Status Report - AMR (South Africa)

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1. Overview

- ☐ **In Operation**
- ☐ **Under Construction**
- ☐ **Described in**

Link to PRIS	--

- ☑ **New Concept**

Number of Units	--
Year	--

Reference Plant

Name of Site	--
Link to PRIS	--
Net Power Output (MWe)	3
Gross Power Output (MWe)	--

1.1 Introduction

STL Nuclear (Pty) Ltd., the University of Pretoria, the North-West University in conjunction with the South African Nuclear Energy Corporation (NECSA) are developing a 10 MW(t) Small Modular Reactor (SMR) called the Advanced Micro Reactor (AMR). This reactor falls in the category of the High-Temperature, Gas Cooled Reactors (HTGRs). The AMR uses helium as the coolant and is graphite moderated. It uses graphite hexagonal blocks as the moderator and these blocks are arranged to form a cylindrical configuration. The individual SiC fuel assemblies contain TRISO coated particles with either uranium dioxide (UO2) or uranium oxycarbide (UCO) ceramic fuel kernels of between 10 wt% to 19.9 wt% enriched uranium. The voids between the coated particles are filled with a Lead Bismuth Eutectic (LBE) alloy to provide good heat transfer from the fuel particles to the fuel assembly wall.

The AMR can supply electric power to any distribution grid and to standalone or isolated electricity users. It can be deployed as single modules or multi-module plants as well as for process heat applications.

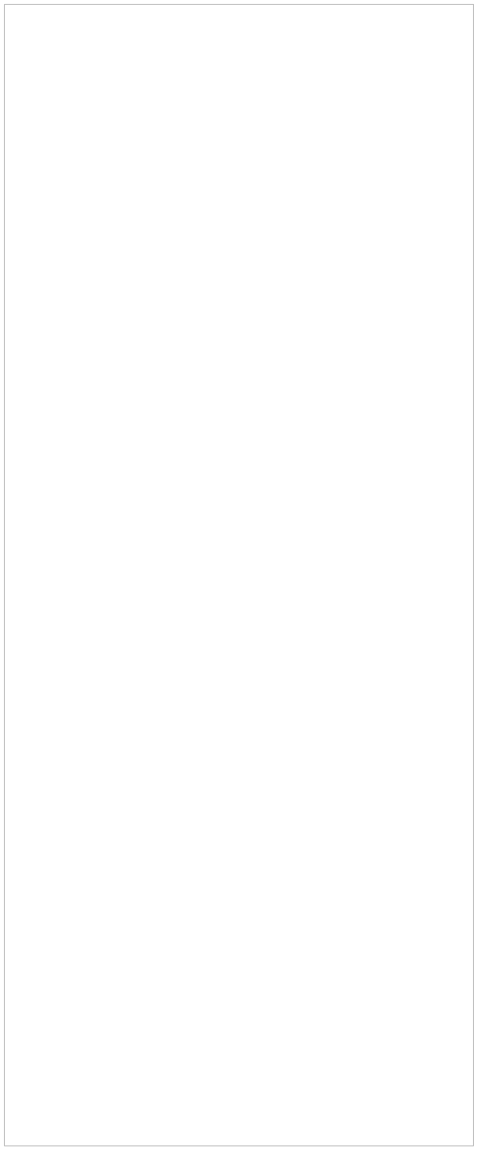


Figure 1. Design concept of AMR

1.2 Development Milestones

2020	Project started
2021	Pre-conceptual design
2022	To begin with conceptual design

1.3 Design organization or vendor company

1.4 Links to designer/vendor website

1.5 Design Description

AMR design utilizes proven HTR technologies albeit in a different configuration The reactor is designed to have excess reactivity to operate for several years before refuelling is required. The design is factory assembled to enable road transportation.

1.6 Licensing Application Support Documents

1.7 Reactor Unit in PRIS

2. Category Fields

Table 1: ARIS Category Fields

ARIS Category	Value	Units of Examples
Current/Intended Purpose	Commercial – Electric/Non-Electric	e.g. Commercial – Electric/Non-electric, Prototype/FOAK, Demonstration, Experimental
Main Intended Application (once commercial)	Baseload, Off - grid / Remote, Non-electric (Process heat applications)	e.g. Baseload, Dispatchable, Off-grid/Remote, Mobile/Propulsion, Non-electric (specify)
Reference Location	Inland	e.g. On Coast, Inland, Below-Ground, Floating-Fixed, Marine-Mobile, Submerged-Fixed (Other-specify)
Reference Site Design (reactor units per site)		e.g. Single Unit, Dual Unit, Multiple Unit (# units)
Core Coolant	He	H2O, D2O, He, CO2, Na, Pb, PbBi, Molten Salts, (Other-specify)
Reactor Core Size (1 core)	Thermal Power < 30 MWth	e.g. Thermal Power < 30 MWth, 30 MWth ≤ Thermal power < 1000 MWth, 1000 MWth ≤ Thermal power ≤ 3000 MWth, Thermal power > 3000 MWth
Reactor Type	GCR	e.g. PWR, BWR, HWR, SCWR, GCR, GFR, SFR, LFR, MSR, ADS
Reactor Size	Microreactor	e.g. PWR, SMR
Neutron Moderator	Graphite	e.g. H2O, D2O, He, CO2, Na, Pb, PbBi, Molten Salts, (Other-specify)
NSSS Layout		e.g. Loop-type (# loops), Direct-cycle, Semi-integral, Integral, Pool-type
Primary Circulation	Forced	e.g. Forced (# pumps), Natural
Thermodynamic Cycle		e.g. Rankine, Brayton, Combined-Cycle (direct/indirect)

Secondary Side Fluid		e.g. H2O, He, CO2, Na, Pb, PbBi, Molten Salts, (Other-specify)
Fuel Form	Coated Sphere	e.g. Fuel Assembly/Bundle, Coated Sphere, Plate, Prismatic, Contained Liquid, Liquid Fuel/Coolant
Fuel Lattice Shape		e.g. Square, Hexagonal, Triangular, Cylindrical, Spherical, Other, n/a
Rods/Pins per Fuel Assembly/Bundle		e.g. #, n/a
Fuel Material Type	Oxide	e.g. Oxide, Nitride, Carbide, Metal, Molten Salt, (Other-specify)
Design Status	Pre-Conceptual Design	e.g. Conceptual, Detailed, Final (with secure suppliers)
Licensing Status		e.g. DCR, GDR, PSAR, FSAR, Design Licensed (in Country), Under Construction (# units), In Operation (# units)
Neutron Spectrum	Thermal	e.g. Fast, Thermal

3. Parameter Fields

Table 2: ARIS Parameter Fields

ARIS Parameter	Value	Units of Examples
Plant Infrastructure		
Design Life	40	Years
Lifetime Capacity Factor		%, 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		n Units/Modules
Capacity to Electric Grid	3	MWe (net to grid)

Non-electric Capacity		e.g. MW(th) heat at x ºC, m3/day desalinated water, kg/day hydrogen, etc.
In-House Plant Consumption		MWe
Plant Footprint	2500	m2 (rectangular building envelope)
Site Footprint		m2 (fenced area)
Emergency Planning Zone		km (radius)
Releases during Normal Operation		TBq/yr (Noble Gases / Tritium Gas / Liquids)
Load Following Range and Speed		x – 100%, % per minute
Seismic Design (SSE)	0.3	g (Safe-Shutdown Earthquake)
NSSS Operating Pressure (primary side)	4	MPa(abs), i.e. MPa(g)+0.1, at core outlet
NSSS Operating Pressure (secondary side)	1.05	MPa(abs), i.e. MPa(g)+0.1, at secondary side outlet
Primary Coolant Inventory (incl. pressurizer)		kg
Nominal Coolant Flow Rate (primary)		kg/s
Nominal Coolant Flow Rate (secondary)		kg/s
Core Inlet Coolant Temperature	450	ºC
Core Outlet Coolant Temperature	750	ºC
Available Tempeature as Process Heat Source		ºC
NSSS Largest Component	Reactor vessel	e.g. RPV (empty), SG, Core Module (empty/fuelled), etc.
- NSSS Largest Component Length	5960	mm
- NSSS Largest Component Diameter	2780	mm
- NSSS Largest Component Thickness		mm

- NSSS Largest Component Weight	115	tonne
Reactor Vessel Material		e.g. SS304, SS316, SA508, 800H, Hastelloy N
Steam Generator Design		e.g. Vertical/Horizontal, U-Tube/ Straight/Helical, cross/counter flow
Secondary Coolant Inventory		kg
Pressurizer Design		e.g. separate vessel, integral, steam or gas pressurised, etc.
Pressurizer Volume		m3 / m3 (total / liquid)
Containment Type		Dry (single/double), Dry/Wet Well, Inerted, etc.
Containment Volume		m3
Spent Fuel Pool Capacity and Total Volume		Years of full-power operation / m3
Non Electric Application		-
Core Delta Temperature	300	ºC
Fuel/Core		
Single Core Thermal Power	4	MW(th)
Refuelling Cycle	96	months or “continuous”
Fuel Material	LEU UO2	e.g. UO2, MOX, UF4, UCO
Enrichment (avg./max.)	10-20	%
Average Neutron Energy		eV
Fuel Cladding Material		e.g. Zr-4, SS, TRISO, E-110, none
Number of Fuel “Units”		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		Applicable to online refuelling and molten salt reactors
Fraction of fresh-fuel fissile material used up at discharge		%

Core Discharge Burnup	80-90	MWd/kgHM (heavy metal, eg U, Pu, Th)
Pin Burnup (max.)		MWd/kgHM
Breeding/Conversion Ratio		Fraction of fissile material bred in-situ over one fuel cycle or at equilibrium core
Reprocessing		e.g. None, Batch, Continuous (FP polishing/actinide removal), etc.
Main Reactivity Control	Control and shutdown rods	e.g. Rods, Boron Solution, Fuel Load, Temperature, Flow Rate, Reflectors
Solid Burnable Absorber		e.g. Gd2O3
Core Volume (active)		m3 (used to calculate power density)
Fast Neutron Flux at Core Pressure Boundary		n/(cm²*s)
Max. Fast Neutron Flux		n/(cm²*s)
Core Control Rod Absorber		-
Core Soluble Neutron Absorber		-
Safety Systems		
Number of Safety Trains	Active / Passive	% capacity of each train to fulfil safety function
- reactor shutdown	Active/Passive	- / - / -
- core injection	Active/Passive	- / - / -
- decay heat removal	Passive	- /- / -
- containment isolation and cooling	Active/Passive	- / - / -
- emergency AC supply (e.g. diesels)	Active/Passive	- / - / -
DC Power Capacity (e.g. batteries)		Hours
Events in which Immediate Operator Action is required		e.g. any internal/external initiating events, none
Limiting (shortest) Subsequent Operator Action Time		Hours (that are assumed when following EOPs)

Severe Accident Core Provisions		e.g. no core melt, IVMR, Core Catcher, Core Dump Tank, MCCI
Core Damage Frequency (CDF)		x/reactor-year (based on reference site and location)
Severe Accident Containment Provisions		e.g., H2 ignitors, PARs, filtered venting etc.
Large Release Frequency (LRF)		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)		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) (----------) (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)
Nuclear System		
System Steam Flow Rate		kg/s
System Steam Pressure		MPa
System Steam Temperature		ºC
System Feedwater Flow Rate		kg/s
System Feedwater Temperature		ºC

Reactor Core		
Active Core Height		m
Equivalent Core Diameter		m
Average Linear Heat Rate		kW/m
Average Fuel Power Density		kW/kgU
Average Core Power Density		MW/m3
Outer Diameter Of Fuel Rods		mm

4. Plant Layout, Site Environment and Grid Integration

SUMMARY FOR BOOKLET

The reactor building contains the safety equipment that provides the necessary functions for the safe shutdown of the reactor under all design basis conditions. The reactor building (RB) is partially submerged below ground level such that the reactor and heat exchanger cavities are completely protected against postulated external threats. The reactor building, electrical building and auxiliary buildings are connected by means of underground tunnels, providing protection for interlinked services. The RB is seismically designed to withstand a design basis earthquake (DBE) and is the only safety related building structure of the AMR.

4.1 Site Requirements during Construction
4.2 Site Considerations during Operation
4.3 Grid Integration

5. Technical NSSS/Power Conversion System Designn

SUMMARY FOR BOOKLET

Power Conversion

A Heat Pipe Heat Exchanger (HPHE) is used to transfer heat from the reactor core to the secondary power conversion loop containing air. The LBE alloy is used to absorb heat from the primary helium coolant bundle (located in the centre) and surrounded by a flow-directing shroud. This heat is then exchanged by means of natural convection with the secondary power loop (in the form of a multiplicity of U-tubes) located in the annulus between the flow-directing shroud and the inner wall of the outer shell of the heat exchanger. The LBE returns to the central hot helium bundle at the bottom through several portals in the flow-directing shroud. This flow of LBE in this design can be described as

"toroidal natural convection flow"

Reactor Core

The AMR is a high temperature helium-gas cooled reactor with a power of 10 MW(t). The helium coolant is circulated through the reactor core by an electric blower located within the pressure boundary of the heat exchanger. As is the custom for thermal neutron-spectrum high temperature reactors, graphite is used as moderator, which in this design, is in the form of hexagonal graphite blocks packed to form an approximate cylindrical configuration with a diameter and height (including radial reflectors as well as top, bottom and) respectively of ~2.2 m (~1.72 m active diameter), and 2.4 m (active length 2.2 m) with a volume of 5.103 m3 which results in a core power density of ~2 MW/m3. The fuel assemblies are silicon carbide tubes that contain the fuel in the form of low-enriched uranium (LEU) dioxide (UO2) or uranium oxycarbide (UCO) TRIstructural-ISOtropic (TRISO) coated particles, immersed in an LBE (45% Pb and 55% Bi) alloy.

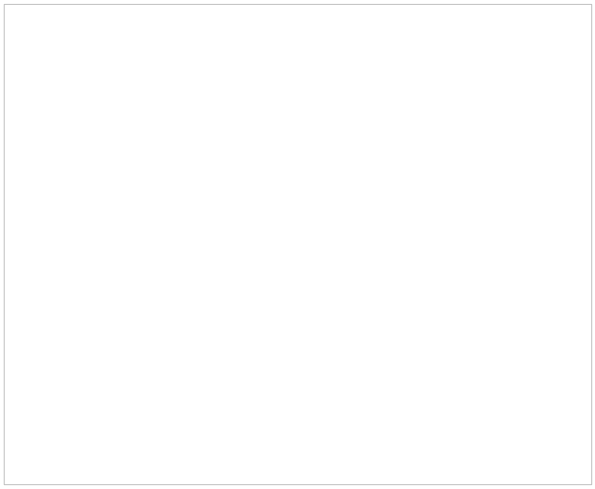


Figure 2. Reactor core

Fuel Characteristics

In typical coated particle. The SiC is the main layer for the retention of fission products. The AMR is also not only limited to kernel and coated particle diameters of 425 microns (µm) and 855 µm respectively but can also utilize kernel diameters of 500 µm and coated particle diameters of 920 µm. The AMR is not restricted to using only high assay low enriched uranium (HALEU) it can utilize enrichments of ~10 wt% to 15 wt%. Approximately ~463 775 coated particles will be contained in a typical fuel assembly.

Fuel Handling System

The AMR is designed to operate between 8 to 10 years without the need for refuelling. Burnable absorbers are used to supress the flux at the beginning of life and extend the life of the reactor as they deplete. The reactor at time of refueling, will be transported back under IAEA seals to the NECSA site where the fuel will be unloaded under continuous IAEA containment and surveillance measures. The spent fuel will be removed and stored during the initial post-operational cooling period on-site in shielded vessels under IAEA seals. After this initial cooldown period and depending on the spent fuel storage strategy in force at the time, it will be transported to its final storage location. A new core will

be loaded in the reactor vessel using the same process as described, and the newly loaded vessel will be transported its operational site.

Reactivity Control

As a defence-in-depth, two diverse shutdown systems, each capable of shutting the reactor down with fresh fuel when the reactor is cold and with one member (of highest reactivity worth) stuck in the full extracted position. The shutdown margin is 8%. Thirteen neutron absorber rods are provided in graphite sleeves; 7 within the core and 6 within the side graphite side reflector blocks. There are also 6 shutdown rods located within the core. The absorber rods can be operated independently as a group or as sub-groups, as required by the reactor operating control system. A control rod consists of several rod absorber material segments, pinned together to form articulating joints. The segments consist of sintered B4C absorber material, sandwiched between an inner and an outer tube segment. The inner tube segment allows cooling helium gas to flow form the top down in the circular channels. If all control and shutdown systems are accidentally withdrawn, it will not lead to fuel damage. This is normally defined as a "start-up accident".

Reactor Pressure Vessel and Internals

The Reactor Pressure Vessel (RPV) is constructed in compliance with the ASME III subsection NB code. It comprises two main components reactor of vessel body and vessel head which is bolted to the vessel body. The reactor vessel body consists of several forged ring-components circumferentially welded together.

The core structures consist of the metallic parts and the graphite structures. The function of these internal structures is to provide stable core geometry, neutron reflection, cold and hot gas channelling, fuel element flow, shielding, thermal insulation and support of the control and shutdown systems guide tubes and the neutron source. The functional design of the structural core internals is such that they can withstand the steady state and transient loadings during normal operation, anticipated operational occurrences and design basis accidents. The loads borne by the ceramic internals are transferred to the stainless-steel core barrel and then to the reactor pressure vessel through metallic components such as the lower support structure and the core barrel axial and radial supports. All areas of the core internals are designed for the service life of the reactor. Access for ceramic structure inspections can be done through the fuel loading channel and the reflector rod holes.

Reactor Coolant System

The helium coolant enters the reactor vessel at 450°C through the annulus of the co-axial duct. The helium then flows upwards in the helium risers located in the outer graphite reflector. Helium leak flow also enters the annular space between the Core Barrel (CB) and the inside of the Reactor Pressure Vessel (RPV). The helium flow enters the top of the reactor core where it is evenly directed to the 420 borings containing the fuel assemblies as well as between the annuli of the control rod guide-tubes. The helium leak flow also enters the top and bottom RPV domes. The helium from the bottom dome re-joins the leak annulus between the CB and RPV, while the helium entering the upper dome flows past the control rod guides and metallic components and connects to the upper gas plenum and is routed downwards to join the major coolant flow past the fuel assemblies. Some helium from the upper dome is also forced into coolant holes within the control rod guide sleeves which flows in the inner anulus of the control rods, this then exits the sleeve and re-joins the major downward flow in the core. The helium then flows downward through the annulus in the borings past the fuel assemblies to remove

heat and exits the core at 750°C. It is then collected in a lower core hot gas plenum that is part of the lower core support structures and flows back through a hot duct (connected to the hot gas plenum) to the HPHE.

Instrumentation and Control System

The Automation System (ATS) comprises the group of safety and non-safety I&C systems that provide automated protection, control, and human-system interfaces. Three specific systems in the AMR that define I&C are plant control, data and instrumentation system, investment protection system and protection system.

5.1 Primary Circuit
5.2 Reactor Core and Fuel
5.3 Fuel Handling
5.4 Reactor Protection
5.5 Secondary Side
5.6 Containment/Confinement
5.7 Electrical, I&C and Human Interface
5.8 Unique Technical Design Features (if any)

6. Technology Readiness

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Testing Conducted for Design Verification and Validation

Experimental activities are being conducted to determine heat transfer enhancement of the Lead Bismuth Eutectic (LBE) in SiC fuel tubes. It is anticipated that the core neutronics will be verified in a future critical facility at the NECSA site. The Helium Test Facility on the NECSA site will be used to test the operational performance of key components under non-nuclear operational conditions of temperature, flow and pressure.

Design and Licensing Status

The AMR is at pre-conceptual phase. The neutronics, thermo-hydraulics and heat transfer analyses are being conducted to verify the safety analysis. Mechanical design and material selection are also underway.

6.1 Deployed Reactors
6.2 Reactors under Licensing Review
6.3 Reactors in the Design Stage

7. Safety Concepts

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Engineered Safety System Approach and Configuration

The plant is designed to perform its safety functions without reliance on the automated plant control system, or the operator. The plant has no engineered safety systems in terms of active human or machine intervention to assure nuclear safety.

Nuclear stability: If all control and shutdown systems are accidentally withdrawn, it will not lead to fuel damage or a radionuclide release. There is no requirement for active safety systems or operator action to prevent fuel damage. This is achieved with a relatively large negative temperature coefficient of reactivity over the entire operational range, a low core power density, a core geometry that will ensure passive decay heat removal and the radionuclide retention capacity of the TRISO particle fuel as well as the SiC structure of the fuel assembly. Xenon oscillations is damped due to the H/D ratio of the core of less than 3 which is normally used as guideline for inherent stability.

Thermal stability: The low power density is ensured in the core design as well as a high thermal capacity and height to diameter ratio (H/D) greater than 0.97 to ensure that the decay heat removal can solely be achieved through conduction, natural convection, and radiation through the reactor structures. It was determined that increasing the height/diameter ratio beyond 0.97 in a trade-off between neutron losses versus the advantage of gaining passive decay heat removal via the walls of a steel pressure vessel in the event of a DLOFC.

Mechanical stability: The design also ensures that the materials of construction remain below the structural design limits and the maximum fuel temperatures in an accident condition remain below the set fuel damage limits

Decay Heat Removal System / Reactor Cooling Philosophy

The Reactor Cavity Cooling System (RCCS) removes heat radiated from the reactor towards the reactor cavity walls. It consists of welded membrane tubes arranged side-by-side on the inside of in the reactor cavity wall. Water is circulated through the tubes to form a cold wall. The RCCS is a passive system and consists of independent cooling trains and is designed for all postulated design basis conditions.

Spent Fuel Cooling Safety Approach / System

The spent fuel will be stored in special tanks of which the height/diameter is in excess of 4. Thermosiphons (heat pipes) are attached to the outside walls of these tanks which removes heat to the outside of the spent fuel area. The condenser ends of these heat pipes are then fitted with fins to dissipate the heat to atmosphere in an entirely passive way. There is also the possibility to use Stirling engine/generators on the condenser ends to generate electricity for charging batteries and in so doing provide a measure of energy conservation.

Containment System

The reactor has two barriers of SiC, that being the SiC layer surrounding each fuel kernel as well as the SiC fuel tube of the fuel assembly. This introduces an additional barrier which will further reduce the probability of any radioactivity being released into the environment. In addition to the two

abovementioned barriers, the pressure boundary serves as a third barrier against release of radioactivity, and then as a final barrier the reactor building can also be accredited as a final enclosure.

Chemical Control

Chemical stability: The design of the core and its coolant routing is such that in an event that could allow air to leak into the pressure boundary, there is no possibility that a sustained corrosion of core components by air can take place. The reactor also does away with the possibility of a water or steam ingress scenario as the helium coolant will transfer heat to a HPHE which is a single-phase natural convection heat pipe heat exchanger using LBE as working fluid. This heat exchanger is then coupled to a Brayton power conversion cycle. The use of a HPHE also introduces another important safety feature by eliminating the possibility of tritium, produced in the primary helium cooling circuit to contaminate the air in the secondary circuit by diffusing through a single tube wall.

Plant Safety and Operational Performances

The thermal-hydraulic calculations show the maximum fuel temperatures for the calculations was 1101.5°C and the maximum central fuel temperatures determined using a validated computer code being 1084°C (a difference of only ~17.5°C) which is 1.6%. LBE is used as filler material in the fuel assembly due to the fact that it reduces the central fuel temperature by ~130°C compared to a fuel assembly only containing helium as the filler material. The fuel will remain below the normal operational temperature guideline chosen of 1130°C and in the case of a DLOFC event will remain below the Germany set temperature limit of 1600°C.

7.1 Safety Philosophy and Implementation
7.2 Transient/Accident Behaviour

8. Fuel and Fuel Cycle

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Fuel Cycle Approach

The AMR is designed for UO2 and UCO. However, it is not limited to the use these types of fuel. The AMR while maintaining safety characteristics, can use alternate fuels without modifications. Advanced fuel cycles for later investigation may range from a (Th, U)O2 using both LEU and HEU, to a UC2 fuel cycle.

Waste Management and Disposal Plan

Disposal of spent fuel elements from the AMR is performed in the following sequence: (i) Direct transfer of spent fuel elements into a flask inside the cast iron high energy spent fuel casks (Hi-cask); (ii) Immediately after filling the H-cask they are sealed and transferred to the spent fuel cool-down facility; (iii) Once cooled down, the flask filled with fuel is transferred from the Hi-cask to a low energy

spent fuel concrete cask (Low-Cask); iv) The Lo-Cask is transported to the low energy on-site interim storage facility; v) For offsite transport the flask is transferred to a shipping/transport cask for shipping to an ultimate repository.

8.1 Fuel Cycle Options
8.2 Resource Use Optimization
8.3 Unique Fuel/Fuel Cycle Design Features

9. Safeguard & Physical Security

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9.1 Safeguards
9.2 Security
9.3 Unique Safeguards and/or Security Features

10. Project Delivery & Economics

SUMMARY FOR BOOKLET

10.1 Project Preparation and Negotiation
10.2 Construction and Commissioning
10.3 Operation and Maintenance