Status Report - EM2 (United States of America)

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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)	1060
Gross Power Output (MWe)	--

1.1 Introduction

This reactor design is an evolution from the previous EM2 which is described in https://aris.iaea.org/Publications/SMR_booklet_2022.pdf.

Energy Multiplier Module (EM2) is a helium-cooled fast reactor with a core outlet temperature of 850°C. It is designed as a modular, grid-capable power source with a net unit output of 265 MW(e). The reactor converts fertile isotopes to fissile and burns them in situ over a 30-year core life. EM2 employs a closed Brayton cycle gas turbine power conversion unit (PCU) with a Rankine bottoming cycle for 53% net power conversion efficiency, assuming evaporative cooling. EM2 is multi-fuel capable, but the reference design uses low-enriched uranium (LEU) with depleted uranium (DU) carbide fuel pellets enclosed in silicon carbide (SiC) composite cladding (i.e., SiGA®).



Fig. 1. Elevation view of EM2 modular building element employing two modules on a single seismically isolated platform

1.2 Development Milestones

2009	Start of design
2013	Pre-conceptual design complete
2020	Pre-application license review (in USA)

1.3 Design organization or vendor company

Christina.Back@ga.com

1.4 Links to designer/vendor website

https://www.ga.com/

1.5 Design Description

1.6 Licensing Application Support Documents

Most Recent Licensing Application Support Document

- Accelerated Fuel Qualification Strategy

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	e.g. Baseload, Dispatchable, Off-grid/Remote, Mobile/Propulsion, Non-electric (specify)
Reference Location	Below-Ground	e.g. On Coast, Inland, Below-Ground, Floating-Fixed, Marine-Mobile, Submerged-Fixed (Other-specify)
Reference Site Design (reactor units per site)	Multiple Units (4 units)	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)	30 MWth <= Thermal power < 1000 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	GFR	e.g. PWR, BWR, HWR, SCWR, GCR, GFR, SFR, LFR, MSR, ADS
Reactor Size	SMR	e.g. PWR, SMR
Neutron Moderator	None	e.g. H2O, D2O, He, CO2, Na, Pb, PbBi, Molten Salts, (Other-specify)
NSSS Layout	Direct-cycle	e.g. Loop-type (# loops), Direct-cycle, Semi-integral, Integral, Pool-type
Primary Circulation	Forced (1 pumps)	e.g. Forced (# pumps), Natural
Thermodynamic Cycle	Brayton	e.g. Rankine, Brayton, Combined-Cycle (direct/indirect)

Secondary Side Fluid	Other	e.g. H2O, He, CO2, Na, Pb, PbBi, Molten Salts, (Other-specify)
Fuel Form	Fuel Assembly/Bundle	e.g. Fuel Assembly/Bundle, Coated Sphere, Plate, Prismatic, Contained Liquid, Liquid Fuel/Coolant
Fuel Lattice Shape	Triangular	e.g. Square, Hexagonal, Triangular, Cylindrical, Spherical, Other, n/a
Rods/Pins per Fuel Assembly/Bundle	91	e.g. #, n/a
Fuel Material Type	Carbide	e.g. Oxide, Nitride, Carbide, Metal, Molten Salt, (Other-specify)
Design Status	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	Fast	e.g. Fast, Thermal

3. Parameter Fields

Table 2: ARIS Parameter Fields

ARIS Parameter	Value	Units of Examples
Plant Infrastructure		
Design Life	60	Years
Lifetime Capacity Factor	95	%, defined as Lifetime MWe-yrs delivered / (MWe capacity * Design Life), incl. outages
Major Planned Outages	2 months (refuelling)	# days every # months (specify purpose, including refuelling)
Operation / Maintenance Human Resources	20/100	# Staff in Operation / Maintenance Crew during Normal Operation
Reference Site Design	4	n Units/Modules
Capacity to Electric Grid	1060	MWe (net to grid)

Non-electric Capacity	N/A	e.g. MW(th) heat at x ºC, m3/day desalinated water, kg/day hydrogen, etc.
In-House Plant Consumption	7.7	MWe
Plant Footprint	5000	m2 (rectangular building envelope)
Site Footprint	85000	m2 (fenced area)
Emergency Planning Zone		km (radius)
Releases during Normal Operation	0 / 0 / 0	TBq/yr (Noble Gases / Tritium Gas / Liquids)
Load Following Range and Speed	10 – 100%, 5% per minute	x – 100%, % per minute
Seismic Design (SSE)	0.3	g (Safe-Shutdown Earthquake)
NSSS Operating Pressure (primary side)	13.3	MPa(abs), i.e. MPa(g)+0.1, at core outlet
NSSS Operating Pressure (secondary side)		MPa(abs), i.e. MPa(g)+0.1, at secondary side outlet
Primary Coolant Inventory (incl. pressurizer)	1200	kg
Nominal Coolant Flow Rate (primary)	275	kg/s
Nominal Coolant Flow Rate (secondary)		kg/s
Core Inlet Coolant Temperature	550	ºC
Core Outlet Coolant Temperature	850	ºC
Available Tempeature as Process Heat Source	N/A	ºC
NSSS Largest Component	RPV (empty)	e.g. RPV (empty), SG, Core Module (empty/fuelled), etc.
- NSSS Largest Component Length	12500	mm
- NSSS Largest Component Diameter	4600	mm
- NSSS Largest Component Thickness		mm

- NSSS Largest Component Weight	280	tonne
Reactor Vessel Material	SA533	e.g. SS304, SS316, SA508, 800H, Hastelloy N
Steam Generator Design	N/A	e.g. Vertical/Horizontal, U-Tube/ Straight/Helical, cross/counter flow
Secondary Coolant Inventory	N/A	kg
Pressurizer Design	None	e.g. separate vessel, integral, steam or gas pressurised, etc.
Pressurizer Volume	N/A	m3 / m3 (total / liquid)
Containment Type	Dry (single)	Dry (single/double), Dry/Wet Well, Inerted, etc.
Containment Volume	3400	m3
Spent Fuel Pool Capacity and Total Volume	60/7700	Years of full-power operation / m3
Non Electric Application		-
Core Delta Temperature		°C
Fuel/Core		
Single Core Thermal Power	500	MW(th)
Refuelling Cycle	360	months or “continuous”
Fuel Material	UC	e.g. UO2, MOX, UF4, UCO
Enrichment (avg./max.)	6.5/17	%
Average Neutron Energy	1000000	eV
Fuel Cladding Material	SiC	e.g. Zr-4, SS, TRISO, E-110, none
Number of Fuel “Units”	85	Specify as Assembly, Bundle, Plate, Sphere, or n/a
Weight of one Fuel Unit	560	kg
Total Fissile Loading (initial)	2600/235U/UC	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	85	%

Core Discharge Burnup	140	MWd/kgHM (heavy metal, eg U, Pu, Th)
Pin Burnup (max.)	290	MWd/kgHM
Breeding/Conversion Ratio	1	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	B4C	e.g. Gd2O3
Core Volume (active)	8.6	m3 (used to calculate power density)
Fast Neutron Flux at Core Pressure Boundary	4E12	n/(cm²*s)
Max. Fast Neutron Flux	8.3E14	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	100 / - / -
- core injection	N/A	100 / - / -
- decay heat removal	Active/Passive	100 /100 / -
- containment isolation and cooling	Passive	- / 100 / -
- emergency AC supply (e.g. diesels)	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		Hours (that are assumed when following EOPs)

Severe Accident Core Provisions	No core melt	e.g. no core melt, IVMR, Core Catcher, Core Dump Tank, MCCI
Core Damage Frequency (CDF)	0	x/reactor-year (based on reference site and location)
Severe Accident Containment Provisions	None	e.g., H2 ignitors, PARs, filtered venting etc.
Large Release Frequency (LRF)	0	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)	42	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	58.14	MW/m3
Outer Diameter Of Fuel Rods		mm

4. Plant Layout, Site Environment and Grid Integration

SUMMARY FOR BOOKLET

The baseline EM2 plant is composed of four 265 MW(e) modules for a combined net power of 1060 MW(e) to a utility grid for evaporative cooling and 960 MW(e) net for dry cooling. Each module consists of a complete powertrain from reactor to heat rejection such that the modules can be built sequentially and operated independently. The plant layout covers 9.3 hectares (23 acres) not including the switchyard. The maintenance hall floor is at grade level, and the roof serves as a protective shield structure. The maintenance hall serves all four reactors.

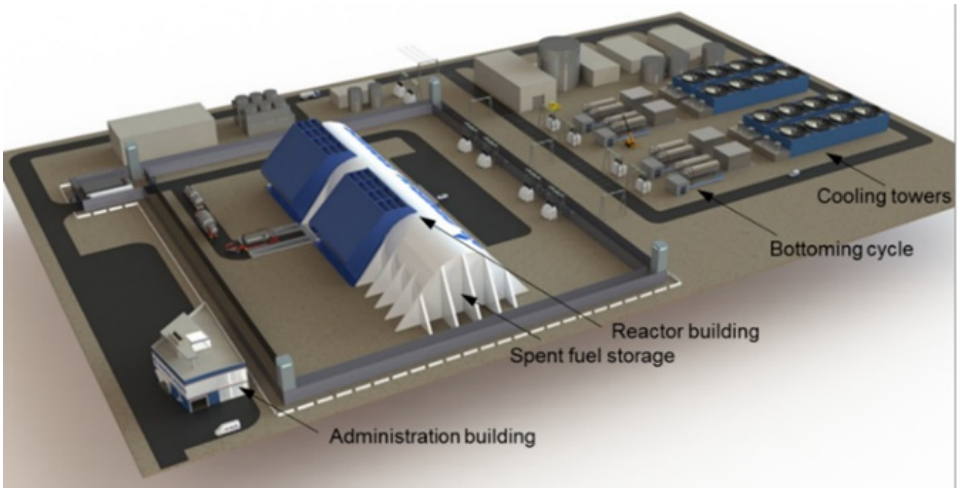


Figure 2. EM2 plant layout on 9 hectares of land.

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

Primary Circuit

The reactor coolant system (RCS) encloses the reactor and PCU and includes all subsystems that contain, transfer, regulate, purify, monitor, and store primary coolant helium. The RCS provides controlled pressurized helium for transport of heat from the reactor to the PCU during normal operation and from the reactor to the direct reactor auxiliary cooling system (DRACS) during shutdown conditions when the PCU is not available. It also provides a Safety Class I barrier against the release of radioactivity to the containment during normal and abnormal conditions.

Reactor Core and Fuel

The EM2 core utilizes the “convert and burn” concept, in which the core is divided into fissile and fertile sections. The fissile section contains ~14.5% LEU to sustain the chain reaction and provide excess neutrons to convert DU fertile to fissile material. The average enrichment of the total active core is 7.7%. The reflector consists of an inner section of zirconium-alloy blocks and an outer section of graphite blocks. The basic building block of the EM2 fuel system is the hexagonal assembly, of which there are 85 in the core. Uranium carbide (UC) is used to meet the high uranium loading requirement and is compatible with the SiGA cladding. Each annular fuel pellet is a sintered “sphere-pac” with a specified interstitial and internal distributed porosity to allow for faster migration of volatile fission products. Both the fuel and cladding materials meet temperature design limits for both normal operations and accident conditions.

Fuel Handling

The core is accessed by a refuelling machine from the maintenance hall floor. An articulated arm extends through the containment and reactor vessel penetration to select and withdraw a tri-bundle assembly and load it into a sealed, air-cooled storage container. The container is moved to the end of the maintenance hall where it is lowered into the fuel storage facility. This facility has the capacity for 60 years of operation. The spent fuel is cooled within the sealed containers by passive natural convection of air. No water or active cooling is required.

Reactor Protection

Reactivity control is provided by the 18 control rods and 12 shutdown rods. Both control rod and shutdown rod systems have sufficient negative reactivity to render the core cold subcritical. The control and shutdown drives are located at the top of the reactor vessel. The control rod drives utilize a ball-screw drive, while the shutdown rods use linear motors.

Secondary Side

The power conversion is based on a combined cycle with a direct helium Brayton cycle and a Rankine bottoming cycle. The helium Brayton cycle is provided by the PCU under the reactor building, while the Rankine cycle is implemented in the facility outside the reactor building. The Brayton cycle incorporates the turbo-compressor and generator which are mounted on an in-line vertical shaft suspended by active magnetic bearings. The cycle also incorporates two heat exchangers: a recuperator and a precooler. The generator uses a permanent magnet rotor to eliminate losses associated with a wound rotor and exciter.

Containment

The containment is a sealed, below-grade system that enclosures the primary heat transport system (PHTS). It is divided into two connected chambers with structural ligaments around the reactor chamber that also serve as shielding to all access to the other chamber. The containment is hermetically sealed with an inert (argon) atmosphere at ~20 psig (0.14 MPa). The peak pressure rating is 90 psig (0.62 MPa). The design leakage rate is less than 0.2% per day.

Electrical, I&C and Human Interface

EM2 deploys advanced sensors for high operating temperature condition such as solid-state and SiC neutron flux monitors. The plant control including startup, operation, and shutdown is conducted through integrated control system actions, which regulate reactor power and turbomachinery to respond to the plant transients. Plant control functions are performed by the power control and process component control systems. The power control system includes control rod drive mechanism (CRDM) and reactor coolant flow. The process component control system includes a non-synchronous, variable speed generator and a frequency inverter.

Unique Technical Design Features

The EM2 core was specifically designed to extend the fuel burnup to maximize the fuel utilization. The core was designed as a convert-and-burn system with the rod-type fuel, not tri-structural isotropic (TRISO) particles, and the fission gases are removed from the fuel. The EM2 design greatly saves the capital cost by combining substantially higher net efficiency and reduced equipment due to the Brayton cycle.

5.1 Primary Circuit

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5.7 Electrical, I&C and Human Interface

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transients. Plant control functions are performed by the power control and process component control systems. The power control system includes control rod drive mechanism (CRDM) and reactor coolant flow. The process component control system includes a non-synchronous, variable speed generator and a frequency inverter.

5.8 Unique Technical Design Features (if any)

The EM2 core was specifically designed to extend the fuel burnup to maximize the fuel utilization. The core was designed as a convert-and-burn system with the rod-type fuel, not tri-structural isotropic (TRISO) particles, and the fission gases are removed from the fuel. The EM2 design greatly saves the capital cost by combining substantially higher net efficiency and reduced equipment due to the Brayton cycle.

6. Technology Readiness

SUMMARY FOR BOOKLET

The technology readiness level is at 4 as the experimental measurements have been partially conducted for: i) UC spherical kernel irradiation tests in High Flux Isotope Reactor (HFIR) in 2021 and measurements of fission gas release and swelling in 2022, ii) a series of thermal, mechanical, and safety measurements of the SiC composite tube, and iii) a low-fluence irradiation of zirconium silicide reflector material in 2016.

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

7. Safety Concepts

SUMMARY FOR BOOKLET

The EM2 safety design uses a defense-in-depth approach, which employs three successive, encompassing barriers against the release of radionuclides. Each barrier relies ultimately on passive means for protection of its integrity for normal and abnormal operation. The first barrier is the SiGA cladding. The second barrier is the primary vessel system, which encompasses the reactor, PCU, and DRACS. The third barrier is the free-standing, below-grade containment. Because the fuel is vented,

the fission gas collection system (FGCS) is an extension of the first barrier.

The engineered safety features (ESFs) are designed to detect incipient conditions that pose a threat to the fission product barriers and initiate protective actions including reactor shutdown, sustained heat removal from the core, and protected integrity of the primary pressure boundary and/or containment. EM2 incorporates several systems classified as ESFs, emergency systems or systems with safety significance such as DRACS, containment system, reactivity control system, reactor protection system, Class 1E Alternating Current (AC) and Direct Current (DC) power systems, and fission product vent system (FPVS).

The DRACS safely removes core decay heat during normal shutdown and accident conditions when the PCU is not available. It provides controlled core heat removal during an anticipated transient without scram (ATWS) and active core heat removal during special maintenance conditions characterized by need for low temperatures and/or low helium pressures.

Helium coolant is maintained at a high level of purity by the helium purification system (HPS). The HPS maintains the total oxidant (O2, CO, H2O, CO2) concentration in the helium below 0.35 ppmv and N2 and H2 concentrations below 10 ppmv; at these levels of purity, chemical interactions between coolant contaminants and the fuel are not life limiting. The high temperature adsorber (HTA) removes halides and metals. The effluent from the HTA is transported to the reactor auxiliary building where the remaining oxidants and noble gases are removed.

7.1 Safety Philosophy and Implementation

7.2 Transient/Accident Behaviour

8. Fuel and Fuel Cycle

SUMMARY FOR BOOKLET

The EM2 open fuel cycle with LEU/DU vented fuels exceeds 30 years without refuelling or shuffling, leading to a reduced cost of power, low proliferation risk, high fuel utilization, and low mass of waste streams. The core can burn used light water reactor (LWR), plutonium, and thorium fuels. Fissile self-sufficient fuel cycle is feasible by removing fission products from the EM2 spent fuel.

8.1 Fuel Cycle Options

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

9. Safeguard & Physical Security

SUMMARY FOR BOOKLET

The EM2 security and safeguards design implements the physical protection against theft, sabotage, and other terrorist activities; protection, control, and accountability of nuclear materials; and international safeguards. The plant design incorporates measures to prevent unauthorized access and/or theft of nuclear material, complying with 10 CFR 73.55 for the physical protection of licensed activities in nuclear power reactors against radiological sabotage and 10 CFR 73.67 for the physical protection of special nuclear material of moderate and low strategic significance.

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

10. Project Delivery & Economics

SUMMARY FOR BOOKLET

The EM2 power generation cost reflects technical features that contribute to lower cost relative to other nuclear reactor technologies such as high net efficiency of 53%, compact PCU in a single vessel, small component sizes amenable to serial production, reduced fuel cycle cost associate with 30-year core, modularized construction resulting in a 42-month on-site construction period, and reduced site footprint and associated construction cost. The overnight capital cost for a four-module Nth-of-a-kind (NOAK) plant with evaporative cooling is $4,500/kWe installed. The levelized cost of electricity (LCOE) is $72/MWh.

10.1 Project Preparation and Negotiation

10.2 Construction and Commissioning

10.3 Operation and Maintenance