Status Report – UK SMR (Rolls-Royce and Partners)
United Kingdom 2019/09/30

This reactor design is a new concept with a projected earliest deployment (start of construction) time of 2025.

INTRODUCTION

Indicate which booklet(s): [ ] Large WCR [x] SMR [ ] FR

The UK SMR (Figure 1) has been derived to deliver a market driven, affordable, low carbon, energy generation capability. The developed design is based on optimized and enhanced use of proven technologies that presents a class leading safety outlook and attractive market offering with minimum regulatory risk.

A three loop, close-coupled, Pressurised Water Reactor (PWR) provides a power output of 443MWe from 1276 MWth using industry standard UO_2 fuel. Coolant is circulated via three centrifugal Reactor Coolant Pumps (RCPs) to three corresponding vertical U-tube Steam Generators (SGs). The design includes multiple active and passive safety systems, each with substantial internal redundancy. Rapid, certain and repeatable build is enhanced through site layout optimization and maximizing modular build, standardization and commoditization.

Development Milestones

2015	Rolls-Royce development of initial reference design
2016	Formation of consortium for design of whole power station concept
2017	Conceptual design developed
2025	Projected earliest start of construction
2030	Planned first of a kind commercial operation

Design organization or vendor company (**e-mail contact**): –

Links (www…) to designer/vendor homepage: https://www.rolls-royce.com/products-and-services/nuclear/small-modular-reactors.aspx

Detailed Design Description: –

Most Recent Licensing Application Support Document, e.g.: –

Figure 1 - UK SMR Architectural View

Table 1: ARIS Category Fields (see also Spreadsheet “Categories”) for Booklet

ARIS Category	Input	Select from
Current/Intended Purpose	Commercial – Electric, FOAK	Commercial – Electric/Non-electric, Prototype/FOAK, Demonstration, Experimental
Main Intended Application (once commercial)	Baseload	Baseload, Dispatchable, Off-grid/Remote, Mobile/Propulsion, Non-electric (specify)
Reference Location	On Coast / Inland	On Coast, Inland, Below-Ground, Floating-Fixed, Marine-Mobile, Submerged-Fixed (Other-specify)
Reference Site Design (reactor units per site)	Single Unit	Single Unit, Dual Unit, Multiple Unit (# units)
Reactor Core Size (1 core)	Medium	Small (<1000 MWth), Medium (1000-3000 MWth), Large (>3000 MWth)
Reactor Type	PWR	PWR, BWR, HWR, SCWR, GCR, GFR, SFR, LFR, MSR, ADS
Core Coolant	H_2O	H_2O, D_2O, He, CO_2, Na, Pb, PbBi, Molten Salts, (Other-specify)
Neutron Moderator	H_2O	H_2O, D_2O, Graphite, None, (Other-specify)
NSSS Layout	Loop-type (3 loops)	Loop-type (# loops), Direct-cycle, Semi-integral, Integral, Pool-type
Primary Circulation	Forced (3 pumps)	Forced (# pumps), Natural
Thermodynamic Cycle	Rankine	Rankine, Brayton, Combined-Cycle (direct/indirect)
Secondary Side Fluid	H_2O	H_2O, He, CO_2, Na, Pb, PbBi, Molten Salts, (Other-specify)
Fuel Form	Fuel Assembly	Fuel Assembly/Bundle, Coated Sphere, Plate, Prismatic, Contained Liquid, Liquid Fuel/Coolant
Fuel Lattice Shape	Square	Square, Hexagonal, Triangular, Cylindrical, Spherical, Other, n/a
Rods/Pins per Fuel Assembly/Bundle	264	#, n/a
Fuel Material Type	Oxide	Oxide, Nitride, Carbide, Metal, Molten Salt, (Other-specify)
Design Status	Conceptual	Conceptual, Detailed, Final (with secure suppliers)
Licensing Status	Preparing for GDA	DCR, GDR, PSAR, FSAR, Design Licensed (in Country), Under Construction (# units), In Operation (# units)

Table 2: ARIS Parameter Fields (see also Spreadsheet “Data”) for Booklet

ARIS Parameter	Value	Units or Examples
Plant Infrastructure		
Design Life	60	years
Lifetime Capacity Factor	>90%	%, defined as Lifetime MWe-yrs delivered / (MWe capacity * Design Life), incl. outages
Major Planned Outages	–	# days every # months (specify purpose, including refuelling)
Operation / Maintenance Human Resources	– / –	# Staff in Operation / Maintenance Crew during Normal Operation
Reference Site Design	1 unit	n Units/Modules
Capacity to Electric Grid	443	MWe (net to grid)
Non-electric Capacity	–	e.g. MWth heat at x °C, m3/day desalinated water, kg/day hydrogen, etc.
In-House Plant Consumption	–	MWe
Plant Footprint	–	m^2 (rectangular building envelope)
Site Footprint	40,000	m^2 (fenced area)
Emergency Planning Zone	–	km (radius)
Releases during Normal Operation	– / – / –	TBq/yr (Noble Gases / Tritium Gas / Liquids)
Load Following Range and Speed	50- 100 3-5	x – 100%, % per minute
Seismic Design (SSE)	>0.3g	g (Safe-Shutdown Earthquake)
NSSS Operating Pressure (primary/secondary)	15.5 / 7.6	MPa(abs), i.e. MPa(g)+0.1, at core/secondary outlets
Primary Coolant Inventory (incl. pressurizer)	–	kg
Nominal Coolant Flow Rate (primary/secondary)	– / –	kg/s
Core Inlet / Outlet Coolant Temperature	296 / 327	°C / °C
Available Temperature as Process Heat Source	–	°C
NSSS Largest Component	RPV (empty)	e.g. RPV (empty), SG, Core Module (empty/fuelled), etc.
• dimensions	11.3 / 4.5 / 220,000	m (length) / m (diameter) / kg (transport weight)
Reactor Vessel Material	SA508M Class 1, Grade 3	e.g. SS304, SS316, SA508, 800H, Hastelloy N
Steam Generator Design	Vertical U-Tube	e.g. Vertical/Horizontal, U-Tube/ Straight/Helical, cross/counter flow

ARIS Parameter	Value	Units or Examples
Secondary Coolant Inventory	–	kg
Pressurizer Design	Separate Vessel, Steam Pressurised	e.g. separate vessel, integral, steam or gas pressurized, etc.
Pressurizer Volume	– / –	m^3 / m^3 (total / liquid)
Containment Type and Total Volume	Steel / 40250	Dry (single/double), Dry/Wet Well, Inerted, etc. / m^3
Spent Fuel Pool Capacity and Total Volume	5 years of full-power operation / 740 m^3	years of full-power operation / m^3
Fuel/Core		
Single Core Thermal Power	1276	MWth
Refuelling Cycle	18-24 months	months or “continuous”
Fuel Material	UO_2	e.g. UO_2, MOX, UF_4, UCO
Enrichment (avg./max.)	– / 4.95	%
Average Neutron Energy	–	eV
Fuel Cladding Material	Zr-4	e.g. Zr-4, SS, TRISO, E-110, none
Number of Fuel “Units”	121 Assemblies	specify as Assembly, Bundle, Plate, Sphere, or n/a
Weight of one Fuel Unit	–	kg
Total Fissile Loading (initial)	–	kg fissile material (specify isotopic and chemical composition)
% of fuel outside core during normal operation	N/A	applicable to online refuelling and molten salt reactors
Fraction of fresh-fuel fissile material used up at discharge	–	%
Core Discharge Burnup	55,000-60,000	MWd/kgHM (heavy metal, eg U, Pu, Th)
Pin Burnup (max.)	–	MWd/kgHM
Breeding Ratio	–	Fraction of fissile material bred in-situ over one fuel cycle or at equilibrium core
Reprocessing	None	e.g. None, Batch, Continuous (FP polishing/actinide removal), etc.
Main Reactivity Control	Rods	e.g. Rods, Boron Solution, Fuel Load, Temperature, Flow Rate, Reflectors
Solid Burnable Absorber	Gd_2O_3	e.g. Gd_2O_3,
Core Volume (active)	–	m^3 (used to calculate power density)
Fast Neutron Flux at Core Pressure Boundary	–	N/m^2-s
Max. Fast Neutron Flux	–	N/m^2-s

ARIS Parameter	**Value**	**Units or Examples**
Safety Systems		
Number of Safety Trains	Active / Passive	% capacity of each train to fulfil safety function
• reactor shutdown	0 / 2	N/A / 100
• core injection	2 / 2	100 / 100
• decay heat removal	0 / 3	N/A / 100
• containment isolation and cooling	0 / 3	N/A / 66
• emergency AC supply (e.g. diesels)	2 / 0	100 / N/A
DC Power Capacity (e.g. batteries)	–	hours
Events in which ***Immediate Operator Action*** is required	None	e.g. any internal/external initiating events, none
Limiting (shortest) ***Subsequent Operator Action*** Time	72	hours (that are assumed when following EOPs)
Severe Accident Core Provisions	In Vessel Retention	e.g. no core melt, IVMR, Core Catcher, Core Dump Tank, MCCI
Core Damage Frequency (CDF)	$<10^{-7}$	x / reactor-year (based on reference site and location)
Severe Accident Containment Provisions	PARs, Filtered Venting	e.g. H_2 ignitors, PARs, filtered venting, etc.
Large Release Frequency (LRF)	$<10^{-7}$	x / reactor-year (based on reference site and location)
Overall Build Project Costs Estimate or Range (excluding Licensing, based on the Reference Design Site and Location)		
Construction Time (nth of a kind)	24	months from first concrete to criticality
Design, Project Mgmt. and Procurement Effort	–	person-years (PY) [DP&P]
Construction and Commissioning Effort	–	PY [C&C]
Material and Equipment Overnight Capital Cost	–	Million US$(2015) [M&E], if built in USA
Cost Breakdown	%[C&C] / %[M&E]	
• Site Development before first concrete	– / –	(e.g. 25 / 10) (30 / 40) (20 / 25) (20 / 10) (5 / 15) (----z-------) (to add up to 100 / 100)
• Nuclear Island (NSSS)	– / –	
• Conventional Island (Turbine and Cooling)	– / –	
• Balance of Plant (BOP)	– / –	
• Commissioning and First Fuel Loading	– / –	
Factory / On-Site split in [C&C] effort	– / –	% / % of total [C&C] effort in PY (e.g. 60 / 40)

1. Plant Layout, Site Environment and Grid Integration

SUMMARY FOR BOOKLET

The power station is designed for installation on an extensive range of in-land and coastal sites, across a wide range of soil conditions. This flexibility is enabled through design features such as seismic isolation for safety related areas. The threeloop PWR is located in the Nuclear Island, adjacent to Turbine Island with the Cooling Water Pump House following (Figure 2). Support buildings and auxiliary services are situated within a berm that sweeps around the site and provides protection from external hazards such as tsunami or aircraft impact.

The plant produces 443MWe and is capable of load following and operation on house load where required. As a result of the passive nature of safety systems, the plant is not reliant on grid power for safety related functions. The UK SMR is primarily intended for electricity production; however, the design can be configured to support other heat-requiring or cogeneration applications.

1.1. Site Requirements during Construction

The UK SMR has been designed to maximise constructability, operability and resistance to natural and man-made hazards, whilst maintaining a compact site footprint of approximately 40,000m^2.

Design features such as seismic isolation for safety related areas and road transportable modules ensure that the power station can be constructed on a wide range of sites with varying soil conditions. Although the baseline design utilises direct cooling, and as such would be required to be installed in locations with access to sufficient cooling water, indirect or direct air cooling may be specified, facilitating installation on a wider range of in-land sites.

The three-loop PWR is located in the Nuclear Island, shown in red in Figure 2, adjacent to Turbine Island, shown in yellow, with the Cooling Water Pump House following, shown in blue. These facilities are protected by a robust hazard shield. Support buildings and those containing auxiliary services are situated within a berm that sweeps around the site and provides further protection from external hazards, for example a tsunami or aircraft impact.

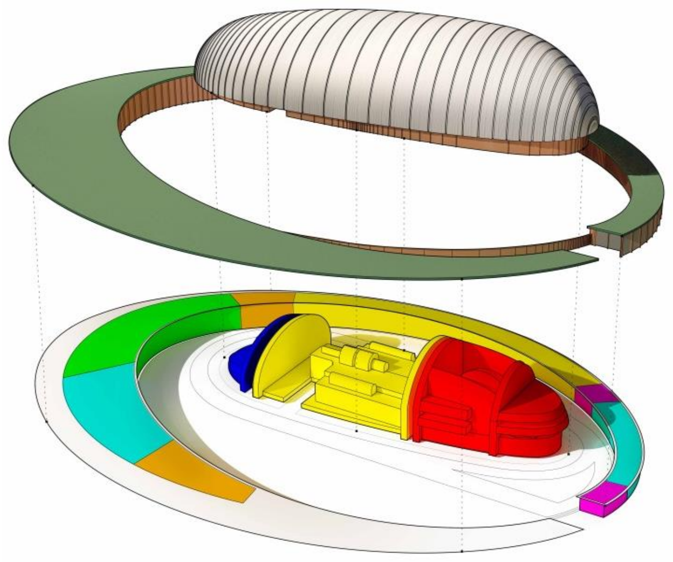

Figure 2 - Simplified Site Plan

An architectural representation of the power station can be seen below in Figure 3. The UK SMR is primarily intended for electricity production; however, the design can be configured to support other heat-requiring or cogeneration applications, as well as provide a primary, carbon free, power source for the production of e-fuels.

Figure 3 – View of UK SMR from Access Road

1.2. Grid Integration

The UK SMR produces 443MWe at 50 Hz and is capable of load following where required. When disconnected from the grid, the plant is capable of load rejection and stable self-sustaining operation on house load subsequent to the disconnection.

The plant is not reliant on grid power for safety related functions due to the passive nature of the UK SMR safety systems; see Chapter **Error! Reference source not found.** for further details on the safety concept.

2. Technical NSSS/Power Conversion System Design

SUMMARY FOR BOOKLET

Overview

The design philosophy for the UK SMR is to optimise levelised cost of electricity against low capital cost. The power output is maximised whilst delivering robust economics for nuclear power plant investment and a plant size that enables modularisation and standardisation throughout.

The primary circuit is a three loop, close-coupled configuration; Steam Generators (SGs) are located around the circumference of the Reactor Pressure Vessel (RPV), with short close-coupled pipework connections between them (Figure 4). The pressuriser is connected to the reactor coolant system pipework hot leg. A centrifugal Reactor Coolant Pump is mounted via a close-coupled nozzle, from the bottom of each SG outlet header.

RPV

The RPV assembly consists of an RPV body, a tori-spherical closure head assembly and a bolting arrangement comprising studs, washers and mechanical seals. The RPV diameter is constrained to be less than 4.5m to ensure that the UK road transport height of 4.95m is not exceeded.

Steam Generator

A vertical u-tube SG design has been selected as a mature and readily deployable technology; other configurations were considered but deemed insufficiently mature for commercial deployment in 2030.

Pressuriser

Primary circuit pressure is controlled by electrical heaters located at the base of the pressuriser and spray from a nozzle located at the top. Steam and water are maintained in equilibrium to provide the necessary overpressure. The pressuriser is a vertical, cylindrical vessel constructed from low alloy steel, sized to provide passive fault response for bounding faults, with accidents causing either rapid and significant cooldown or heat-up accommodated.

Reactor Core and Reactivity Control

Nuclear fuel is industry standard UO_2 enriched up to 4.95%, clad with a zirconium alloy and arranged in a 17x17 assembly. The core contains 121 fuel assemblies and has an active fuelled length of 2.8 m, delivering a thermal power of 1276MWth. Each fuel assembly contains 40 poisoned fuel pins, with the remaining 224 fuel pins being unpoisoned. The poison used is distributed Gd_2O_3 (containing natural gadolinium) at 8 wt%.

No concentration of soluble boron is maintained in the primary coolant for duty reactivity control, which facilitates a simplified plant design and eliminates risks associated with handling hazardous boric acid as well as the environmental impact of boron discharge. Duty reactivity control is instead provided through movement of control rods and use of the negative moderator temperature coefficient inherent to PWRs. It is a goal to achieve a zero discharge plant.

Fuel Cycle and Refuelling

The UK SMR operates on an 18-24 month fuel cycle, with a three core shuffle. The duration of refuelling outage is currently estimated at 18 days, with significant scope for further optimisation as the design progresses. Refuelling is managed through the provision of an in-containment refuelling pool which temporarily stores both new and spent fuel during a refuelling outage. Spent fuel is subsequently transferred to an external spent fuel pool for storage prior to transfer to long term dry cask storage.

Instrumentation and Control Systems

The plant is controlled and protected by a number of control and instrumentation (C&I) systems. The reactor plant control system, which manages duty operations, uses an available in industry programmable logic controller (PLC) or distributed control system (DCS). Opportunities to use smart devices and wireless technologies as part of these systems are being pursued.

The reactor protection system (RPS) provides safe shutdown in response to a fault. The RPS contains priority logic, which from the range of input signals received determines whether to initiate reactor shutdown. The RPS uses digital systems, designed specifically for the nuclear industry. The hardwired diverse protection system (HDPS) uses non-programmable electronics and as such provides a diverse means to shut down the plant in response to fault conditions.

All systems have been designed in line with recognised and endorsed best practices, such as provision of adequate reliable engineering solutions, defence in depth, provision of diversity and redundancy, etc.

Containment

The primary circuit and other key systems are located within a steel containment vessel to confine release of radiation sources during both normal and faulted operation.

2.1. Primary Circuit

The UK SMR primary circuit comprises a reactor core, containing the reactor fuel, mounted in an RPV that is closely coupled through large bore pipework to three SGs. Nuclear fission in the reactor core produces heat which is transferred to coolant in the primary loop through thermal conduction and convection. A pressuriser is connected to the primary circuit via a surge line to provide the necessary overpressure to prevent boiling in the reactor coolant circuit.

The reactor core has been sized to optimise power output within an RPV that is sized to maximise road transportability, producing 1276 MWth. Coolant is transferred via three canned sealless centrifugal Reactor Coolant Pumps (RCPs) to three corresponding vertical u-tube steam generators, each rated to remove approximately 425 MWth during normal power operation. The RCPs are mounted, via close-coupled nozzles, to the bottom of the SG outlet header.

A schematic of the primary circuit (including pressuriser) is presented below in Figure 4. In subsequent subsections, more detail is provided on the primary circuit vessels and components.

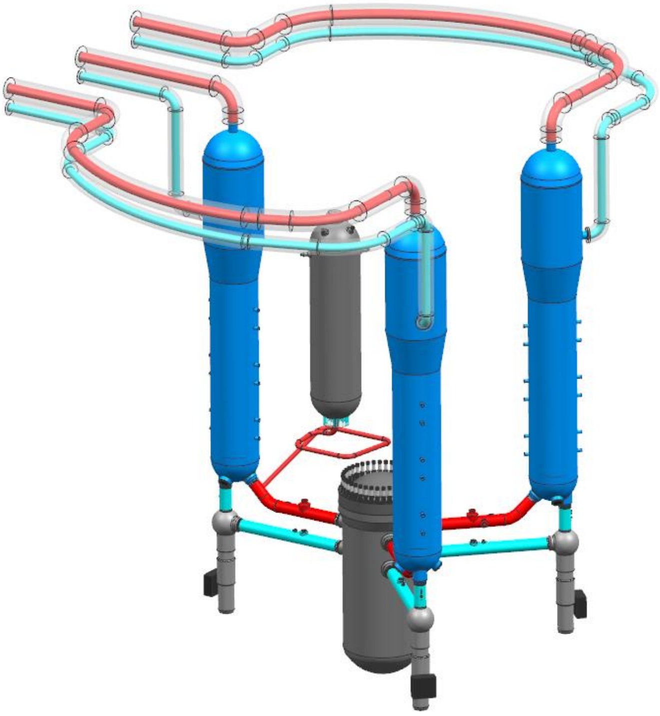

Figure 4 - UK SMR Primary Circuit (inc. Pressuriser)

RPV

The RPV assembly consists of an RPV body, a torispherical closure head assembly and a bolting arrangement comprising studs, nuts, spherical washers and mechanical seals. The primary material for the RPV forgings is ASME SA-508M Grade 3 Class 1 due to its extensive operational history on PWR pressure vessels. The material is also used on other major forgings including the SGs and the pressuriser.

The close-coupled loops are connected to the RPV above the fuelled region with no connections or penetrations below this so that the Loss of Coolant Accident (LOCA) risk is minimised.

Pressuriser

Primary circuit pressure is controlled through the use of electrical heaters located at the base of the pressuriser and spray from a nozzle located at the top of the pressuriser. Steam and water are maintained in equilibrium to provide the necessary overpressure. The pressuriser is a vertical, cylindrical vessel with hemispherical top and bottom heads.

The UK SMR employs surge induced spray whereby primary coolant passively expands into the spray line causing spray. This provides a simple and safe configuration. The pressuriser is sized to provide robust and passive fault response for bounding faults, with accidents causing either rapid and significant cooldown or heat-up accommodated.

Steam Generators

A vertical u-tube SG configuration has been selected as a mature and readily deployable technology. Other designs have been considered but deemed insufficiently mature for commercial deployment in 2030 in the first of a kind plant.

Each of the three steam generators removes approximately 425MWth of heat from the primary circuit, generating dry steam which drives the turbine to generate electricity.

The SG design includes an economiser which preferentially directs feedwater to the cold leg of the tube bundle, and the majority of the recirculated water to the hot leg, resulting in an increased thermal efficiency compared to a conventional equivalent design.

Reactor Coolant Pumps

The pump and motor in the RCP is combined in a sealless design; this avoids potential issues with seals which have been a cause of leaks in previous RCP designs. Each RCP is fitted with a flywheel in order to achieve an extended pump coast-down time, ensuring sufficient cooling flow is pumped through the core in case of a loss of electrical power.

The RCP design provides a flow rate of 3.95 m^3/s and generates 56 m of head (4 bar).

In addition to the primary circuit, a number of auxiliary duty systems are present on the UK SMR. Information on these systems is provided below. It should be noted that safety related systems are not discussed in this chapter; a description of each system is presented in Chapter 4.

Chemistry and Volume Control System (CVCS)

The primary functions of the CVCS system are to control primary plant corrosion, control reactor coolant total dissolved gas, control material deposition and control reactor coolant volume.

The CVCS system is comprised of three subsystems; the chemistry control circuit, the chemical and dosing subsystem and the make-up and discharge subsystem. The chemistry circuit purifies the coolant and helps maintain coolant activity between specified limits, using filters and ion exchange columns.

The chemical and dosing subsystems facilitate zinc dosing, chemical addition and coolant degassing. Finally, the make-up and discharge subsystem helps to control and maintain coolant inventory.

Duty Decay Heat Removal (DHR) System

The primary function of DHR systems is to control core temperature following routine shutdown operations. Two subsystems support this function; Condenser DHR and Normal Residual Heat Removal (NRHR).

Condenser DHR refers to the DHR system that utilises the SGs and normal duty steam condenser to cool the primary plant. It utilises the majority of the same equipment used for steam condensing during critical operation. However, steam is bypassed around the turbines straight to the condenser, whereby it is cooled and condensed by the ultimate heat sink.

NRHR operates by circulating heated primary coolant via dedicated pumps to heat exchangers for cooling. The system is capable of operating when the primary circuit is both pressurised and depressurised (for example during refuelling operations).

Waste Treatment Systems (WTS)

The WTSs provide for the collection and processing for disposition and discharge of gaseous, liquid and solid radioactive wastes generated within the SMR. They are formed from the Gaseous Waste Treatment System (GWTS), Liquid Waste Treatment System (LWTS) and Solid Waste Treatment System (SWTS), which are located in the radioactive waste area next to the reactor containment vessel.

Auxiliary Supporting Systems

To support the operation of the key nuclear systems introduced above, a number of auxiliary systems have been defined.

Two closed-loop cooling water systems are present on the UK SMR. The component cooling system provides cooling water to components including the RCP motors, and the reactor auxiliary system supplies cooling water to the NRHR heat exchangers.

Additionally, the gas supply system, which consists of an air, nitrogen and oxygen supply subsystems, supplies gas to fulfil various auxiliary functions throughout the plant.

2.2. Reactor Core and Fuel

The reactor core is the heart of the reactor design, providing the fuel for generation of nuclear heat for transfer to pressurised water flowing through the core and onward heat transfer to the secondary systems so that electrical power can be generated.

The nuclear fuel is industry standard UO_2 enriched up to 4.95%, arranged in a 17x17 assembly. UO_2 pellets are contained in tubes made from zirconium alloys, which give good neutron economy, structural stability and corrosion resistance in the PWR environment.

The core contains 121 fuel assemblies and has an active fuelled length of 2.8 m. Each fuel assembly contains 40 poisoned fuel pins, with the remaining 224 fuel pins being unpoisoned. The poison used is distributed Gd_2O_3 (containing natural gadolinium) at 8 wt%. The average core burn-up is 55-60GWd/Te.

The advanced yet proven nature of the fuel selected means that there is a mature global supply chain available, minimising risks associated with the expensive and time consuming nature of developing new fuel technologies. The plant has the capability to take advantage of future developments in cladding technology upon maturity, where deemed beneficial.

2.3. Fuel Handling

The UK SMR fuel handling system covers the fuel route from initial receipt of new fuel to final disposal. The primary function of the system is to move fuel between the outside containment storage and the RPV, providing cooling and shielding of the fuel throughout.

The key aspects of the fuel handling system are the fuel handling machine, the in-containment refuelling pool, the spent fuel pool and the long term storage facility.

During refuelling operations, the RPV head, stud tensioner and RPV internals are lifted using and moved away from the RPV body to facilitate the movement of fuel.

Fuel assemblies are lifted in and out of the RPV using a fuel handling machine mounted on rails to and from the refuelling pool. The refuelling pool temporarily stores both new and spent fuel during a refuelling outage.

In the refuelling pool, spent fuel is re-orientated using an upender and subsequently transported out of containment horizontally through an underwater transfer channel, directly into the spent fuel pool. The spent fuel pool is designed to store fuel assemblies for up to 5 years prior to transferring the fuel to dry storage casks.

Transporting new fuel into the RPV is achieved using the reverse of the spent fuel route, following initial receipt and inspection. New fuel will be loaded to the refuelling pool shortly prior to reactor shutdown to reduce the number of fuel movements required on the critical path when the reactor is shutdown.

Both the refuelling pool and spent fuel pool are supported by a dedicated chemistry control and heat removal system.

The UK SMR operates on an 18-24 month fuel cycle, with a three core shuffle. The duration of refuelling outage is estimated at 18 days, though it is expected that this time is reduced as refuelling operations are further optimised and novel technologies incorporated into the process.

2.4. Reactor Protection

The SMR employs SCRAM and Emergency Boron Injection (EBI) to shut down the plant where required in faulted conditions. The functions are triggered from independent and diverse Control and Instrumentation (C&I) systems. Where available, SCRAM is the preferred shutdown method due to the clean-up required after EBI initiation.

The control rod negative reactivity worth alone is sufficient for plant shut down (and hold down of reactivity) independent of use of the boron injection system, demonstrating the redundancy of the protection systems.

2.5. Secondary Side

The turbo-generator system, located in the Turbine Island, is based around conventional power station technology optimised for both thermal efficiency and modular build.

Steam produced in the steam generator passes through the high pressure turbine and into the moisture separator and dual-stage reheater. The steam is superheated before entering the low pressure turbine and condensers. Condensate is subsequently preheated for return to the steam generators through the feedwater system.

2.6. Containment/Confinement

The reactor containment system can be separated into two main elements, the containment vessel and the hazard protection barrier. The principal function of the containment vessel is to confine release of radiation sources during both normal and faulted operation. The hazard protection barrier, which surrounds the containment vessel, protects the plant from external hazards, such as large aircraft impact. In addition to these two main components, the containment system includes a number of additional features to manage radiation confinement.

The UK SMR employs a steel containment vessel material design, which presents significant scope for build schedule improvements when compared to a conventional Post-Tensioned (PT) concrete design. The vessel has been sized and designed to enable modular build, leading to further reductions in construction complexity and build time.

Vessel thickness is driven by the requirement to withstand the pressure increase associated with primary circuit blowdown following a large LOCA. The Passive Containment Cooling System (PCCS) has been specified to allow a reduced vessel thickness, facilitating easier on site welding and eliminating the requirement for post weld heat treatment on the structure.

The containment diameter in this layout has been largely driven by the major RCS components and their supporting structures.

Other relevant design features include the provision of In-Vessel Retention (IVR), which provides protection in the highly unlikely event of a fault followed by successive failure of all protective safety measures resulting in core melt.

The containment system also incorporates features to minimise and mitigate postulated severe accident phenomena. These include passive hydrogen re-combiners to prevent hydrogen explosions and containment vessel overpressure protection via filtered containment venting.

2.7. Electrical, I&C and Human Interface

Electrical aspects of the UK SMR can be divided into the Electrical Power System (EPS), and the Controls and Instrumentation (C&I) system.

The principal functions of the EPS are to transmit electrical power from the main generator to the grid connection point, and to supply electrical power to site loads. Electrical power is generated using the steam turbine-driven main generator described above, which produces electricity at a voltage of approximately 20 kV. A Generator Transformer subsequently “steps up” the voltage for connection to the grid.

Other key elements of the Electrical Power System (EPS) include emergency diesel generators (which supply backup power to essential loads during loss of other supplies), power transformers (which step up and down voltages throughout the site), energy storage systems (which supply short-term power demands of essential equipment) and conductors (i.e. cables and bus-bars to transmit power). All EPS components are selected based on the philosophy of using the best available technology, optimised for constructability.

The C&I systems control and protect the plant in both normal operations and faulted conditions. C&I systems have been designed in line with recognised and endorsed best practices, such as provision of adequate and reliable engineering solutions, defence in depth, minimisation of design complexity, provision of diversity and redundancy, etc. Guidance from key international standards and industrial best practice has been followed to develop a robust and high performing solution.

The Reactor Plant Control System uses an available in industry Programmable Logic Controller (PLC) or Distributed Control System (DCS). The system employs mixed analogue and non-programmable digital sensors and will communicate on hardwired multichannel digital electrical networks. Opportunities to use smart devices and wireless technologies are being pursued.

The Reactor Protection System (RPS) provides safe shutdown in response to a fault. The RPS contains priority logic, which from the range of input signals received determines whether or not to initiate a reactor trip. The RPS will use digital systems, designed specifically for the nuclear industry. It will use mixed analogue/nonprogrammable digital sensors and communicate on hardwired multichannel digital electrical networks by preference.

Hardwired systems are systems which, ideally, do not use digital, software-based logic devices, sensors, displays or other components/sub-systems. The Hardwired Diverse Protection System (HDPS) is diverse to the RPS and therefore uses non-programmable, simple electronics.

The experience of Three Mile Island and other accidents has shown the need for clear plant status displays for long-term essential systems, over days and months, following an accident.

As such, the UK SMR design includes Post-Accident and Severe Accident Management Systems within the Nuclear C&I System. The Control Room Human Machine Interface has been defined encompassing displays, alarms and manual controls. The Nuclear C&I definition also covers the fuel route and hazardous material monitoring system.

Non-Nuclear C&I features include distributed control, networked communications and both traditional and ‘smart’ instruments/actuators.

During normal operations, the plant will be controlled by operators in a control room. An advanced but conventional control room design, using established C&I architecture and technology, comprises the SMR solution. The C&I architecture includes provision for the design of a human-machine interface, optimised to meet Human Factors requirements for an information rich interface to facilitate delivery of the role of the operating personnel.

2.8. Unique Technical Design Features (if any)

Unlike most PWR plants currently in operation or development, no concentration of soluble boron is maintained in the primary coolant for duty reactivity control. This affords a simplified design and eliminates risks associated with hazardous boric acid and environmental impact of boron discharge. It is a design goal to achieve a zero discharge plant.

Duty reactivity control is instead provided through movement of control rods and use of the negative moderator temperature coefficient inherent to PWRs, as well as burnable poisons in the fuel. Control rods are raised and lowered by Control Rod Drive Mechanisms (CRDM), the design of which is based on using an extant linear magnetic jack CRDM design modified accordingly to meet the UK SMR requirements.

3. *Technology Maturity/Readiness*

SUMMARY FOR BOOKLET

The UK SMR is at a mature concept stage; a Rolls-Royce design certificate has been issued which reflects the product definition, covering a wide range of aspects from design and operation through to security and environmental considerations. The project targets completion of the UK Office for Nuclear Regulation Generic Design Assessment process in time for construction of the first of a kind power station to commence in 2025.

This timescale is considered to be achievable through the optimised use of proven technologies to minimise development time and regulatory risk. Innovation is carefully targeted at areas such as civils, and advanced digital and manufacturing technologies, where significant benefits may be achieved, in terms of capital cost and build schedule. A consortium has been formed to deliver the UK SMR, with a wide range of additional UK based academic and industrial partners engaged to further develop capability.

3.1. Deployed Reactors

3.2. Reactors under Licensing Review

3.3. Reactors in the Design Stage

The UK SMR is at a mature concept stage, termed “Basis of Design”. A Rolls-Royce Design Certificate has been issued reflecting the product definition, which covers the following aspects:

- Power Station Definition and Principles of Operation
- Reactor Island Systems Definition
- Turbine Island Systems Definition
- Civil Engineering Solution
- Site Layout
- Electrical Power System
- Safety Management Principles
- Preliminary Safety and Environmental Report
- Preliminary Security Solution

The project aims to deploy the first unit in the UK by 2030; completion of the UK Office for Nuclear Regulation Generic Design Assessment process is planned to coincide with construction of the first of a kind power station to begin in 2025.

The design is based on the optimised and enhanced use of proven technologies to minimise regulatory risk and time to market. As such, innovation is primarily focused on areas where significant value may be added. These areas are primarily civils, and advanced manufacturing and digital technologies; the selection of these areas has been informed by a site-wide TRL assessment of the power station.

A wide ranging consortium has been formed to deliver all aspects of the UK SMR power station. In order to further develop the capability and expertise of the development programme, the consortium has engaged with a broad range of UK based academic and industry-based research programmes.

4. *Safety Concept*

SUMMARY FOR BOOKLET

The design has been developed through a combined systems engineering and safety assessment approach. Based on compliance with relevant good practice and the use of best available technology, the safety concept supports the process by which risks are demonstrated to be tolerable and As Low as Reasonably Practicable. Defence in depth is provided through the provision of robust active and passive safety measures, designed against conservative conditions, which meet the guidelines from the deterministic design basis analysis.

A wide range of safety measures are present on the UK SMR. In addition to heat removal via the closed loop SG steam and feed cycle, the Passive Decay Heat Removal (PDHR) system and the Emergency Core Cooling System (ECCS) are passive, redundant, diverse and segregated protective safety measures that provide multiple means of decay heat removal in response to faults. Additional diverse protection is available from the Small Leak Injection System (SLIS) for smaller leaks. Three safety relief valves are present to protect against overpressure hazards. Control Rod shutdown (SCRAM) and Emergency Boron Injection are employed to shut down the plant where required in faulted conditions; these functions are triggered from independent and diverse systems. Steel containment is provided to mitigate the release of fission products to the environment in the unlikely event of core damage.

Reflecting the design philosophy which prioritises use of passive safety features, active components and supporting electrical supply are identified as not significantly important to the UK SMR risk. As such, hazards which render active systems unavailable such as complete loss of electrical supplies (station blackout) present very low risk. Similarly, failures of operator actions in delivery of safety functions are also identified to not be significantly important, with automated delivery of one-time-movement valve alignment for safety measure actuation, such that the burden on the operator in delivering safety actions is extremely low. As a result, a “walk away” grace time of 72 hours is predicted before human intervention is required.

The behaviour of the plant during abnormal operating conditions has been analysed and assessed using industry validated codes to demonstrate sufficient margin against plant damage for all postulated faults. A Probabilistic Safety Assessment (PSA) indicates an overall Core Damage Frequency (CDF) of $<10^{-7}$ per year of power operation. PSA results identify that the UK SMR presents a balanced design with no single initiating event making a disproportionate CDF contribution.

Internal and external hazard assessments have defined the design basis and informed the plant layout from a perspective of segregation and separation of safety related equipment, with key equipment protected by the hazard barrier which is resilient against external hazards including aircraft impact and tsunami.

4.1. Safety Philosophy and Implementation

The design has been developed through a combined systems engineering and safety assessment approach. Based on compliance with relevant good practice, the use of best available technology and sound engineering underpinned by a strong safety culture, the safety informed baseline design supports the process by which risks are demonstrated to be tolerable and As Low as Reasonably Practicable (ALARP).

The design philosophy is to maximise the number of passive, diverse redundant safety measures, whilst minimising the burden placed on the operator during a plant fault. Individual safety systems are discussed below in Chapter 4.2.

A Probabilistic Safety Assessment (PSA) has been undertaken on the plant design in order to quantify the probability of Core Damage Frequency (CDF) and Large Release Frequency (LRF).

4.2.Transient/Accident Behaviour

For all Design Basis Accidents (DBA), defence in depth is provided through the provision of robust safety measures, designed against conservative conditions, which meet the guidelines from the deterministic design basis analysis.

Multiple layers of fault prevention and protection are provided through diverse and independent active and passive systems, comprehensively ensuring UK SMR safety for design basis and design extension conditions, for all modes of operation and during all lifecycle stages.

In addition to heat removal via the closed loop SG steam and feed cycle, the Passive Decay Heat Removal (PDHR) system and the Emergency Core Cooling System (ECCS) are passive, redundant, diverse and segregated protective safety measures that provide multiple means of decay heat removal in response to faults.

All design basis Loss of Coolant Accidents (LOCA) are protectable by ECCS, with diverse protection additionally available from the Small Leak Injection System (SLIS) for smaller leaks. Control Rods (scram) and Emergency Boron Injection provide two diverse and highly reliable means of reactor shutdown. Three Safety Relief Valves are provided to protect against over pressure hazards, each fully capable of providing relief.

A steel containment vessel is included to mitigate the release of fission products to the environment in the unlikely event of core damage; this system is discussed in more depth above in Chapter 2.6.

Internal and external hazard assessments have defined the design basis and informed the plant layout from a perspective of segregation and separation of safety related equipment, with key equipment protected by the hazard barrier which is resilient against external hazards including aircraft impact and tsunami.

The behaviour of the plant during design basis accident and transient conditions has been assessed using industry validated codes to demonstrate sufficient margin against plant damage for all postulated faults.

The safety benefits afforded by the design of the SMR are reflected within the PSA which calculates an overall CDF from all plant hazards at $<10^{-7}$ per year of power operation. This is an order of magnitude smaller than the individual risk Basic Safety Objective (BSO) provided by the UK ONR. PSA additionally identifies that the UK SMR presents a balanced design with no single initiating fault making a disproportionate CDF contribution.

Reflecting the design philosophy which prioritises use of passive safety features, active components and supporting electrical supply are identified as not significantly important to the UK SMR risk. As such, hazards which render active systems unavailable such as complete loss of electrical supplies (station blackout) present very low risk. Similarly, failures of operator actions in delivery of safety functions are also identified to not be significantly important, with automated delivery of one-time-movement valve alignment for safety measure actuation, such that the burden on the operator in delivering safety actions is extremely low. The plant targets a 72 hour grace time following a DBA, during which time no operator action is required.

A variety of protections and mitigations are also present to limit the impact of a beyond design basis accident (i.e. a severe accident).

In the highly unlikely event of a fault resulting in core melt, an In-Vessel Retention (IVR) system is present to minimise the risk of damaging the integrity of the containment vessel. IVR is achieved by externally cooling the RPV lower head by flooding the reactor cavity pit with water, maintaining the structural integrity of the RPV.

The containment system also incorporates features to minimise and mitigate postulated severe accident phenomena. These include passive hydrogen re-combiners to prevent hydrogen explosions and containment vessel overpressure protection via filtered containment venting. The PSA calculated the resultant Large Release Frequency (LRF) at $<10^{-7}$ per year of power operation.

In the case of a severe accident, the emergency response would be managed by a dedicated Emergency Control Centre.

5. Fuel and Fuel Cycle

SUMMARY FOR BOOKLET (optional)

5.1. Fuel Cycle Options

5.2. Resource Use Optimization

5.3. Unique Fuel/Fuel Cycle Design Features (if any)

6. Safeguards and Physical Security

SUMMARY FOR BOOKLET (optional)

6.1. Safeguards

6.2. Security

The design and use of the UK SMR Security Solution seeks to be pragmatic, effective, and to not unduly impact the efficient day-to-day running of the operations that they seek to protect. Further to this, the Security Solution complements the nuclear and conventional safety of the site, presenting a balance in cases where safety and security may be in conflict with one another. For example, although a more secure environment is provided by restricting access, this approach can impact on evacuation/escape from an area (such as in the event of a fire) or access for emergency services.

The security solution is designed against the UK Office for Nuclear Regulation (ONR) Security Assessment Principles (SyAPS), which drive the design to a solution that fulfils the following functions against any threats: Deter, Detect, Delay and Respond. As opposed to a standard prescriptive security solution, a goal based and risk informed approach has been taken to identify and mitigate any specific threat areas, providing significant levels of defence in depth.

Security is assured through physical and cyber security measures that fall into one of the following two tranches, underpinned by a strong security culture.

1. Dedicated security measures, the primary functions of which are for the purpose of security (for example, access control system, security fencing, vehicle barriers etc.)
2. Security measures which are integrated into the general design features of the SMR and its plant layout (for example, entry/exit points, building/equipment location, structural resilience etc.)

6.3. Unique Safeguards and/or Security Features (if any)

7. *Project Delivery and Economics*

SUMMARY FOR BOOKLET (optional)

Detailed and comprehensive cost analysis, complemented through market demand analysis, has determined that the design is capable of delivering a Levelised Cost of Electricity of around £40-60/MWh for n'th of a kind implementations, depending on financing and project specific requirements. The overnight capital cost is approximately £1.8Bn. The design life of the plant is 60 years.

This cost is achieved through a shortened 48 month build schedule, which includes site preparation, construction and commissioning. This schedule is enabled through a focus on constructability, which is considered a key aspect of the design and has been extensively modelled from an early stage in the design process (Figure 5). To minimise the construction phase of the programme and reduce the resultant capital cost, all aspects of the UK SMR are extensively standardised and appropriately modularised. Mechanical and Electrical (M&E) and civil modules are manufactured in a factory environment prior to be transported to site by road, rail or sea. This concept minimises the onsite time and effort required to construct and build the plant, allowing power generation to commence at the earliest possible point. A cover is installed to fully enclose the site during the construction phase to eliminate the impact of adverse weather conditions on programme schedules, whilst enabling 24/7 working. The site cover provides both isolation of the site from the environment, and isolation of the environment from the site.

During operation, units can be managed through a fleet approach, whereby aspects such as maintenance personnel and spares inventory are managed across multiple plants in a central operations centre. Benefits of this include optimised maintenance schedules, higher availability factors and reduced unplanned outages.

7.1. Project Preparation and Negotiation

Various options exist for customer member states and private entities who are interested in procuring a UK SMR. A customer may choose to procure a single, or multiple SMRs to complement a new or existing power generation portfolio. In such an arrangement, a low proportion of the construction programme would be localised, as required, with the majority of modules, components and systems being provided from existing facilities.

For customers who have a larger requirement, for a fleet approach to SMR deployment, then further localisation may be possible depending on the availability of funding/finance, capability and market/unit demand.

In some cases, where demand, capability and funding potential are strong, then significant localisation may be possible including the establishment of a 'regional hub' for SMR production and export to customers within the local regional area.

7.2.Construction and Commissioning

Once a site has been selected and confirmed, the UK SMR will be constructed using a 2+2 construction plan. A 2 year site preparation phase is followed by plant construction and commissioning, which will be undertaken over an additional 2 years. In order to ensure the viability of the programme, constructability has been considered as a key aspect of the power station design and extensively modelled from early stages of the development programme (Figure 5) to minimise project risk.

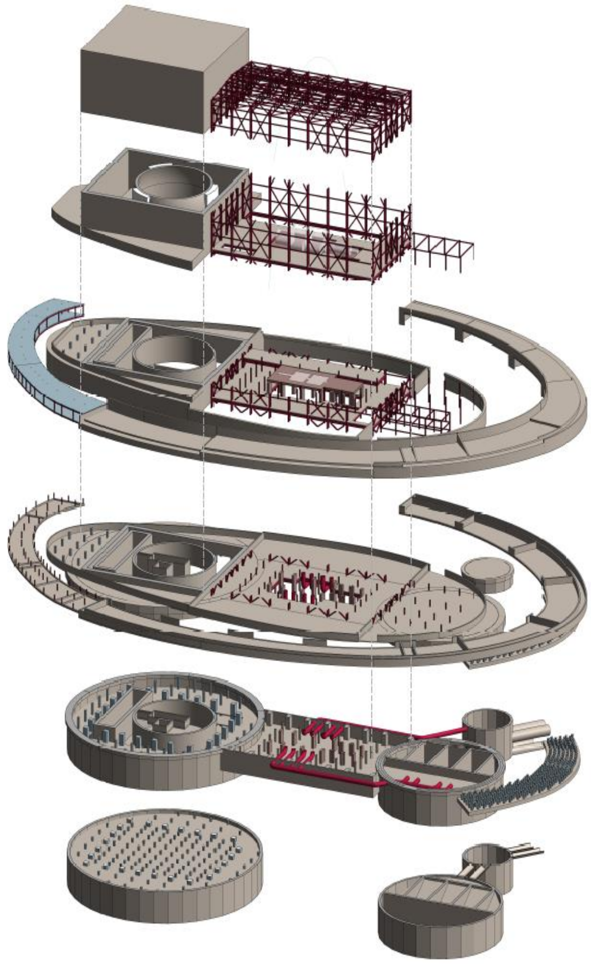

Figure 5 - UK SMR Cross-Section

To shorten the construction phase of the programme and reduce the resultant capital cost, all aspects of the UK SMR are extensively standardised and appropriately modularised. Mechanical and Electrical (M&E) and civil modules are manufactured in a factory environment prior to be transported to site by road, rail or sea. This concept minimises the onsite time and effort required to construct and build the plant, allowing power generation to commence at the earliest possible point. A cover is installed which encloses the site during the construction phase to eliminate the impact of adverse weather conditions on programme schedules, whilst enabling 24/7 working. The site cover provides both isolation of the site from the environment, and isolation of the environment from the site.

The resultant overnight capital cost (including labour) of an n'th of a kind SMR is ~£1.8bn. Enhanced certainty of construction schedule and reduced capital costs leads to a lower project risk, enabling lower financing costs and consequently a reduced Localised Cost of Electricity (LCOE).

7.3.Operation and Maintenance

Detailed and comprehensive cost analysis of the UK SMR, complemented through market demand analysis, has determined that the plant is capable of delivering an LCOE of around £40-60/MWh for n'th of a kind implementation of the design. The costs associated with decommissioning are embedded within the operations and maintenance cost model, and accounted for in the LCOE values quoted.

The UK SMR can also be managed using a fleet approach, where aspects such as maintenance and spares inventory are managed across multiple plants by a centralized operations centre. All units can be monitored against the performance of other units, with advanced data analytics used to facilitate predictive maintenance, minimising downtime and maximising operational performance across the 60 year design life of the plant.