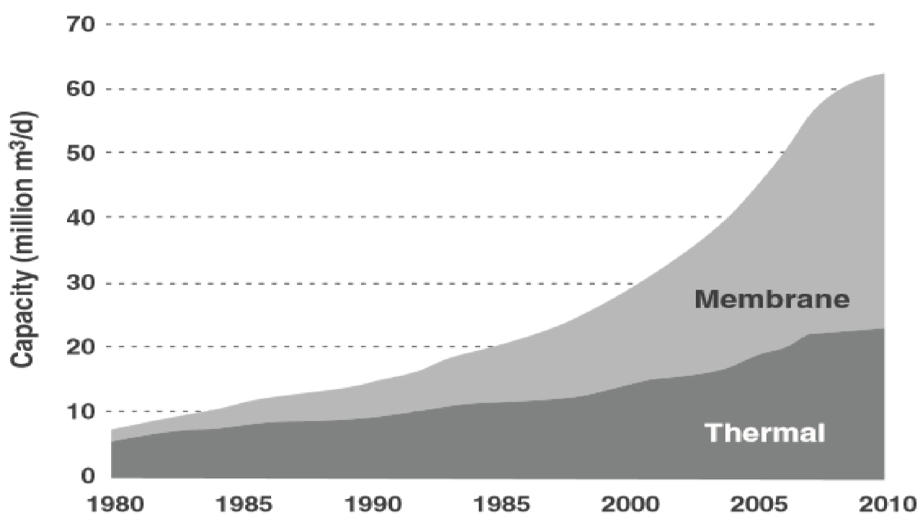

Figure 9 : Thermal and membrane based worldwide desalination capacity (Alonso et al, 2014)

Figure 6 is a depiction of worldwide desalination capacity from 1980 to 2020. Clearly membrane based technology has higher capacity than the thermal based technology.

5.1.1 Multi-Effect Distillation (MED)

Multi-effect distillation process also known as multiple stage distillation method where water which needs to be purified (usually sea water) is evaporated and condensate in different stage in order to get the desired purified water. In every successive stage feed water is evaporated and passed on to the next cycle as a heating medium to evaporate the concentrated steam of brine. This evaporating vapor which acts as the heating medium is a low pressure saturated steam. Specifically, this steam vapor is considered as pure water when condensed. This cycle is repeated until the water is fully purified. The whole process is shown in figure 7.

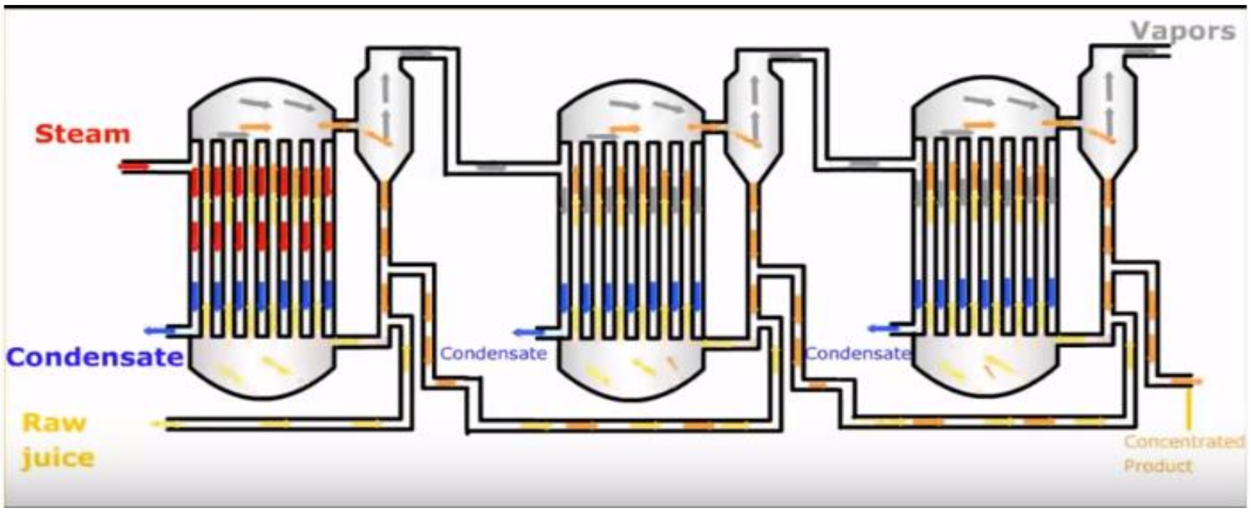

Figure 10 : Multiple stage evaporation technology (YouTube, 2019).

A NuScale SMR can be equipped to an MED distillation cycle.

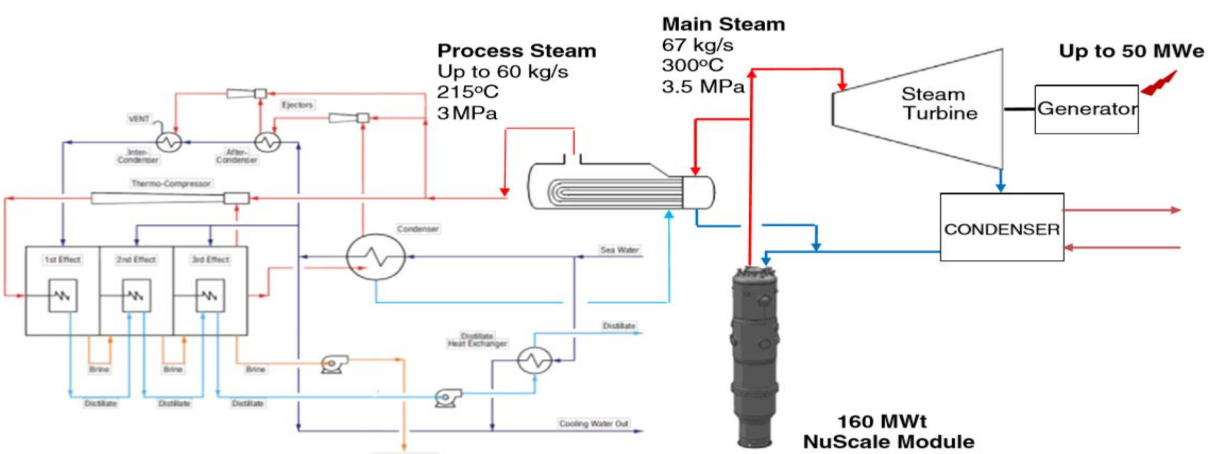

Figure 11 : Coupling of a NuScale plant with an MED thermal compressor distillation process. (Ingersoll et al, 2014).

As shown in the figure 8 steam from the NuScale steam generator is divided into two section and transferred to the turbine and boiler. Steam from the boiler runs the MED thermal compressor as depicted in figure 8. One NuScale module is capable of producing more than 87,000 m^3/d.

5.1.2 Multi-Stage Flash Distillation (MSF)

This is a similar process to MEF where the heated water flashes to steam in multiple successive stage. As shown is figure 9, hot brine is passed through vacuum flash chamber. Vacuum pressure is bit lower than the saturation pressure but the temperature is higher, as a result some amount of water flashes to steam. Then the role of condenser comes into place to condense the steam into pure water.

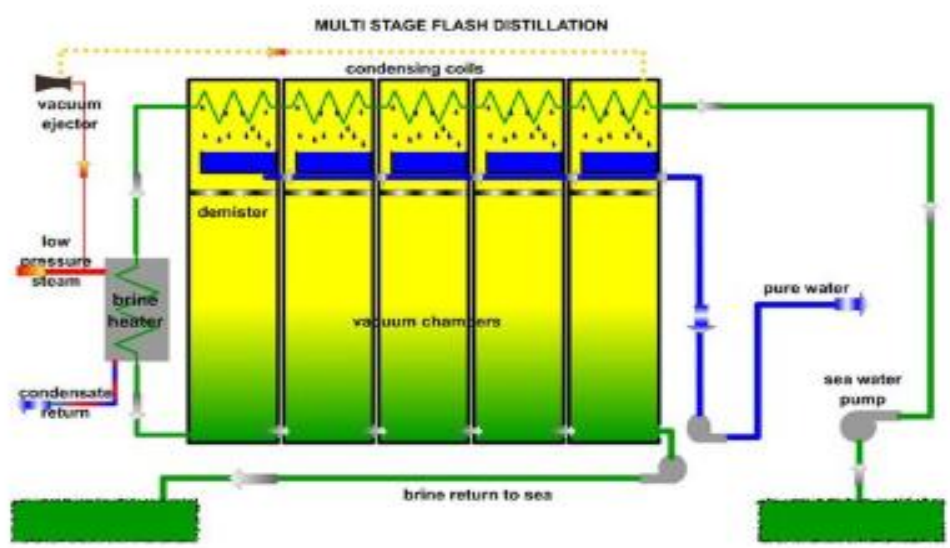

Figure 12 : Multi-Stage Flash Distillation Process (Bright Hub Engineering, 2019).

The figure below (figure 10) is a conceptual design of how a NuScale power module can be coupled to an MSF distillation process. The whole process is similar to as described in figure 8, where controlled extracted steam from the turbine is transferred to a reboiler which then is pushed as a saturated steam to an MSF or MED cycle at 200 kPa.

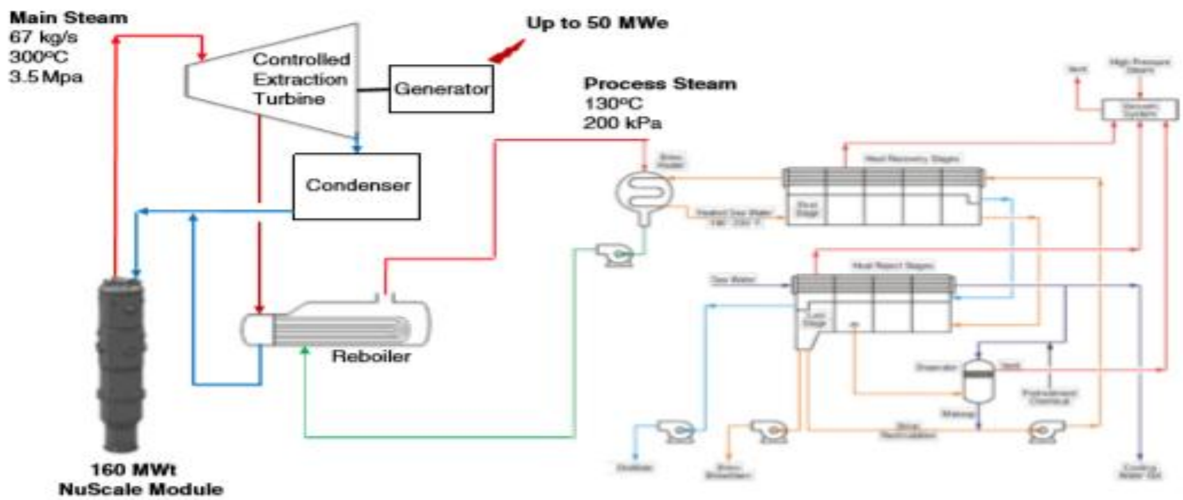

Figure 13 : NuScale SMR integrated to an MSF desalination method via controlled extraction turbine (Ingersoll et al, 2014).

5.1.3 Reverse Osmosis (RO)

As discussed above Reverse Osmosis is a membrane based technology, where the water passes through pressure vessel surrounded by membrane because of pressure difference between hydrostatic pressure and osmotic pressure. Two types of water is produced during the process, one which permeates through the membrane is found as clean water and water which doesn't permeate is found a concentrated water. The concentrated water is more salty and followed by the same process again by passing through other pressure tubes (Sciencedirect, 2019).

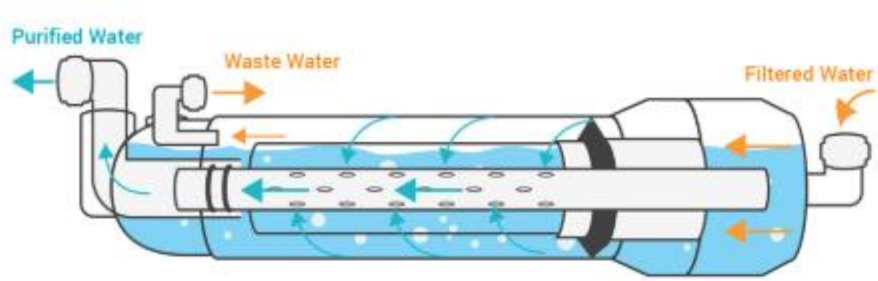

Figure 14 : Reverse Osmosis (RO) pressure tube. (MAX WATER, 2019).

For a RO process to operate, a power source only electricity is needed to run the pump in-order to create pressure head. Figure 12 represents a facility of RO integrated with NuScale SMR.

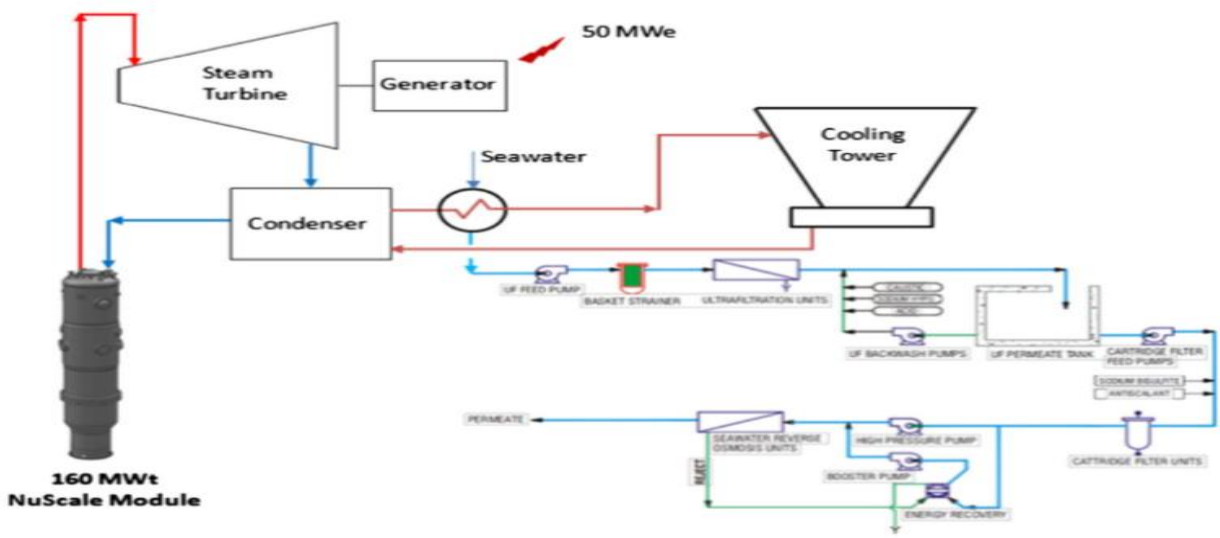

Figure 15 : RO desalination plant equipped with a NuScale SMR (Ingersoll et al, 2014).

5.2 DATA ON DIFFERENT DESALINATION TECHNOLOGY

5.2.1 Result oriented data

Comparing the overall desalination process is essential to differentiate between different desalination technologies, which will give more clear idea about each technology available. Moreover, it is important to collect data such as economical and engineering related data of the plant which is coupled with NuScale SMR.

The main difference between MED, MSF and RO is the method of coupling with a power source. As discussed above RO is much simpler way to connect it with any electrical power source. Since no thermal steam extraction is needed, it is not necessary to couple it with the NuScale or any other power module just in the same location. As long as the grid connection is on RO desalination process can run. But it might be beneficiary to couple it with the plant just in the same location considering the fact that both the plant and RO technology can share the same infrastructure. Another advantage of coupling the RO and NuScale could be no break of the operation even if there is any loss of grid connection happens.

On the other hand MED and MSF desalination technology requires thermal source, generally comes from extracted steam. And the source of this steam could be low pressure turbine stage, extracted from a NuScale power module. Correspondingly, a NuScale SMR can be used simultaneously for electricity production and desalination. Actually, the electricity output will decrease because of operation of one NuScale plant for two purpose simultaneously.

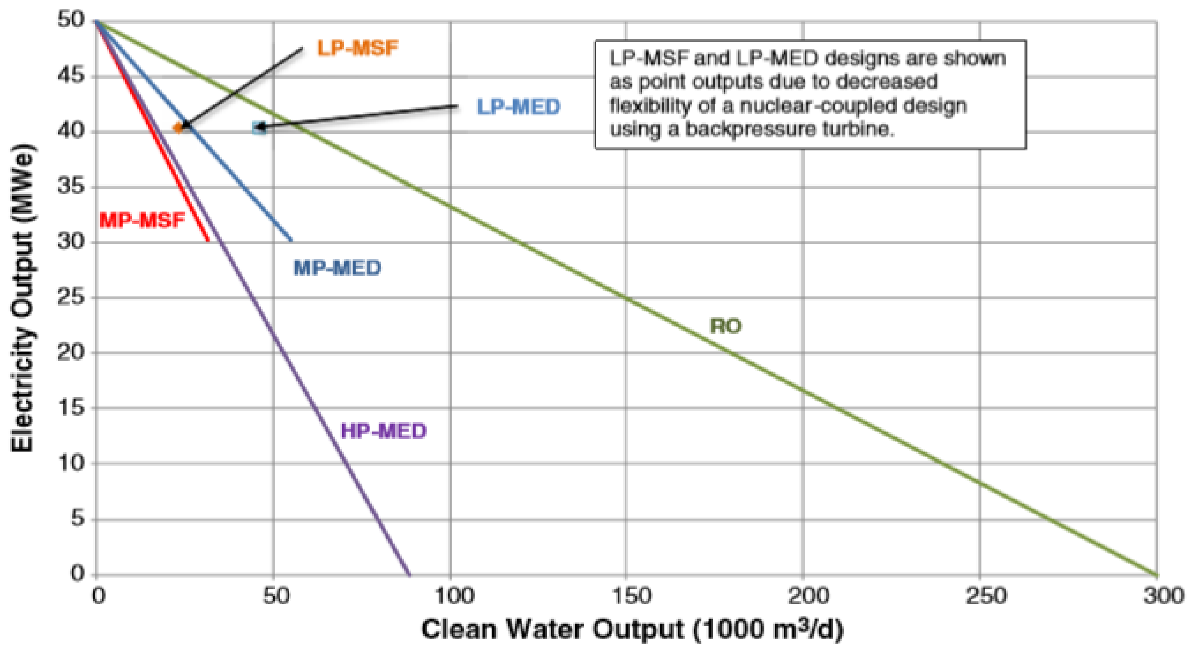

Figure 16 : Result of one NuScale power module while integrated with different desalination process (Ingersoll et al, 2014).

Figure 11 is an illustration of how efficient RO process could be regarding electrical output and clean water output. One reason for this case could be the water that needs to be purified is not that much dirty, since too much dirty water will cause the membrane to be damaged. Also, the water that is produced via RO process is drinkable quality water, while thermal distillation process produce high purity water. From the figure it is also distinct that as the steam pressure decreases, electrical output as well as the clean water output increases.

5.2.2 Cost related data

Since no SMR has been commercialized yet on desalination purpose, all the cost related data has been provided is an assumption which is a strong identical to an existing desalination plant called Carlsbad desalination plant in California, one of the largest desalination plants as considered, producing 190000 m^3/d. Table 4 below shows the important parameters of the plant covering four desalination options (MP-MSF, MP-MED, LP-MED and RO). Here MP and LP means medium pressure and large pressure respectively.

Table 4: Parameters of 190000 m^3/d desalination plant (Ingersoll et al, 2014).

Desalination technology	MP–MSF	MP–MED	LP–MED	RO
Electrical consumption (kWh/m^3)	3	1	1	4
Unit steam consumption (kg/s)	39.3	22.4	45.8	N/A
GOR (kg water/kg steam)	8	14	12	N/A
Top brine temperature	90	70	70	N/A
Number of units required	7	7	4	N/A

In order to produce the similar amount of distilled water with NuScale, eight module of SMR with a capacity of 160MWt for each module is needed. Below parameters of eight module NuScale power plant has been given in table 5.

Table 5 : Important parameters of a NuScale power module producing 190000 m/d (Ingersoll et al, 2014).

Power plant parameters	
Total plant thermal power	1280 MWt
Number of power modules	8
Thermal power per module	160 MWt
Thermal efficiency	>30%
Capacity factor	>95%
Primary system pressure	12.8 MPa (1850 psia)
Main steam supply pressure	3.5 MPa (500 psia)
Main steam temperature	302 °C (575 °F)
Final feedwater temperature	149 °C (300 °F)
Power plant footprint	40–45 acres

Table 6 represents the final cost related data on different desalination options. All the cost related data is an approach similar to section 4.2 as described previously, where the cost has been estimated regarding 12-module plant as a reference. In order to estimate the capital and operational cost, account from FOAK to NOAK has been considered. In engineering economics FOAK is the related cost for the production of first item, which is relatively much higher than the later items to be produced, namely as NOAK.

Table 6 : Final cost of desalination plants integrated with NuScale (Ingersoll et al, 2014).

Desalination technology	MP–MSF	MP–MED	LP–MED	RO
Coupled plant production rates				
Water produced (m^3/d)	190,000	190,000	190,000	190,000
Net plant electrical output (MWe)[a]	227	293	334	348
Capital cost ($ millions)				
NuScale plant	$1800	$1800	$1800	$1800
Desalination plant	$379	$311	$311	$256
Operation & maintenance cost[b] ($ millions)				
NuScale plant	$185	$185	$185	$185
Desalination plant	$15.1	$13.3	$13.3	$14.2
Annual revenue ($ millions)				
Annual revenue from water sales (at $1.67/$m^3$ wholesale price)	$101	$101	$101	$101
Annual revenue from electricity sales (at $75/MWh wholesale price)	$142	$183	$209	$217
Coupled plant net annual revenue	$43	$86	$111	$119
Coupled plant simple payback (years)[b]	51	25	19	17

[a] Net electrical output available to the grid after accounting for reduced generation due to extraction steam and electricity consumed by desalination process.
[b] Does not include financing costs.

From the table it is clear that the cost (capital & maintenance) is higher in MSF desalination technology as a result the annual revenue from electricity sale is lower than the other two desalination method. On the other hand RO process is more efficient with higher revenue and lowest capital and maintenance cost. Moreover RO has the shortest payback time when coupled with a NuScale plant.

5.3 DISTRICT HEATING

Another most identical use of SMRs other than electricity can be district heating. Even though nuclear power has been used in district heating in the form of traditional large reactor and other fossil fuel energy source, it is often limited because of their large size, safety consideration and other factors such a environment. If SMR is considered for district heating, those limitations related to safety and decarbonization can be eliminated. Hot water/steam produced in the reactor is driven through the pipeline up to the households in order to keep them warm during the winter season. An SMR can be coupled with district heating and electrical purpose simultaneously, since it can be used for both thermal and electrical purpose.

Among the other European nations Finland is focusing on carbon neutral energy production on a vision of 2035 (Värri and Syri, 2019). On a target to achieve the goal Finland is planning to cover the district heating part with small modular reactor, although currently it is mostly covered with energy generated from fossil fuel such as coal, natural gas, woody biomass. (World-nuclear-news, 2019). Regarding to this issue different research has already been carried out. Specially, VTT is working as a coordinator with ELSMOR (European licensing of Small Modular Reactor) to overcome any obstacle on the path of deployment of SMR (Ville. T, 2019). In addition to that VTT has carried out a research by modeling a Finnish city district heating system with NuScale SMR. They have found that Espoo city could be modeled with a unit of NuScale SMR with high utilization rate. Eventually, the payback time would be between 10 - 20 years as estimated depending on the capital cost as well as operation and maintenance cost.

Table 7 below is a result of a research conducted by VTT, where they modeled a district heating grid of a Finnish city at a vision of 2030 , backed by a payback time of 10 - 20 years depending on the capital cost. Start up cost of SMR is unknown in the section, while operation and maintenance cost is higher than the other scenarios of energy sources. But this cost can be reduced in an accountability from FOAK to NOAK as discussed in the previous section in 4.2.

Table 7: Assumption of district heating grid of a Finnish city (Espoo) by 2030 (Tulkk et al, 2017)

DH production unit	Code	DH capacity	ELC capacity	OM *	Minimum load	Total efficiency	Start-up cost
Scenario 1: NuScale DH	NuScale DH	152 MW	-	5.6 €/MWh**	40%	81%	-
Scenario 2: NuScale CHP	NuScale CHP	94 MW	35 MW	8.9 €/MWh**	40%	94%	-
Scenario 3: no NuScale							
Natural gas combined cycle CHP	NGCC	214 MW	234 MW	0.7 €/MWh	50%	90%	11700 €
Biomass steam turbine CHP	BioCHP	156 MW	74 MW	1.8 €/MWh	25%	88%	4500 €
Gas turbine + waste heat CHP	GtCHP	76 MW	42 MW	0.4 €/MWh	40%	90%	2100 €
Heat pump	HP	40 MW	-	-	-	400% ***	-
Biomass heat plant	BioDH	80 MW	-	2.1 €/MWh	-	90%	-
Natural gas heat plant	GasDH	580 MW	-	0.8 €/MWh	-	90%	-

in all 3 scenarios

Here,

* OM cost per produced DH -> Operation and maintenance cost
** Includes fuel cost
*** COP value 4.0

6. DATA ON WATER COOLED SMALL MODULAR REACTOR

6.1 ENGINEERED SAFETY FEATURES

Design parameters of nuclear reactor also known as engineered safety features (ESF) are important components that ensures protection against any possible dangerous situation happened in the past, also minimizes radioactive material release into the environment even if any kind of accident happens. A listing of common ESF has been given those are used to remove decay heat and to protect over pressure.

Steam generator & heat exchanger connected with water pool

Removing decay heat is one of the most important criteria in a nuclear power plant as the radioactive isotopes produce decay heat even after the reactor shut down. Emergency safety features (ESF), those are associated with removing decay heat produced in the reactor core are given below.

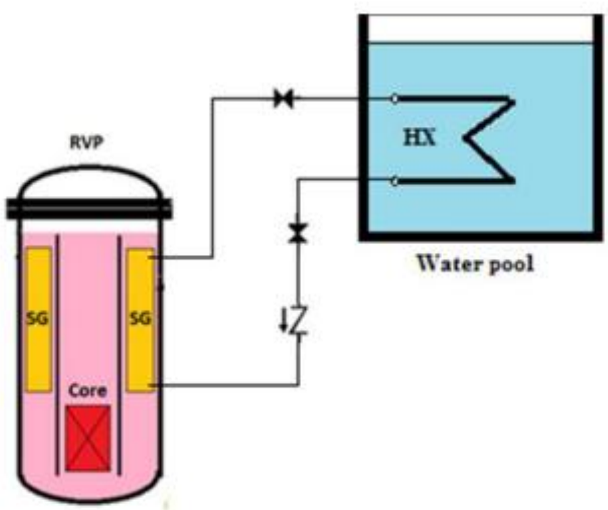

Figure 17 : Decay heat removal system through steam generator and heat exchanger (IAEA, 2016).

This is a passive core cooling system where a steam generator is connected with water pool, and the driven steam from the steam generator is condensed in the pool, which then flows back to the steam generator through feed water inlet. SMRs to implement this method are SMART and NuScale.

Re-circulating redundant valves

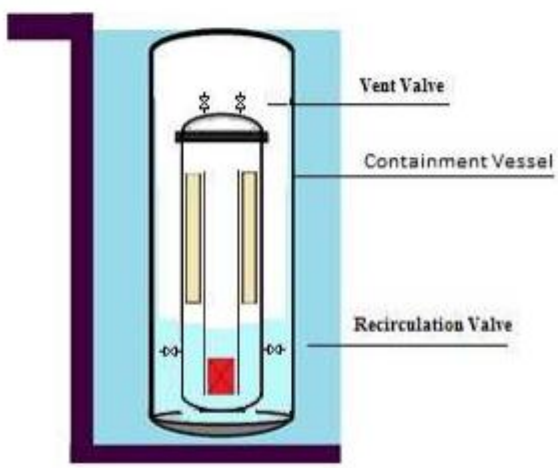

figure 18 : Safety injection using redundant valve (IAEA, 2016).

Reactor vent valve and recirculation valve are redundant valves those are used to remove decay heat. The process is to open the vent valve so that the steam from the reactor passes to the containment, where is it cooled and condensed on the wall of the containment vessel which is surrounded by the pool of water from the outside. As the steam is condensed it is reserved on the bottom of the containment. Recirculation valve is placed above the top of the reactor core so that the core remains under water even if the valve opens spuriously . As a result as soon as the water level reaches up to the recirculation valve it opens up, and start a natural circulation loop from containment to the reactor vessel. NuScale will have this design implementation.

Spray system inside the containment

In a similar case to the above phenomenon during over pressure protection, instead of using redundant valve a pump is used to spray water inside the containment. The water supply comes either from the tank outside the containment or from the in-containment reservoir. When the steam comes in contact with water it condenses. SMART has this technology in it's design feature. Figure 9 depicts this technology.

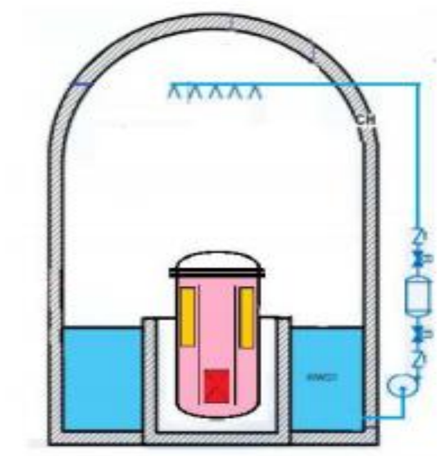

Figure 19 : Condensation of steam by spraying water (IAEA, 2016).

Low-head pump injection from a pressurized tank

It has been previously said that LOCA can be minimized in SMRs. But in case of an emergency situation if the reactor pressure goes down, then borated water from the accumulator comes to the reactor pressure vessel in order to refill the vessel. SMR named CAREM is using this facility.

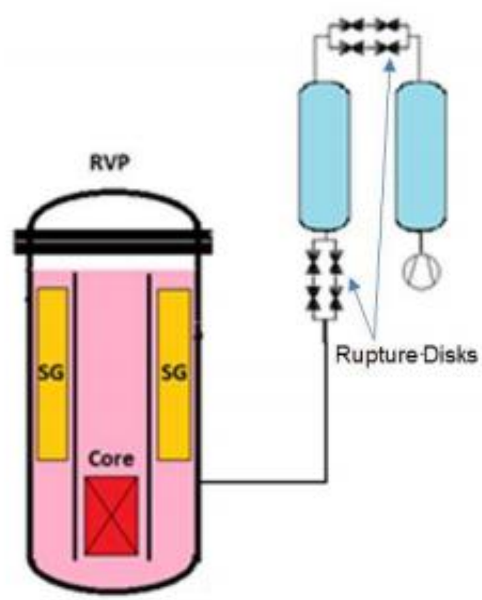

Figure 20 : Gravity driven boron injection (IAEA, 2016).

High-head pump boron injection

This is very common conventional type approach of injecting boron into the reactor vessel using an electricity driven pump, while any emergency situation occurs in order to shut down the reactor as a secondary option.

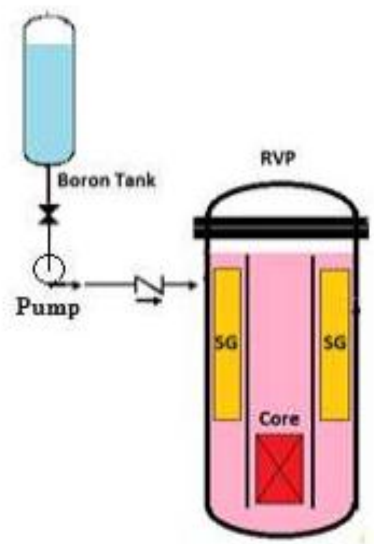

Figure 21 : Pump driven boron injection (IAEA, 2016).

SMART will have this feature implemented in it's design.

6.2 DESIGN FEATURES CONTRIBUTING TO DEFENSE - IN - DEPTH

In order to ensure nuclear safety performance several layers of protection is maintained since the very beginning of nuclear energy production, which is known as defense-in-depth (DiD). From 1st level up to 5th level of DiD is maintained to protect from any radioactive release to the environment. Each level of protection has different meanings contributing to different engineering design features.

- The point of the first level of protection is to restrain deviations from ordinary activity of the reactor, eventually what's more is to anticipate system failures. In order to implement such protection concerning factors those comes in place to play the role are material selection and equipments fabrication (IAEA, 2016).
- Second level of protection is maintained considering the fact that over a service lifetime of a nuclear power plant any kind of fluctuation from normal operation may accelerate towards severe damage. But needs to be prevented by second level of protection (IAEA, 2016).
- Even though the second level of defense is established, it may not be superior to prevent any lead towards an accident. An additional layer of protection is established taking into account also the engineering safety features which might help to achieve a safety shutdown (IAEA, 2016)
- The fourth level of defense is established to minimize any radioactive release considering the fact that all the preceding levels (1st to 3rd) has and now it is crucial to keep the radioactive release as low as possible (IAEA, 2016)
- The fifth level of protection actually determines the emergency control because of radiological consequence (IAEA, 2016)

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All the design features related to defense in depth is given below as a chart.

Table 8 : Design features contributing to level 1 of defense in depth (IAEA ,2009).

#	Design features	What is targeted	SMR designs
1	Elimination of liquid boron reactivity control system	Exclusion of inadvertent reactivity insertion as a result of boron dilution	KLT-40S, CAREM-25, SCOR
2	Relatively low core power density	Larger thermal-hydraulic margins	MARS, IRIS, CAREM-25, SCOR
3	Integral design of primary circuit with in-vessel location of steam generators and (hydraulic) control rod drive mechanisms	Exclusion of large-break loss of coolant accidents (LOCA), exclusion of inadvertent control rod ejection, larger coolant inventory and thermal inertia	CAREM-25, IRIS, SCOR
4	Compact modular design of the reactor unit, eliminating long pipelines in the reactor coolant system	Decreased probability of LOCA	KLT-40S
5	Primary pressure boundary enclosed in a pressurized, low enthalpy containment	Elimination of LOCA resulting from failure of the primary coolant pressure boundary, elimination of control rod ejection accidents	MARS
6	Leaktight reactor coolant system (welded joints, packless canned pumps, and leaktight bellows, sealed valves, etc.)	Decreased probability of LOCA	KLT-40S
7	Internal, fully immersed pumps	Elimination of pump seizure, rotor lock, and seal LOCA	MARS, IRIS, SCOR
8	Leak restriction devices in the primary pipelines	Limitation of the break flow in case of a pipeline guillotine rupture	KLT-40S
9	A single, small diameter double connecting line between the primary coolant pressure boundary and auxiliary systems	Prevention of LOCA caused by rupture of the connecting line	MARS
10	Natural circulation based heat removal from the core in normal operation, eliminating main circulation pumps	Elimination of loss of flow accidents (LOFA)	CAREM-25
11	Steam generator with lower pressure inside the tubes in normal operation mode	Reduced probability of a steam tube rupture; prevention or downgrading of a steam line break or a feed line break	MARS, KLT-40S, IRIS
12	Steam generator designed for a full primary system pressure	Prevention or downgrading of a steam line break or a feed line break	IRIS, MARS

Table 9 : Design features contributing to level 2 of defense in depth (IAEA ,2009).

#	Design feature	What is targeted	SMR designs
1	Active systems of instrumentation and control	Timely detection of abnormal operation and failures	All designs
2	Negative reactivity coefficients over the whole cycle	Prevention of transient over-criticality due to abnormal operation and failures	All designs
3	A relatively large coolant inventory in the primary circuit, resulting in large thermal inertia	Slow progression of transients due to abnormal operation and failures	CAREM-25, SCOR, IRIS, MARS
4	High heat capacity of nuclear installation as a whole	Slow progression of transients due to abnormal operation and failures	KLT-40S
5	Favourable conditions for implementation of the leak before break concept, through design of the primary circuit	Facilitate implementation of leak before break concept	KLT-40S
6	Little coolant flow in the low temperature pressurized water containment enclosing the primary pressure boundary	Facilitate implementation of leak before break concept	MARS
7	Redundant and diverse passive or active shutdown systems	Reactor shutdown	All designs

Table 10 : Design features contributing to level 3 of defense in depth (IAEA, 2016).

No.	Design features	Design objectives	SMR designs	Relevant safety requirements
1.	Negative reactivity coefficients over the whole cycle	Prevention of transient over-criticality and bringing the reactor to a subcritical state in design basis accidents	All designs	IAEA Safety Standards Series Specific Safety Requirements No. SSR–2/1 (Rev. 1), Safety of Nuclear Power Plants: Design Requirement 20, Paragraph 4.11 [(a) and (d)] and relevant Paragraphs. [11]
2.	A relatively large coolant inventory in the primary circuit	Slow progression of transients in design basis accidents	CAREM25, IRIS	
3.	High heat capacity of nuclear installation as a whole	Limitation of temperature increase in design basis accidents	KLT-40S	
4.	Restriction devices in pipelines of the primary circuit, with primary pipelines being connected to the hot part of the reactor	Limitation of scope and slower progression of LOCA	KLT-40S	

No.	Design features	Design objectives	SMR designs	Relevant safety requirements
5.	Use of once-through steam generators	Limitation of heat rate removal in a steam line break accident	KLT-40S	
7.	Soft pressurizer system	Damping pressure perturbations in design basis accidents	KLT-40S, RITM-200	
8.	Self-pressurization, large pressurizer volume, elimination of sprinklers, etc.	Damping pressure perturbations in design basis accidents	CAREM25, IRIS, DMS, SMART, VBER-300, VK-300, UNITHERM, mPower, NuScale, Westinghouse SMR, SMR-160	
9.	Limitation of inadvertent control rod movement by an overrunning clutch and by the limiters	Limitation of the scope of reactivity insertion in an accident with control rod drive bar break	KLT-40S	
10.	Redundant and diverse reactor shutdown and heat removal systems	Increased reliability in carrying out safety functions	All designs	
11.	Insertion of control rods to the core, driven by gravity	Reactor shutdown	KLT-40S, CAREM25, ACP100, IRIS, IMR, SMART, VBER-300, ABV-6M, UNITHERM, RUTA-70, NuScale, Westinghouse SMR	
12.	Insertion of control rods to the core, driven by force of springs	Reactor shutdown	KLT-40S	
13.	Non-safety-grade control rod system with internal control rod drives	Reactor shutdown	IRIS	
14.	Gravity driven high pressure borated water injection device (as a second shutdown system)	Reactor shutdown	CAREM25 and AHWR300	
15.	Injection of borated water from the emergency boron tank at high pressure (as an auxiliary shutdown measure)	Reactor shutdown	IRIS	

No.	Design features	Design objectives	SMR designs	Relevant safety requirements
16.	Emergency injection system (with borated water), actuated by rupture disks	Reactor shutdown plus prevention of core uncovery in LOCA	CAREM25	
17.	Natural convection core cooling in all modes	Passive heat removal	CAREM25, AHWR-300, DMS, IMR, ABV-6M, VK-300, UNITHERM, ELENA, NuScale, SMR-160	
18.	Safety (relief) valves	Protection of reactor vessel from over pressurization	IRIS, CAREM25, it should be available in all designs	
19.	Long term gravity make-up system	Assures that the core remains covered indefinitely following a LOCA	IRIS and ACP100	

Table 11 : Design features contributing to level 4 of defense in depth (IAEA, 2009).

#	Design feature	What is targeted	SMR designs
1	Relatively low core power density	Limitation or postponement of core melting	IRIS, CAREM-25, SCOR, MARS
2	Relatively low temperature of reactor coolant	Limitation or postponement of core melting	MARS
3	Low heat-up rate of fuel elements predicted in a hypothetical event of core uncovery, owing to design features	Prevention of core melting due to core uncovery	CAREM-25
4	Low enthalpy pressurized water containment embedding the primary pressure boundary	Additional barrier to possible radioactivity release into the environment	MARS
5	Passive emergency core cooling, often with increased redundancy and grace period (up to infinite in time)	Provision of sufficient time for accident management, e.g., in the case of failure of active emergency core cooling systems	KLT-40S, IRIS, CAREM-25 SCOR, MARS
6	Passive system of reactor vessel bottom cooling	In-vessel retention of core melt	KLT-40S
7	Natural convection of water in flooded reactor cavity	In-vessel retention of core melt	SCOR
8	Passive flooding of the reactor cavity following a small LOCA	Prevention of core melting due to core uncovery; in-vessel retention	IRIS
9	Flooding of the reactor cavity, dedicated pool for steam condensation under a steam generator tube rupture	Reduction of radioactivity release to the environment due to increased retention of fission products	SCOR

#	Design feature	What is targeted	SMR designs
10	Containment and protective enclosure (shell) or double containment	Prevention of radioactive release in severe accidents; protection against external event impacts (aircraft crash, missiles)	KLT-40S, IRIS, CAREM-25 MARS
11	Containment building	Prevention of radioactive release in severe accidents; protection against external event impacts (aircraft crash, missiles)	All designs
12	Very low leakage containment; elimination or reduction of containment vessel penetrations	Prevention of radioactivity release to the environment	IRIS
13	Reasonably oversized reactor building, in addition to a primary coolant pressure boundary and additional water filled pressurized containment	Prevention of radioactivity release to the environment in unforeseen LOCA and severe accidents (LOCAs are prevented by design through the CPP	MARS
14	Indirect core cooling via containment cooling	Prevention of core melting; in-vessel retention	IRIS
15	Passive containment cooling system	Reduction of containment pressure and limitation of radioactivity release	KLT-40S
16	Relatively small, inert, pressure suppression containment	Prevention of hydrogen combustion	SCOR
17	Inert containment	Prevention of hydrogen combustion	IRIS
18	Reduction of hydrogen concentration in the containment by catalytic recombiners and selectively located igniters	Prevention of hydrogen combustion	CAREM-25
19	Sufficient floor space for cooling of molten debris; extra layers of concrete to avoid containment basement exposure directly to such debris	Prevention of radioactivity release to the environment	CAREM-25

Table 12 : Design features contributing to level 5 of defense in depth (IAEA, 2009).

#	Design feature	What is targeted	SMR designs
1	Mainly administrative measures	Mitigation of radiological consequences resulting in significant release of radioactive materials	KLT-40S
2	Relatively small fuel inventory, less non-nuclear energy stored in the reactor, and lower integral decay heat rate	Smaller source term	Several designs
3	Design features of Levels 1–4 could be sufficient to achieve defence in depth Level 5[a]	Exclusion of a significant release of radioactive materials beyond the plant boundary or essential reduction of the zone of off-site emergency planning	KLT-40S, IRIS, CAREM,-25 MARS, SCOR

6.3 EXAMPLES OF SMRS WITH THEIR DESIGN FEATURES

CAREM

CAREM is a national SMR advancement venture, in light of LWR innovation, facilitated by Argentina's National Atomic Energy Commission (CNEA) in a joint effort with driving atomic organizations in Argentina with the reason to create, structure and build inventive little atomic power plants with high financial intensity and level of wellbeing. CAREM has been planned as a source of electricity generation for households. In addition to that it can also be used for desalination purpose *(IAEA, 2018)*.

Table 13 : Major technical parameters of CAREM (IAEA, 2018).

MAJOR TECHNICAL PARAMETERS	
Parameter	**Value**
Technology developer, country of origin	CNEA, Argentina
Reactor type	Integral PWR
Coolant/moderator	Light water / light water
Thermal/electrical capacity, MW(t)/MW(e)	100/~30
Primary circulation	Natural circulation
System pressure (MPa)	12.25
Core inlet/exit temperatures (ºC)	284/326
Fuel type/assembly array	UO_2 pellet/hexagonal
Number of fuel assemblies	61
Fuel enrichment (%)	3.1% (prototype)
Fuel burnup (GWd/ton)	24 (prototype)
Fuel cycle (months)	14 (prototype)
Main reactivity control mechanism	Control rod driving mechanism (CRDM) only
Approach to engineered safety systems	Passive
Design life (years)	40
Plant footprint (m^2)	Not available
RPV height/diameter (m)	11/3.2
RPV, internals and SGs weight (metric ton)	267
Seismic design	0.25
Distinguishing features	Core heat removal by natural circulation, pressure suppression containment
Design status	Under construction (as prototype)

Main structural qualities of the SMR are as follows:

- Primary cooling system as integrated
- Self-pressurization
- Cooling mechanism with natural circulation
- In-vessel control rod drive mechanism
- Passive system related safety frameworks

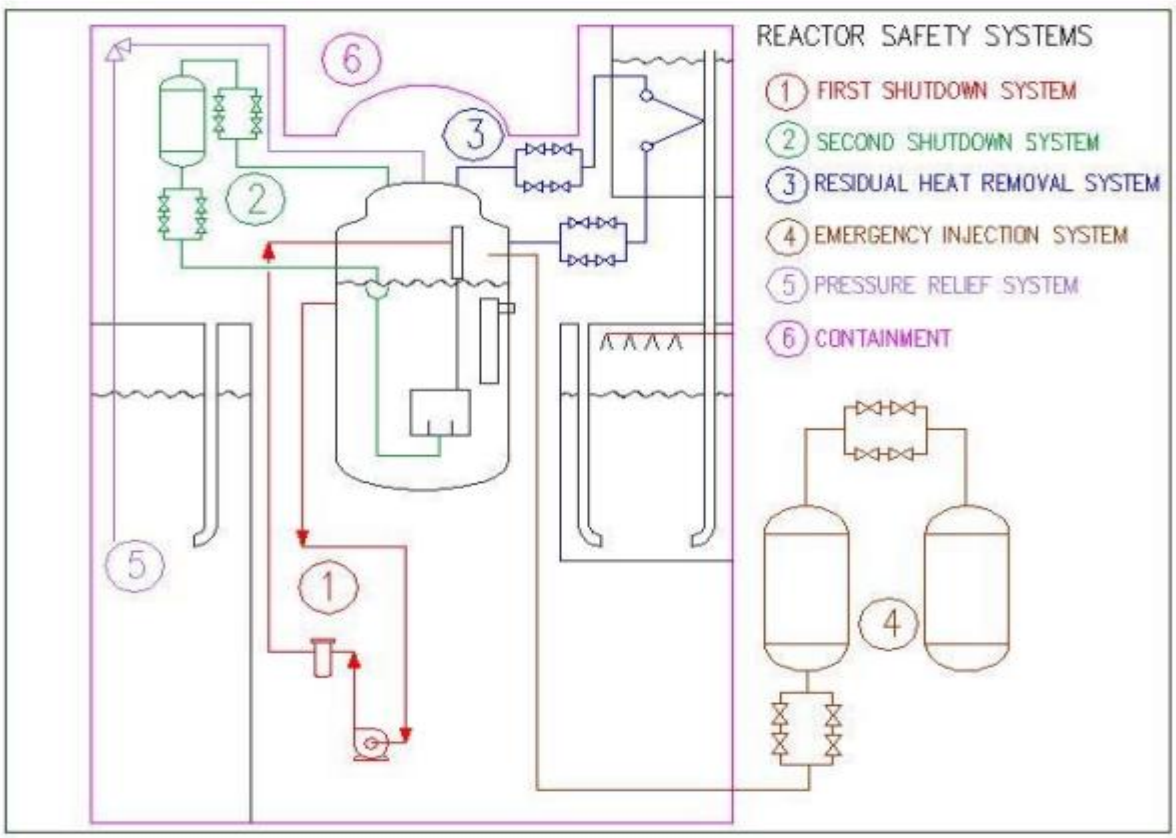

Figure 22 : Layout of safety system and containment (Delmastro et al, 2004)

Figure 22 represents a layout of safety system and containment of CAREM reactor. Reactor pressure vessel (RPV) is protected by three safety relief valves in case of overpressure protection. Low-head pump injection system (described in the section 6.1) controls the emergency situation in case of LOCA.

CAREM is planned to come in operation in 2022 (IAEA, 2022).

SMART

Modular advanced reactor SMART is an integral PWR with an evaluated electrical intensity of 107 MW(e) from 365 MW(t). Advanced configuration of SMART highlights to upgraded safety, unwavering quality and financial matters. The structure and advancements executed in the SMART were confirmed and approved during the standard plan endorsement survey. SMART has been designed to accomplish improvement in financial matters through design simplification, component modularization, decrease of construction time and high plant accessibility (iea, 2018).

Table 14 : Major technical parameters of SMART (IAEA, 2018).

Parameter	Value
Technology developer, country of origin	Korea Atomic Energy Research Institute (KAERI), Republic of Korea
Reactor type	Integral PWR
Coolant/moderator	Light water / light water
Thermal/electrical capacity, MW(t)/MW(e)	330/100
Primary circulation	Forced circulation
System pressure (MPa)	15
Core inlet/exit temperatures (^{0}C)	296/323
Fuel type/assembly array	UO_2 pellet/17x17 square
Number of fuel assemblies	57
Fuel enrichment (%)	< 5
Fuel burnup (GWd/ton)	< 60
Fuel cycle (months)	36
Main reactivity control mechanism	Control rod driving mechanisms and soluble boron
Approach to engineered safety systems	Passive
Design life (years)	60
Plant footprint (m^2)	90000
RPV height/diameter (m)	18.5/6.5
Module weight (metric ton)	1070 (including coolant)
Seismic design	> 0.18 g automatic shutdown
Distinguishing features	Coupling with desalination and process heat application, integrated primary system,
Design status	Licensed/certified (standard design approval)

SMART is a multi-reason application reactor for power generation, ocean water desalination, and district heating.

One unit of reactor pressure vessel contains significant essential parts, for example, a pressurizer, steam generators and reactor coolant pumps. The integrated system of the reactor vessel eliminates the large piping joints, which in result removes large break loss of coolant accident. Moreover, the pump which is used is called canned motor reactor coolant pump, because of not having any pump seals in this pump, loss of coolant associated with pump seal failure is prevented (IAEA, 2018). In case of any small break LOCA there is emergency safety injection system from four core make up tanks (CMTs) and four safety injection tanks (SITs).

ACP100

Table 15 : Major technical parameters of ACP100 (IAEA, 2018)

MAJOR TECHNICAL PARAMETERS	
Parameter	**Value**
Technology developer, country of origin	CNNC(NPIC/CNPE) People's Republic of China
Reactor type	Integral PWR
Coolant/moderator	Light water / light water
Thermal/electrical capacity, MW(t)/MW(e)	385/125
Primary circulation	Forced circulation
System pressure (MPa)	15
Core inlet/exit temperatures (ºC)	286.5/319.5
Fuel type/assembly array	UO_2/17x17 square pitch arrangement
Number of fuel assemblies	57
Fuel enrichment (%)	<4.95
Fuel burnup (GWd/ton)	<52000
Fuel cycle (months)	24
Main reactivity control mechanism	Control rod drive mechanism (CRDM), Gd_2O_3 solid burnable poison and soluble boron acid
Approach to engineered safety systems	Passive
Design life (years)	60
Plant footprint (m^2)	200000
RPV height/diameter (m)	10/3.35
Module weight (metric ton)	300
Seismic design	0.3
Distinguishing features	Integrated reactor with tube-in-tube once through steam generator, nuclear island underground
Design status	Basic design finished

The ACP100 is also integrated PWR configuration developed by China National Nuclear Corporation (CNNC) to produce an electric intensity of 125 MW(e). The ACP100 depends on existing PWR innovation, which is verified by passive safety systems in order to withstand with the result of any accident events. This is also used for various purpose such a electricity production, district heating and sea water desalination. (IAEA, 2018)

Similar to SMART reactor this reactor also uses canned motor reactor coolant pump which prevents loss of coolant accident associated with pump seal failure. It is structured with a few passive safety features and extreme hazard mitigation system, such as passive reactor cavity flooding preventing RPV melt down, automatic pressure relief system, PDHRS preventing core meltdown in case of design basis accident (DBA). The emergency core cooling system (ECCS) consists of two coolant storage tanks (CST), two safety injection tanks (SIT), an in-refuelling water storage tank (IRWST)

Plant arrangement are as follows,

1. Reactor building
2. Connecting building
3. Fuel building

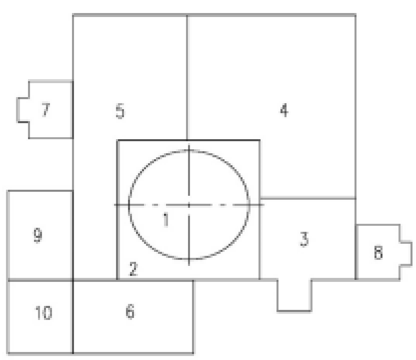

Figure 23 : Plant arrangement of ACP100 (IAEA, 2018)

4. Electrical building
5. Nuclear auxiliary building
6. Access building

7. Emergency diesel generator building
8. Auxiliary diesel generator
9. Fire protection pump station
10. Emergency compressor house.

In April 2016, an understanding of directing a general safety review for ACP100 was marked between the IAEA and CNNC.

7. CONCLUSION

Life source is fundamentally dependent on food, water and air, while the production of these three elements is largely dependent on energy. Day by day, with the increasing number of population the demand for the supply of food, water and clean air is rising, and so the demand for clean and efficient energy supply is also sky rocketing. Definitely when we talk about clean energy we mean carbon neutral energy, which has no negative impact or less impact to the environment . As discussed in this report, nuclear power with small modular reactor could be the best solution in mitigation of the global energy demand. In addition to that it has also been discussed why SMR would be more feasible compared to large reactor, as a reason to that the focus has been generalized to their more compact design, lower risk and economic viability.

Safety or accident mitigation is the most important as well as sophisticated term in nuclear power. While comparing SMR versus traditional large reactor, naturally SMR is ranked higher as a reliable nuclear energy source, because SMR has lower risk to the most known accident called LOCA by eliminating the piping system between the core and steam generator, as well as between the core and pressurizer. Other design basis accident such as rod ejection accident can also be prevented in SMR, since the CRDM is placed inside the reactor pressure vessel. Moreover, SMR has lower CDF which is calculated by PRA as discussed above in this report, which concludes that lower the CDF lower the risk of rupture or damage to the core.

Cost also plays a vital role in the power sector. Unit electricity price depends on the production, operation and maintenance cost. Of course people would buy electricity with the cheapest price available. Although it has been seen on an earlier research that LCOE of SMR is higher than the large reactor, but on a COA approach production cost can be reduced by mass production and transferring from FOAK to NOAK production of the parts.

Not only that SMR can be used as an electrical purpose but also in some other non electrical purpose, for example sea water desalination and district heating are the two most common use of SMRs where a NuScale module can be integrated with a desalination plant or a district heating along with power production.

Some engineering safety features related to SMR has also been discussed in the report which are similar to large reactor, such as redundant valves, high head pump boron injection, low head pump boron injection, spray system inside the containment. Eventually, design features related to defense in depth from level 1 up to level 5 has been discussed in this report.

Comparing between a few comparative sorts of physical parameters with related information gives a reasonable and unmistakable view on which part we have to concentrate on, in order to enhance the performance of one physical parameter contrasted with another. Similarly comparing between SMR and conventional nuclear power plant has broaden views on both the module and has given us an idea why should we choose SMR instead of large reactor in the future, although limited number of available data has kept the term little uncertain. While comparing, NuScale has been taken as identical as SMR. As a future work of the report, upon relevant data availability some other SMR can be taken as identical for doing the cost comparison with large reactor.

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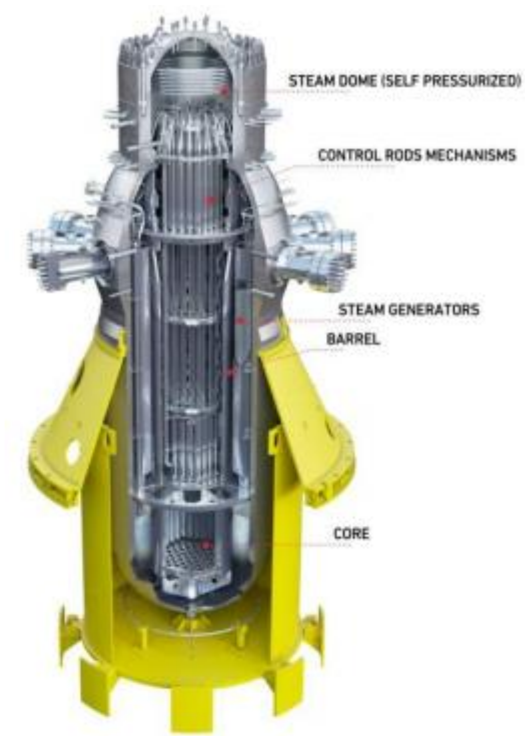
APPENDIX

<u>CAREM</u>



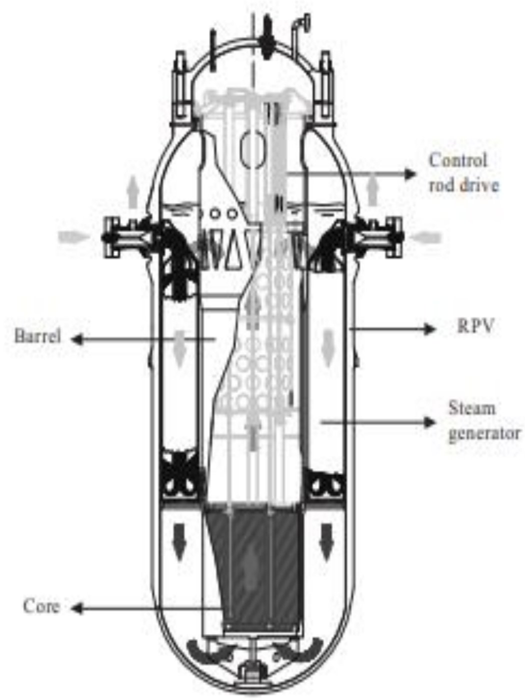


Figure : Schematic diagram of CAREM