Status Report – EM^2 (General Atomics)
USA **DATE (2019/09/30)**

This reactor design is a new concept, of which the technologies have been built from the legacy of gas-cooled reactor development at General Atomics (GA) including the High Temperature Gas-Cooled reactor (HTGR), Gas-Cooled Fast Reactor (GCFR) and Gas-Turbine Modular Helium Reactor (GT-MHR), with a projected earliest deployment (start of construction) time of 2030.

The reference plant has a net power output of 1060 MWe.

INTRODUCTION

Indicate which booklet(s): [ ] Large WCR [X] SMR [ ] FR
Energy Multiplier Module (EM^2) is a helium-cooled fast reactor with a core outlet temperature of 850°C. It is designed by General Atomics (GA) 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. EM^2 employs a direct closed-cycle gas turbine power conversion unit (PCU) with a Rankine bottoming cycle for 53% net power conversion efficiency assuming evaporative cooling. EM^2 is multi-fuel capable, but the reference design uses low-enriched uranium (LEU) with depleted uranium (DU) carbide fuel material with accident tolerant cladding material, i.e. SiGA™ (silicon carbide technology developed by GA). The EM^2 is being developed for the electricity generation and high temperature use.

Development Milestones

2010	Concept design and development – Start of design (changes)
2023	High risk development completed
2024	Start of pre-licencing vendor design review (in U.S.)
2029	Engineering design complete
2030	Start construction of a prototype NPP (in U.S.)
2032	Commercial operation

Design organization or vendor/ company (**e-mail contact**): General Atomics (Ron.Faibish@ga.com)

Links (www…) to designer/vendor homepage: www.ga.com/energy-group

Detailed Design Description:

Most Recent Licensing Application Support Document

- Technical Documentation (TECDOC)
- Conceptual Design Report (CDR)

Fig. 1. Elevation view of EM^2 modular building element employing two modules on a single seismically isolated platform

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

ARIS Category	Input	Select from
Current/Intended Purpose	Commercial – Electric/Non-electric	Commercial – Electric/Non-electric, Prototype/FOAK, Demonstration, Experimental
Main Intended Application (once commercial)	Baseload, Dispatchable	Baseload, Dispatchable, Off-grid/Remote, Mobile/Propulsion, Non-electric (specify)
Reference Location	Below-Ground, Coastal and Inland	On Coast, Inland, Below-Ground, Floating-Fixed, Marine-Mobile, Submerged-Fixed (Other-specify)
Reference Site Design (reactor units per site)	4	Single Unit, Dual Unit, Multiple Unit (# units)
Reactor Core Size (1 core)	Small (<1000 MWth)	Small (<1000 MWth), Medium (1000-3000 MWth), Large (>3000 MWth)
Reactor Type	GFR	PWR, BWR, HWR, SCWR, GCR, GFR, SFR, LFR, MSR, ADS
Core Coolant	He	H_2O, D_2O, He, CO_2, Na, Pb, PbBi, Molten Salts, (Other-specify)
Neutron Moderator	None	H_2O, D_2O, Graphite, None, (Other-specify)
NSSS Layout	Loop-type (1 loop), Direct-cycle	Loop-type (# loops), Direct-cycle, Semi-integral, Integral, Pool-type
Primary Circulation	Forced (1 turbo-compressor)	Forced (# pumps), Natural
Thermodynamic Cycle	Combined cycle	Rankine, Brayton, Combined-Cycle (direct/indirect)
Secondary Side Fluid	N/A	H_2O, He, CO_2, Na, Pb, PbBi, Molten Salts, (Other-specify)
Fuel Form	Fuel Assembly/Bundle	Fuel Assembly/Bundle, Coated Sphere, Plate, Prismatic, Contained Liquid, Liquid Fuel/Coolant
Fuel Lattice Shape	Hexagonal	Square, Hexagonal, Triangular, Cylindrical, Spherical, Other, n/a
Rods/Pins per Fuel Assembly/Bundle	91	#, n/a
Fuel Material Type	Carbide	Oxide, Nitride, Carbide, Metal, Molten Salt, (Other-specify)
Design Status	Conceptual	Conceptual, Detailed, Final (with secure suppliers)
Licensing Status	Pre-licensing	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	95	%, defined as Lifetime MWe-yrs delivered / (MWe capacity * Design Life), incl. outages
Major Planned Outages	18 days per year, maintenance	# days every # months (specify purpose, including refuelling)
Operation / Maintenance Human Resources	377 per 4-unit plant	# 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. MWth heat at x ºC, m3/day desalinated water, kg/day hydrogen, etc.
In-House Plant Consumption	7 MWe per reactor	MWe
Plant Footprint	10000	m^2 (rectangular building envelope)
Site Footprint	85000	m^2 (fenced area)
Emergency Planning Zone	16	km (radius)
Releases during Normal Operation	No planned emissions	TBq/yr (Noble Gases / Tritium Gas / Liquids)
Load Following Range and Speed	10 – 100% 15%/min	x – 100%, % per minute
Seismic Design (SSE)	0.5 g	g (Safe-Shutdown Earthquake)
NSSS Operating Pressure (primary/secondary)	13/	MPa(abs), i.e. MPa(g)+0.1, at core/secondary outlets
Primary Coolant Inventory (incl. pressurizer)	1200	kg
Nominal Coolant Flow Rate (primary/secondary)	320/	kg/s
Core Inlet / Outlet Coolant Temperature	550/ 850	ºC / ºC
Available Temperature as Process Heat Source	N/A	ºC
NSSS Largest Component	RPV (empty)	e.g. RPV (empty), SG, Core Module (empty/fuelled), etc.
- dimensions	11.5/ 4.8/ 301000	m (length) / m (diameter) / kg (transport weight)
Reactor Vessel Material	SA-553 Grade B	e.g. SS304, SS316, SA508, 800H, Hastelloy N
Steam Generator Design	N/A	e.g. Vertical/Horizontal, U-Tube/ Straight/Helical, cross/counter flow

ARIS Parameter	Value	Units or Examples
Secondary Coolant Inventory	N/A	kg
Pressurizer Design	N/A	e.g. separate vessel, integral, steam or gas pressurized, etc.
Pressurizer Volume	N/A	m^3 / m^3 (total / liquid)
Containment Type and Total Volume	Dry/ Inerted/ 2000	Dry (single/double), Dry/Wet Well, Inerted, etc. / m^3
Spent Fuel Pool Capacity and Total Volume	60	years of full-power operation / m^3
Fuel/Core		
Single Core Thermal Power	500	MWth
Refuelling Cycle	360	months or "continuous"
Fuel Material	UC	e.g. UO_2, MOX, UF_4, UCO
Enrichment (avg./max.)	7/ 15	%
Average Neutron Energy	1000000	eV
Fuel Cladding Material	SiC-SiC	e.g. Zr-4, SS, TRISO, E-110, none
Number of Fuel "Units"	85 assemblies	specify as Assembly, Bundle, Plate, Sphere, or n/a
Weight of one Fuel Unit	800	kg
Total Fissile Loading (initial)	42000 U	kg fissile material (specify isotopic and chemical composition)
% of fuel outside core during normal operation	0	applicable to online refuelling and molten salt reactors
Fraction of fresh-fuel fissile material used up at discharge	85	%
Core Discharge Burnup	143	MWd/kgHM (heavy metal, eg U, Pu, Th)
Pin Burnup (max.)	304	MWd/kgHM
Breeding Ratio	1.07	Fraction of fissile material bred in-situ over one fuel cycle or at equilibrium core
Reprocessing	TBD	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	None	e.g. Gd_2O_3,
Core Volume (active)	8.6	m^3 (used to calculate power density)
Fast Neutron Flux at Core Pressure Boundary	3.9×10^{16}	N/m^2-s
Max. Fast Neutron Flux	9.4×10^{18}	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	2 gravity actuated systems	100%
- core injection	None	N/A
- decay heat removal	2 passive loops	100% per loop
- containment isolation and cooling	Active isolation with 2 passive cooling loops	100% per loop
- emergency AC supply (e.g. diesels)	Non-safety diesels	/
DC Power Capacity (e.g. batteries)	72 (monitoring system)	hours
Events in which ***Immediate Operator Action*** is required	None	e.g. any internal/external initiating events, none
Limiting (shortest) ***Subsequent Operator Action*** Time	None	hours (that are assumed when following EOPs)
Severe Accident Core Provisions	Core catcher	e.g. no core melt, IVMR, Core Catcher, Core Dump Tank, MCCI
Core Damage Frequency (CDF)	TBD	x / reactor-year (based on reference site and location)
Severe Accident Containment Provisions	Filtered, vented containment	e.g. H_2 ignitors, PARs, filtered venting, etc.
Large Release Frequency (LRF)	TBD	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 (n^{th} of a kind)	42	months from first concrete to criticality
Design, Project Mgmt. and Procurement Effort	TBD	person-years (PY) [DP&P]
Construction and Commissioning Effort	TBD	PY [C&C]
Material and Equipment Overnight Capital Cost	TBD	Million US$(2015) [M&E], if built in USA
Cost Breakdown	%[C&C] / %[M&E]	
- Site Development before first concrete	TBD	(e.g. 25 / 10)
- Nuclear Island (NSSS)	TBD	(30 / 40)
- Conventional Island (Turbine and Cooling)	TBD	(20 / 25)
- Balance of Plant (BOP)	TBD	(20 / 10)
- Commissioning and First Fuel Loading	TBD	(5 / 15) (-----------) (to add up to 100 / 100)
Factory / On-Site split in [C&C] effort	TBD	% / % of total [C&C] effort in PY (e.g. 60 / 40)

1. Plant Layout, Site Environment and Grid Integration

SUMMARY FOR BOOKLET

The baseline Energy Multiplier Module (EM^2) plant is composed of four 265 MWe modules for a combine net power of 1060 MWe to a utility grid for evaporative cooling and 960 MWe 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 shall be designed for the site parameters such as the maximum ground water level, maximum flood (or tsunami) level, precipitation for roof design, ambient air temperatures, frost line level below grade, site elevation, extreme wind, tornado, soil properties, seismology, etc. A key feature of the power train design is the use of a non-synchronous, variable-speed turbine-generator.

1.1. Site Requirements during Construction

The baseline plant consists of four reactor modules with individual containments sited below grade. It is passively safe and can sustain a Fukushima type station blackout or even a station blackout combined with a loss of coolant accident using only passive safety systems without radioactivity release or loss of plant. For electricity production, EM^2 employs a direct closed-cycle gas turbine with an organic Rankine bottoming cycle for 53% net power conversion efficiency. The reject heat can be released directly to the atmosphere, without evaporative cooling so siting near a large water source is not required. Each primary system is enclosed within a sealed 2-chamber containment, where the chambers are connected by a concentric cross-duct, as shown in Fig. 1. The reactor chamber is enclosed in a concrete shield structure to enable personnel-access to the Power Conversion Unit (PCU) and the Direct Reactor Auxiliary Cooling System (DRACS) located above the reactor vessel.

Site Plans

The plant shall be designed for the site parameters such as the maximum ground water level, maximum flood (or tsunami) level, precipitation for roof design, ambient air temperatures, frost line level below grade, site elevation, extreme wind, tornado, soil properties, seismology, etc. These parameters have been selected to envelope a broad range of U.S. and foreign sites. If a parameter is determined to significantly increase plant cost, a trade study shall be conducted to evaluate necessity for the requirement and the cost-benefit of retaining it in the site envelope.

Acceptable Soil Conditions

Static soil bearing capacity is 425 kPa.

Site Access Needs for Major Equipment and Special Services

All modules and components shall be shippable by truck or rail, or allow for field assembly/ welding of truck or rail shippable sub-modules or component sections. The plant design shall include provisions for replacement of equipment and components designed for less than the plant design life during normal scheduled outages.

Buildings and Structures

The baseline EM^2 plant is composed of four independent modules where each module consists of a complete powertrain from reactor to heat rejection such that the modules can be built sequentially and operated independently. Fig. 2 shows the plant layout, which covers 9.3 hectares (23 acres) not including the switchyard.

Figure 3 shows a cutaway of the reactor building, where grade-level is at the maintenance hall floor. The maintenance hall floor is at grade level, and the roof serves as a protective shield structure. The maintenance hall serves all four reactors. Three sets of rails allow remote handling cars to serve the power conversion, reactor and Direct Reactor Auxiliary Cooling System (DRACS) units, respectively. The DRACS cooling towers, which consist of two 100% towers per module are supported in part by the maintenance hall protective shield and are likewise protected against aircraft crashes. The reactor building is divided into two sets of two module separated by the electrical distribution building and access entry. Two reactor modules with individual containment assemblies are mounted on a seismic isolation platform. The reactor auxiliary building is also mounted on the platform.

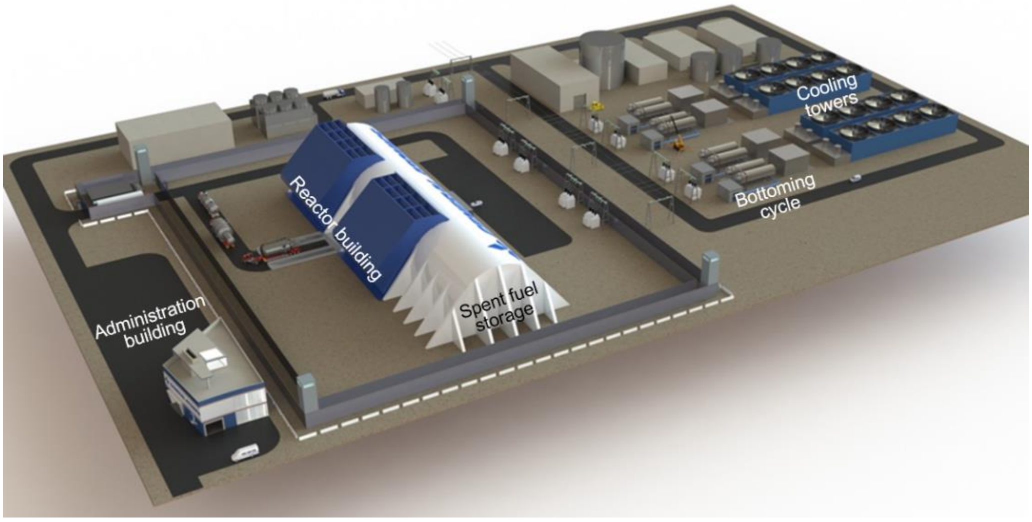

Fig. 2. Site plan for baseline plant arrangement with net 1060 MWe to the grid

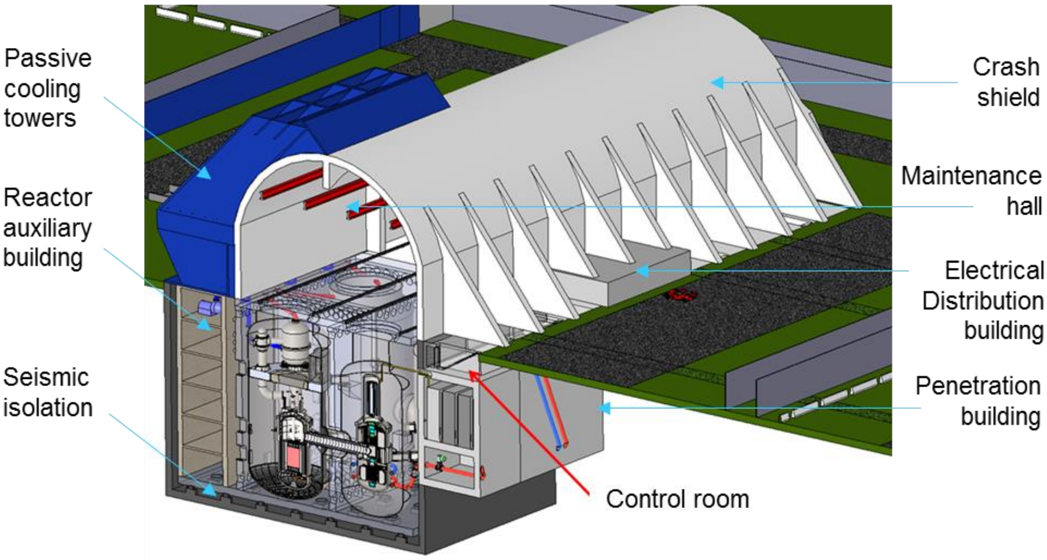

Fig. 3. Illustration four-unit EM^2 plant with below-grade containments

Containment Layout and Structure

Each primary system is enclosed within a sealed 2-chamber containment, where the two chambers are connected by a cross-duct as shown in Fig. 4. The reactor chamber is separated from the Power Conversion Unit (PCU) chamber by a concrete shield structure to enable personnel-access to the PCU. Likewise, access to the DRACS is enabled by a shield structure in the reactor containment chamber. The containment structure is suspended from an approximate mid-plane support frame that also supports the primary system. Access to the reactor, PCU and DRACS units is from the maintenance floor at grade level. Separate access hatches are provided for each containment chamber.

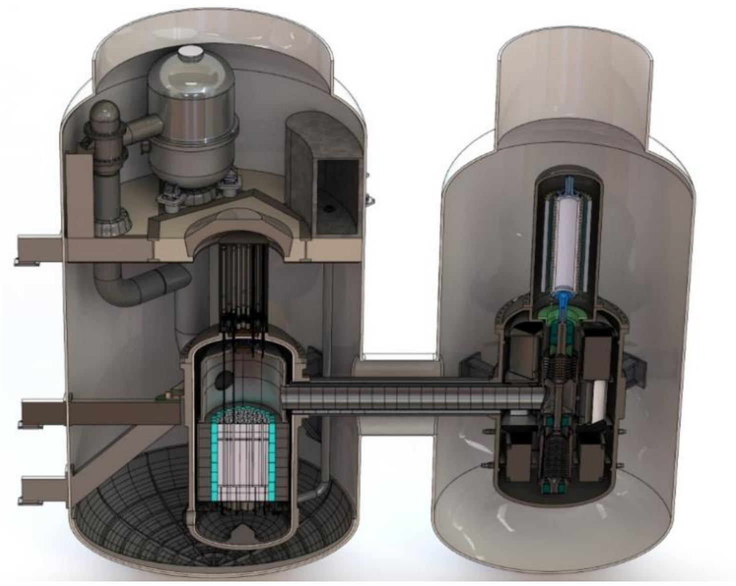

Fig. 4. Illustration of primary system enclosed in free-standing containment

Spent Fuel Facility

The spent fuel storage facility (SFSF) shown in Fig. 5 accommodates 60 years of spent fuel storage. The prototype EM^2 module can store two full cores, and the First-of-a-Kind (FOAK) plant has storage capacity for eight full cores. The SFSF provides adequate passive dry-cooling of the spent fuel, protection from external threats and monitoring for spent fuel storage canister (SFSC) leakage. The SFSF is located below-grade and is protected by an extension of the protective shield that covers the reactor building maintenance hall. The SFSF roof is aligned with the maintenance floor to allow easy transport of the SFSCs to the SFSF. The SFSF has redundant, elevated air intakes and outlets for cooling.

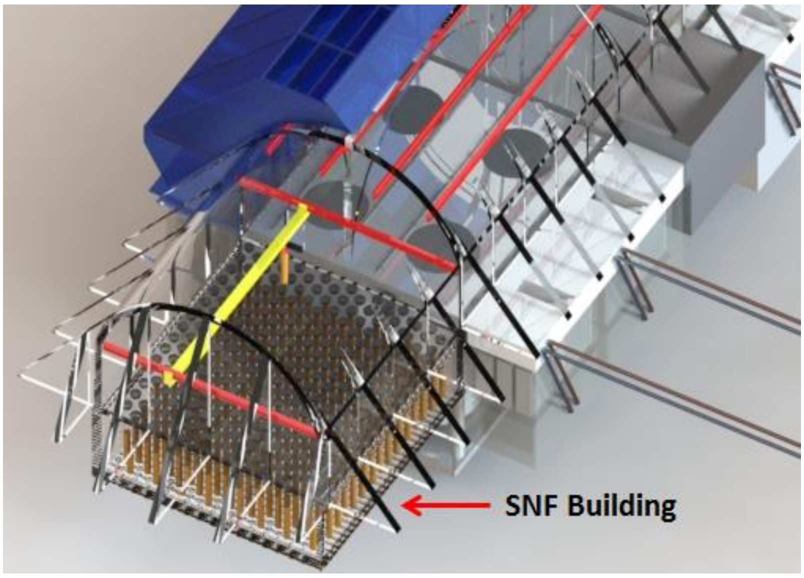

Fig. 5. Illustration of the spent fuel storage facility

Manpower during Construction

Modular design, manufacturing, assembly and construction techniques shall be applied to minimize costs, risks and schedule, plus accommodate sequential deployment of a multi-module plant.

1.2. Site Considerations during Operation

Water Usage Needs for All Plant Systems

The EM^2 plant can be dry cooled and requires no cooling water. If water is available, the water consumption for a 1060 MWe plant would be 415 kg/s. A minor amount of water consumption is required for plant system cooling makeup and convenience water.

Maximum Acceptable Ambient Air Temperature, Humidity, and Heat Sink Temperature

The maximum and minimum dry bulb temperatures are 40ºC and -30ºC, respectively.

Cooling Options

The nominal method of heat rejection shall be wet cooling towers. The plant shall be capable of air heat rejection with no more than a 10% loss of rated output.

Manpower during Operation

Staffing shall be optimized consistent with adapting state-of-the-art automation systems, achieving availability requirements and lowest overall product costs.

On-line and Outage Maintenance Activities

The plant shall be designed for on-line maintenance consistent with availability and economic requirements. The plant design shall include provisions for monitoring equipment status, configuration and performance, and for detecting and diagnosing degradation and/or malfunctions as a basis for predictive maintenance plans and decision making. The reactor design shall provide access to the primary coolant pressure boundary to permit in-service inspection as required by appropriate sections of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (B&PV) Code.

Normal and Abnormal Emissions

There are no planned normal radioactivity emissions.

Thermal Discharges

The nominal heat rejection is 940 MWt per 4-module plant.

Required Infrastructure and Support Systems

The design of plant mechanical and electrical systems and the selection of components and materials shall provide for plant-wide standardization and interchangeability of components and parts.

Provision for the removal of all components within the primary coolant pressure boundary shall be made for inspection, repair, and replacement. This shall include the reactor internals. The degree of difficulty shall be consistent with the likelihood of repair or replacement and availability requirements.

Emergency Planning and Response

The exclusion area boundary is 800 m from the reactor containment building.

1.3. Grid Integration

EM^2 modules operate as base-loaded or load following units. The efficiency is highest in the base-load, full-power mode. An individual unit can follow load between 10-100% of rated output at a maximum rate of 15%/min. This gives the plant a load following range from 2.5 to 100%. At any load point, one module is operated at part load, while the others are operated at 90 to 100% power to maximize overall plant efficiency.

A key feature of the power train design is the use of a non-synchronous, variable-speed turbine-generator. This differs from conventional power plants in which the generator is synchronized with the grid. The incentive for a non-synchronous, variable speed machine is 3-fold:

- The turbo-compressor-generator can be sized for high speed to reduce the size of all three components
- The power output can be controlled by variable speed, which is mechanically easier than turbine by-pass or variable pressure
- The reactor outlet temperature can be maintained constant as a function of load to reduce fatigue damage to structures from load following cycles

The control schematic for response to load demand is illustrated in Fig. 6. In the automatic load following mode, the initial response to load demand changes is provided by the compressor bypass system, which reduces flow to the turbine. This is followed by change in reactor power to maintain constant core outlet temperature. When the temperature set point is reached the bypassed valve is closed.

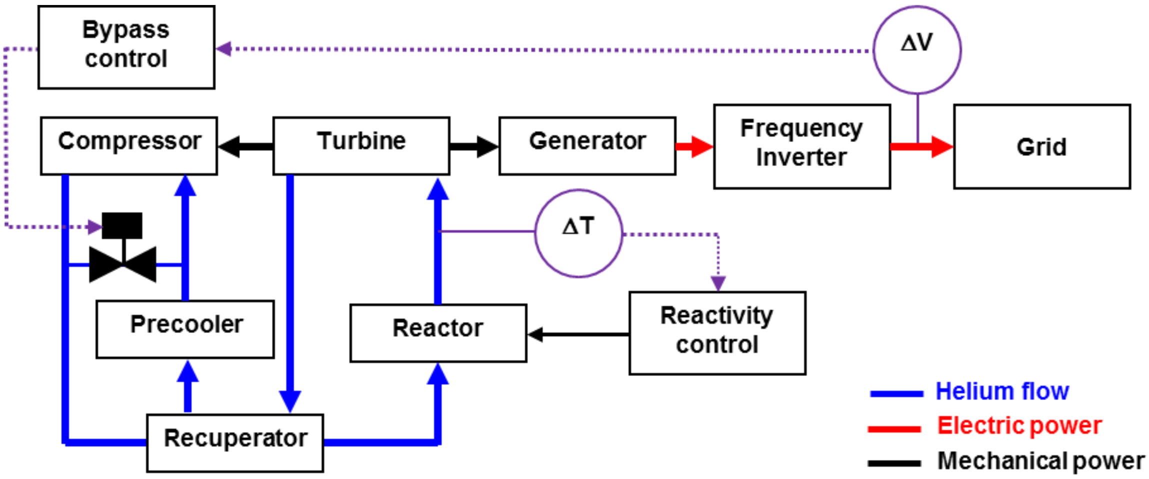

Fig. 6. Conceptual EM^2 plant control response to grid load demand

2. *Technical NSSS/Power Conversion System Design*

SUMMARY FOR BOOKLET

The primary coolant system comprises the reactor system, power conversion unit (PCU), and Direct Reactor Auxiliary Cooling System (DRACS). The primary coolant system includes the vessel system and helium coolant inventory control and purification. The vessel system is divided into two sections connected by a concentric duct where hot helium flows in the inner section and cold helium returns in the outer annular section.

The reactor core, reflector, core barrel and support floor are supported from vessel attachment fixtures. The upper plenum contains a thermal shield structure to protect the top-head from the hot helium gas. The lower plenum contains a core catcher to prevent re-criticality in the unlikely event of a core melt.

The basic building block of the fuel system is the hex-assembly of which there are 85 in an EM^2 core. Eighty-one hex-assemblies are joined into 27 tri-bundles and four remain as individual hex assemblies. The fuel is contained in long cylindrical fuel rods arranged in a triangular pitch. The tri-bundle has a bottom alignment grid, an upper manifold assembly and one intermediate spacer grid.

Fresh EM^2 fuel assemblies are received at the reactor building maintenance hall entrance and stored in a protected dry configuration in the below-grade building space between the module pairs. The refueling equipment consists of a dry spent fuel storage canister (SFSC) for each tri-bundle assembly and a fuel-handling machine. The operation can commence 30 days after reactor shutdown.

Reactivity control is provided by 18 control rods and 12 shutdown rods. The control rods utilize a ball-screw drive while the shutdown rods use linear motors. Both the control rod and shutdown rod systems have sufficient negative reactivity to render the core cold subcritical. The individual control rod worth is kept below 0.26% Δk to mitigate the reactivity insertion due to a single control rod ejection transient. Shutdown rods are fully withdrawn from the core during normal operation.

The EM^2 power conversion scheme uses a combined cycle with a direct helium Brayton cycle on top and an Organic Rankine cycle (ORC) on bottom. The net power delivered to the grid is the power at the generator terminals (gross power) minus house loads and switchyard losses. The plant net efficiency, defined as the net power delivered to the grid divided by the reactor thermal power is 53% for evaporative cooling and 48% for dry-cooling.

Each primary coolant system is enclosed by a sealed, below-grade containment, which is divided into three connected chambers with structural ligaments around the reactor chamber that also serve as shielding to all access to the two side chambers. The containment is hermetically sealed with an inert (argon) atmosphere at ~20 psig. The peak pressure rating is 90 psig. The design leakage rate is less than 0.2% per day.

The turbo-compressor-generator is a non-synchronous machine that rotates at ~6800 rpm at full power. The variable, non-synchronous operation is made possible by commercial power inverters that convert variable input to 50/60 Hz at 99% efficiency.

2.1. Primary Circuit

The primary coolant system encloses the reactor system, PCU, and DRACS. The primary coolant system includes the vessel system and helium coolant inventory control and purification. The vessel system is divided into two sections connected by common concentric ducts where hot helium flows in the inner section and cold helium returns in the outer annular section. The vessels are constructed from standard SA533-Grade B plate steel and internally insulated.

The helium coolant flow path is shown schematically in Fig 7. Hot helium (850ºC) from the core flows at 320 kg/s to the PCU through the inner concentric duct. It expands over the turbine to the recuperator and then to the precooler, which is the cold sink. The helium is pressurized in the compressor and returned to the cold-side of the recuperator. The helium exits the recuperator at the outward side and flows annularly around the recuperator to the outer crossduct annulus. The cold helium (550ºC) exits the crossduct and flows around and down through the inner insulated annular surface of the reactor to the lower plenum below the core. The helium then flows up through the core.

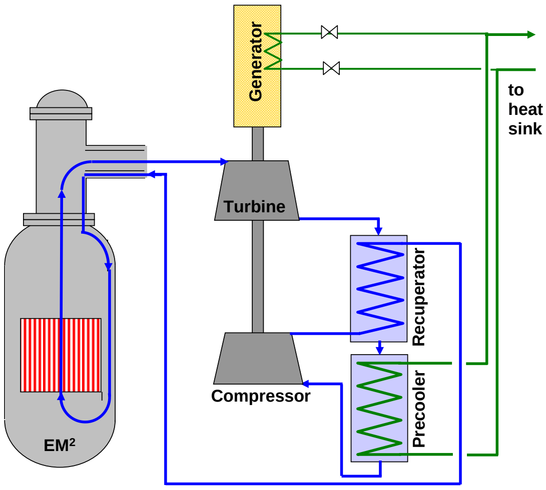

Fig. 7. EM^2 primary coolant helium flow path

2.2. Reactor Core and Fuel

The core is supported by the support floor through the core barrel, which attaches to the vessel below the cross-duct. The upper carbon-composite (C-C) heat shield protects the top head elements from the hot helium. The vessel is internally insulated with silica/alumina fibrous insulation retained with C-C cover plates. This allows the vessel to be constructed from conventional nuclear pressure vessel alloys. The active core is surrounded by top, bottom and radial reflectors. In order to achieve high fuel utilization, the core utilizes the “convert and burn” concept, in which the core is divided into fissile and fertile sections. The fissile section is the “critical” section at beginning of life (BOL). It contains ~14.5% low enriched uranium (LEU) to sustain the chain reaction and provide excess neutrons to convert depleted uranium (DU) from fertile to fissile material. The average enrichment of the total active core is 7.7%. The reflector consists of an inner section of zirconium–silicide blocks and an outer section of graphite blocks.

The basic building block of the EM^2 fuel system is the hexagonal assembly, of which there are 85 in the core. Eighty-one assemblies are joined into 27 tri-bundles and 4 remain as individual assemblies. The tri-bundle is located between separate upper and lower reflector blocks. It has a bottom alignment grid, an upper manifold, and one intermediate spacer grid. The fuel for EM^2 is contained in cylindrical fuel rods arranged in a triangular pitch. Due to the high operating temperatures and long fuel cycle, all tri-bundle structural components and cladding are made of SiGA™ (silicon carbide composite technology developed by General Atomics).

Uranium carbide (UC) is used to meet the high uranium loading requirement. It has a very high thermal conductivity; is compatible with the SiGA cladding; and has a suitably high melting point. 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 to retard fuel swelling over its long core life. SiGA cladding is especially attractive due to its stability under long term irradiation as demonstrated in a multi-year irradiation campaign. Both the fuel and cladding materials meet design criteria temperature limits for both normal operations and accident conditions.

Reactor System

The Energy Multiplier Module (EM^2) core was specifically designed to extend the fuel burnup to maximize the fuel utilization with a reasonable amount of initial uranium loading. From this perspective, a fast neutron spectrum was chosen. High temperature operation was chosen to achieve a high plant thermal efficiency. These design choices require use of high temperature material for the fuel and core structures. To accommodate high fuel burnup, the fission gases are removed from the fuel and stored in a collection system, which maintains the pressure in the fuel slightly lower than the primary system pressure.

The reactor system is shown in Fig. 8. The yellow arrows show the path of primary coolant helium. The core, reflector core barrel and support floor are supported from vessel attachment fixtures located just below the crossducts. The upper plenum contains a thermal shield structure to protect the top-head from the hot helium gas. The lower plenum contains a core catcher to prevent re-criticality in the unlikely event of a core melt.

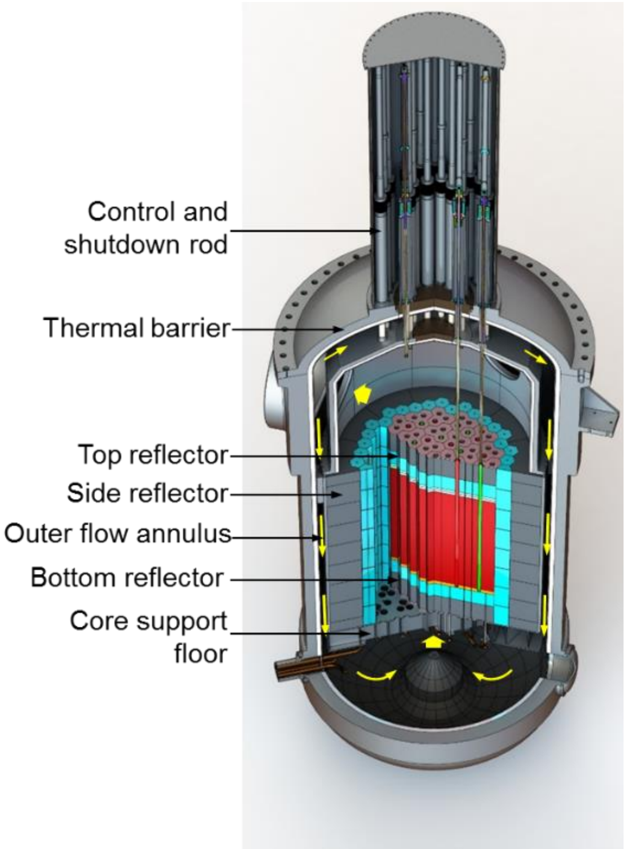

Fig. 8. Cutaway of EM^2 reactor system showing flow path

The core is divided into different enrichment zones. The core is surrounded by reflector, consisting of an inner section of Zr_3Si_2 and an outer section of graphite. The EM^2 core is designed to:

- Maintain a long fuel cycle length with a power level of 500 MW thermal.
- Reduce the excess reactivity of the core to secure the shutdown margin.
- Minimize the local power peaking to preserve a thermal margin of the fuel.
- Use the same fuel form and elemental composition.

The long core life contributes to high uranium utilization. In order to achieve a long core life without refueling, the EM^2 core utilizes the "convert and burn" concept. This necessitates that the reactor be a fast spectrum reactor. At the beginning of life (BOL), the critical reaction takes place mainly in the higher enrichment zones. During operation, excess neutrons are parasitically captured by ^{238}U, which converts to ^{239}Pu through beta emission. As ^{239}Pu is bred, the critical reaction spreads, thereby burning the ^{239}Pu. The total heavy metal loading is 41 ton. The average/peak burnups are 140/250 GWd/t.

The long core life is achieved by converting fertile to fissile fuel. The positive reactivity contribution from fertile-to-fissile conversion roughly balances the negative reactivity from fission products and fuel burnup. The core becomes subcritical when reduced fissile isotope production due to ^{238}U depletion can no longer balance the negative reactivity from fission products. Fig. 9 shows the excess reactivity over core life, which never exceeds 3% Δk. After ~10 years, the majority of the energy comes from fission of ^{239}Pu, which comes from conversion of the fertile ^{238}U. Direct fast-fission of ^{238}U produces about 20% of the energy. The long core life can be achieved with a variety of fuel combinations.

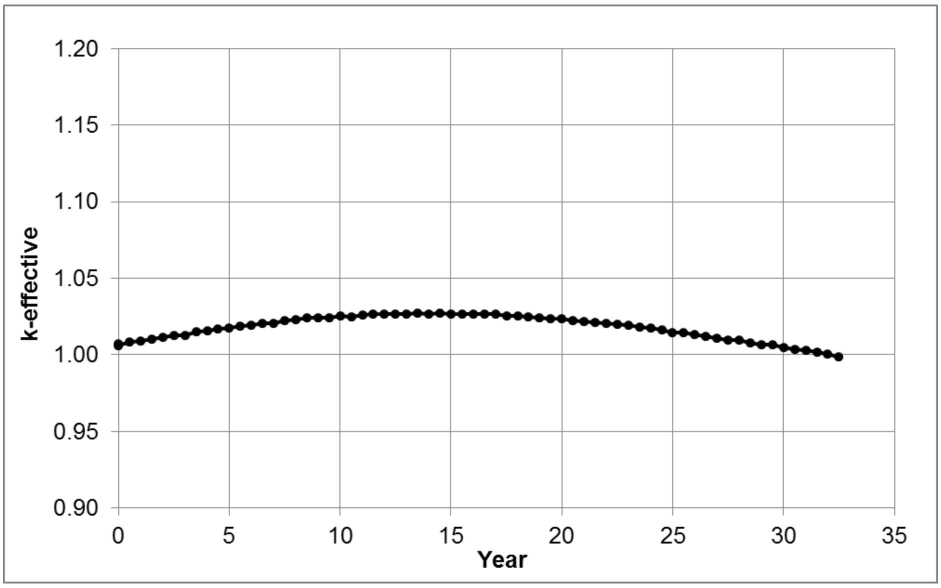

Fig. 9. Evolution of core excess reactivity

Fuel System

The basic building block of the fuel system is the hex-assembly of which there are 85 in an EM^2 core. Eighty-one hex-assemblies are joined into 27 tri-bundles, shown in Fig. 10, and four remain as individual hex assemblies. The fuel is contained in long cylindrical fuel rods arranged in a triangular pitch. The tri-bundle has a bottom alignment grid, an upper manifold assembly and two intermediate spacer grids.

The cladding is chemical vapor infiltrated (CVI) SiC fiber matrix material (SiC-SiC). Each fuel rod is clad in SiC composite with top and bottom end-caps also made of SiC composite. The cladding temperature limit is taken as the maximum temperature for which the SiC composite retains its mechanical strength. This is taken as 1800ºC for normal operation and 2000ºC for short-term accident conditions.

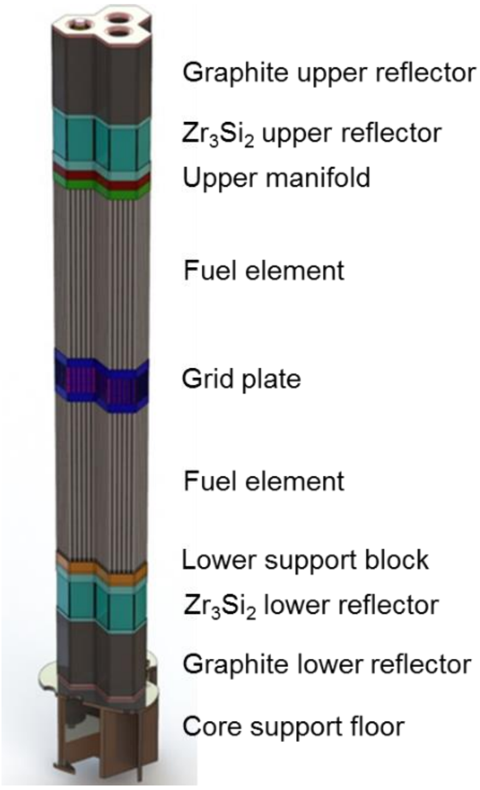

Fig. 10. EM^2 tri-bundle fuel assembly.

2.3. Fuel Handling

Fresh Fuel Receiving and Storage

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.

Fresh EM^2 fuel assemblies are received at the reactor building maintenance hall entrance and stored in a protected dry configuration in the below-grade building space between the module pairs.

Spent Core Removal

Because of the 30-year interval between refuelings, the personnel and equipment for accessing and removing the spent fuel are not normally located at the plant but will be provided as a contracted service. All activities are carried out from the floor of the maintenance hall. All access to and removal of the fuel is by remote handling methods. The refueling equipment consists of a dry spent fuel storage canister (SFSC) for each tri-bundle assembly and a fuel-handling machine. The operation can commence 30 days after reactor shutdown. The SFSCs are positioned inside containment, the refueling hatch at the top of the reactor vessel is opened and an automated articulated arm removes the tri-bundle assemblies into the SFSCs. The SFSCs are moved to the spent fuel storage facility (SFSF) where they are permanently sealed for long-term storage. The SFSC has been developed to safely store a single tri-bundle of fuel. The SFSC enables the spent fuel to be passively cooled by ambient air from the time it is removed from the reactor core while providing shielding and structural protection.

2.4. Reactor Protection

Reactivity control is provided by 18 control rods and 12 shutdown rods. The control rods utilize a ball-screw drive while the shutdown rods use linear motors. Both the control rod and shutdown rod systems have sufficient negative reactivity to render the core cold subcritical. The control and shutdown rods are annular tubes made of boron carbide. The individual control rod worth is kept below 0.26% Δk to mitigate the reactivity insertion due to a single control rod ejection transient. Shutdown rods are fully withdrawn from the core during normal operation. They are inserted as needed to ensure that the control rods have the full range of reactivity control including cold shutdown. When activated, the shutdown rods are inserted rapidly into the core typically within 1-2 sec.

The function of the Reactor Protection System (RPS) is to initiate protective actions in response to abnormal events that may threaten the integrity of the fission product barriers and, consequently, the public safety. These protective actions include rapidly shutting down the reactor and taking additional protective actions such as isolating the containment. The RPS is safety-related, Seismic Category I, and electrical Class 1E. It is physically and electrically separated from the plant control, data and instrumentation system (PCDIS). The RPS sensors provide determination of physical parameters within the reactor system. Trip criteria processors evaluate the levels of the physical parameters and determine whether a protective action is required. The RPS also includes operator interfaces and monitoring displays.

2.5. Turbine/Generator Side

The EM^2 power conversion scheme uses a combined cycle with a direct helium Brayton cycle on top and an Organic Rankine cycle (ORC) on bottom. The calculation of plant net efficiency has a large impact on plant economics. The “net efficiency” is defined as the net power delivered to the grid divided by the reactor thermal power. The net power delivered to the grid is the power at the generator terminals (gross power) minus house loads and switchyard losses. For economic evaluations, the average temperature condition for U.S. is used. In the case of evaporative cooling, this is the average annual U.S. wet bulb temperature (12.2°C) and for dry cooling this is the average annual U.S. dry bulb temperature (20°C).

Power Conversion Unit (PCU) Brayton Cycle

Figure 11 shows a cutaway of the PCU vessel, which contains all components that are in contact with primary coolant. The turbine-compressor and generator are mounted on an in-line vertical shaft. The generator is located in a separate, connected vessel at the top of the PCU. A dry-gas shaft seal isolates the helium in the generator from the primary coolant. The generator cavity is maintained at lower pressure to reduce windage losses. The generator is mounted on active magnetic bearings including two radial bearings and one thrust bearing.

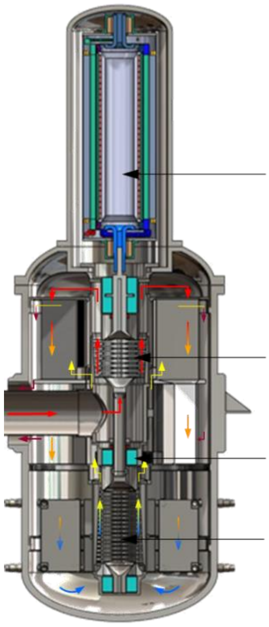

Fig. 11. Principal elements of the power conversion unit

The generator shaft is attached to the turbo-compressor shaft by a spline that enables the generator to be removed for maintenance without having to remove the turbo-compressor. A shaft seal is located between the turbine and compressor to prevent leakage. The turbo-compressor shaft is suspended on active magnetic bearings. The thrust bearing is located above the turbine and is sized for the dead-weight load plus vertical seismic loads. During power operation the thrust counter-balances the weight. Neither the generator nor the turbo-compressor has a bending mode below the 1^{st} critical speed.

Organic Rankine Cycle (ORC)

The ORC operates on a supercritical R-245fa cycle. The cycle does not require a recuperator to achieve good efficiency. Furthermore, the temperature-heat load (T-Q) diagram shows that the evaporator does not have a sharp pinch-point that would limit the effective use of the available energy at higher temperatures. The thermodynamic efficiency of the ORC cycle is 15.8%.

2.6. Containment/Confinement

Each primary coolant system is enclosed by a sealed, below-grade containment, which is divided into two connected chambers with structural ligaments around the reactor chamber that also serve as shielding to all access to the side chambers, shown in Fig. 4. The containment is hermetically sealed with an inert (argon) atmosphere at ~20 psig. The peak pressure rating is 90 psig. The design leakage rate is less than 0.2% per day.

Each chamber has a top hatch to enable access for repair and replacement of equipment. The reactor chamber top-hatch will allow fitting of refueling equipment to remove and replace the core. Access to the DRACS heat exchangers and high temperature absorbers (HTAs) is also through the reactor chamber top-hatch. The PCU top-hatch will allow removal and reinstallation of all PCU equipment. All pipe penetrations through the containment have double isolation valves.

The containment has two cooling systems. During normal operation, an active heat removal system removes heat losses from the primary system as well as instrument, electrical and mechanical equipment heat. For accident conditions, the reactor-chamber liner is cooled by an air convection system. This system is sized to enable protection of the containment liner and removal of heat under all conditions.

2.7. Electrical, I&C and Human Interface

The major functions of the Plant Control, Data, and Instrumentation System (PCDIS) are:

- accept operator direction,
- monitor processes and systems,
- process information and make process control decisions,
- execute control actions by actuating control equipment, and
- report/record information for operators and plant management.

Each module has a dedicated PCDIS, which provides monitoring and control over the full range of operations including pre-operational testing, startup, power operation, shutdown, and abnormal conditions. The PCDIS includes instrumentation, hierarchical sequencing and process control loops and actuators for automatic operation of the plant, but manual control remains available at all times.

The PCDIS transfers both analog and discrete signals through a distributed control systems (DCS), which is a processor-based electronics system, containing programmable software that provides all the logical and analytical decisions. The DCS has real-time inputs and outputs to execute all required functions, analog or discreet, within specified response times. It is a commercially proven technology used for digital control of natural gas-fired, coal-fired, fossil fuel-fired, and nuclear power plants. In addition, the PCDIS also includes a historian/database, which is a programmable database with a dedicated server. The historian stores all of the programmed plant data and makes it available whenever required for analysis or trending.

Each EM^2 module pair has a separate control room with dedicated separate control consoles for each of the two modules. A single remote shutdown facility is provided with separate safe shutdown and post-accident monitoring capability for each module.

2.8. Unique Technical Design Features (if any)

Each EM^2 fuel assembly incorporates a vent port connected to the Fission Gas Venting System (FPVS). Fission gases are released from the fuel pellets and flow up through the fuel rod to a manifold at the top of the tri-bundle. The fission gases are then transported to the sub-header assembly below the core support floor and then to the adsorber in the DRACS chamber. The adsorber container is shielded and cooled by natural convection cooling by the containment atmosphere. The shielding is sufficient to allow personnel-access to the DRACS chamber.

3. *Technology Maturity/Readiness*

SUMMARY FOR BOOKLET

Most Gas-cooled Fast Reactor (GFR) concepts, including the original 600 MWth Generation IV reference design, would use a gas-turbine power conversion system (PCS) operating in the 250 to 850°C range. The technology of such a system is to a large extent the same as that proposed for the Very High Temperature Reactor (VHTR), and thus a reasonable assessment of the maturity can be obtained from the maturity assessment conducted for the Next Generation Nuclear Plant Program (NGNP). For a gas turbine system driven by very high-temperature helium, NGNP technology development roadmaps describe the state of Brayton cycle technology. The overall maturity of the concept was defined as the minimum technology readiness level (TRL) for a set of key subsystems required for a concept to achieve its performance goals. Using this process, the GFR was assessed to be the least technically mature of all of the concepts considered, with an overall TRL of 2.

3.1. Deployed Reactors

N/A

3.2. Reactors under Licensing Review

N/A

3.3. Reactors in the Design Stage

Technology Readiness Assessment

In 2018, as part of a study on Gas-Cooled Fast Reactor Research and Development Roadmap, technological maturity assessments were performed by a team of U.S. Department of Energy (DOE) Idaho National Laboratory (INL) technical staff. For GFR concept, the technological maturity of each subsystem and the encompassing systems were evaluated based on EM^2 design information. The overall maturity of the concept was defined as the minimum technology readiness level (TRL) for a set of key subsystems required for a concept to achieve its performance goals. Using this process, the GFR was assessed to be the least technically mature of all of the concepts considered, with an overall TRL of 2.

Table 3 lists the TRLs assigned to the EM^2 systems and subsystems. Major technologies used in all GFRs proposed to date are largely common in a way that these TRL values can be considered representative of the concept. The shaded cells in the TRL value columns indicate the key systems and subsystems needing to be developed fully in order for a design to achieve its performance objectives.

Most GFR concepts, including the original 600 MWth Generation IV reference design, would use a gas-turbine PCS operating in the 250 to 850°C range. The technology of such a system is to a large extent the same as that proposed for the Very High Temperature Reactor (VHTR), and thus a reasonable assessment of the maturity can be obtained from the maturity assessment conducted for the Next Generation Nuclear Plant Program (NGNP). For a gas turbine system driven by very high-temperature helium, NGNP technology development roadmaps describe the state of Brayton cycle technology.

Table 3: TRLs for each system and subsystem of the EM^2 with a combined cycle PCS

System/Subsystem	EM^2
Nuclear heat supply	2
Fuel element (fuel, cladding, assembly)	2
Reactor internals	3
Reactivity control	6
Reactor enclosure	4
Operations/inspection/maintenance	4
Core instrumentation	3
Heat transport	3
Coolant chemistry control/purification	7
Primary heat transport system (hot duct)	6
Intermediate heat exchanger (if applicable)	3
Pumps/valves/piping	5
Auxiliary cooling	6
Residual heat removal	3
Power conversion	5
Turbine	5
Compressor/recuperator (Brayton)	5
Reheater/superheater/condenser (Rankine)	N/A
Steam generator	7
Pumps/valves/piping	6
Process heat plant (e.g., H_2)	N/A
Balance of plant	6
Fuel handling and interim storage	6
Waste heat rejection	7
Instrumentation and control	7
Radioactive waste management	6
Safety	2
Inherent (passive) safety features	3
Active safety system	2
Licensing	1
Safety design criteria and regulations	3
Licensing experience	3
Safety and analysis tools	3
Fuel cycle	3
Recycled fuel fabrication technology	3
Used fuel separation technology	3
Safeguards	3
Proliferation resistance—intrinsic design features (e.g., special nuclear material accountability)	3
Plant protection—intrinsic design features	3

Licensing

GA ultimately intends to obtain a Design Certification for EM^2 from the U.S. Nuclear Regulatory Commission (NRC) under 10CFR Part 52. EM^2 is a gas-cooled fast reactor, whereas the relevant NRC experience and the body of licensing regulation applies to light water reactors

(LWRs). Therefore, GA will incorporate its licensing strategy within its development plan. The strategy will be conducted in three phases. During Phase 1, GA will engage the NRC on the basis of a pre-application review. This will consist of identifying the principal licensing issues with the NRC and preparing Licensing Topical reports on each issue as the basis for review and determination of specific licensing requirements for EM^2.

During Phase 2, GA will construct and operate a demonstration reactor that will demonstrate the safety characteristics and serve as the basis for qualifying the fuel. Successful operation of the demonstration reactor will then serve as the basis for obtaining the Design Certification during Phase 3, which involves the construction of the prototype reactor.

4. *Safety Concept*

SUMMARY FOR BOOKLET

The EM^2 design includes three principal barriers to the release of radioactive materials to the environment. These include the fuel, the reactor coolant pressure boundary (RCPB), and the containment. The EM^2 safety design effort to-date has mainly been on the reactor system, containment and Direct Reactor Auxiliary Cooling System (DRACS). The EM^2 safety philosophy is built on five premises:

1) EM^2 utilizes a defence-in-depth approach with three barriers to prevent release of fission products to the public: fuel cladding (and vent system), primary coolant pressure boundary (vessel system) and a below-grade sealed containment.
2) A risk-informed approach will be used to determine events and their frequency that could threaten the integrity of the fission product barriers. Plant operating and maintenance systems will be designed to reduce the frequency of accidents and plant safety systems will be designed to reduce the consequence of accidents.
3) Passive safety features are the main line of defence against all abnormal and accident conditions including “beyond design basis events” which can threaten the integrity of the three fission product barriers.
4) All safety-related systems, including passive safety features, must be regularly tested.
5) A comprehensive instrumentation system shall be implemented to provide regularly updated information on the conditions of the fuel clad, primary coolant pressure boundary, and containment.

4.1. Safety Philosophy and Implementation

Safety Concept

The EM^2 design includes three principal barriers to the release of radioactive materials to the environment. These include the fuel, the reactor coolant pressure boundary (RCPB), and the containment. The EM^2 safety design effort to-date has mainly been on the reactor system, containment and DRACS. The EM^2 safety philosophy is built on five premises:

1) EM^2 utilizes a defence-in-depth approach with three barriers to prevent release of fission products to the public: fuel cladding (and vent system), primary coolant pressure boundary (vessel system) and a below-grade sealed containment.
2) A risk-informed approach will be used to determine events and their frequency that could threaten the integrity of the fission product barriers. Plant operating and maintenance systems will be designed to reduce the frequency of accidents and plant safety systems will be designed to reduce the consequence of accidents.
3) Passive safety features are the main line of defence against all abnormal and accident conditions including “beyond design basis events” which can threaten the integrity of the three fission product barriers.
4) All safety-related systems, including passive safety features, must be regularly tested.
5) A comprehensive instrumentation system shall be implemented to provide regularly updated information on the conditions of the fuel clad, primary coolant pressure boundary, and containment.

Reactor Protection System (RPS)

The safety status of the plant is continuously monitored by the RPS. If a condition occurs that can threaten the integrity of a fission product barrier, the RPS terminates power operation and trips the reactor. The RPS also initiates other safety functions such as containment isolation.

Reactor Trip

Normal reactivity control and shutdown is through absorber rods located at the top of the core. The control rods utilize a ball-screw drive while the shutdown rods use linear motors. Both the control rod and shutdown rod systems have sufficient negative reactivity to render the core cold subcritical.

Anticipated Transient without Scram (ATWS)

Because of the very large initial ^{238}U loading, the reactor core has a high negative temperature coefficient throughout the core life. When combined with the high fuel clad temperature limit, the negative temperature coefficient enables the reactor to sustain an anticipated transient without scram (ATWS) by reducing the fission power to zero as the core heats up. No temperature limit is approached during this event.

Direct Reactor Auxiliary Cooling System (DRACS)

Core afterheat is normally removed by the PCU. In the event of a reactor shutdown, the PCU can maintain core flow using core afterheat to drive the turbine until the afterheat heat rate falls below ~3%. At this point, supplemental rotational energy is provided by motoring the generator. If the PCU is not available for shutdown cooling, shutdown heat removal can be provided by forced or natural convection flow from the core to the DRACS water-cooled heat exchangers. Upon loss of forced circulation from the PCU, the bypass prevention valves in the DRACS units will open on gravity action. A backup actuator will ensure that the valve properly opens. With a complete circuit open to the DRACS heat exchangers, natural convection will rapidly cool the core. In addition, a backup circulator is available on each DRACS loop for forced circulation (e.g. for maintenance conditions). Each circulator is designed such that only one circulator is necessary for the shutdown and maintenance operation.

4.2. Transient/Accident Behaviour

Shutdown Cooling by Natural Convection

In a pressurized cooldown following reactor trip, core afterheat is removed by natural convection of helium to either of two 100% water-cooled DRACS heat exchangers. The DRACS water loops also operate by natural convection and reject heat to the air via a water/air heat exchanger. The cooldown transient following shutdown from 100% power is shown in Fig. 12 (left) for the assumption of only one DRACS heat exchanger in operation. The peak fuel temperature is steadily returned to normal shutdown values in 20 minutes. No damage to the reactor is incurred during this transient. The cooling operation is completely passive; no electric power or operator actions are required.

The efficacy of natural convection cooling is highly dependent on the free stream capacity ($\dot{m}$ c_p) and thermal conductivity of the cooling fluid. Therefore, a loss of helium pressure, such as would occur during a depressurization accident, seriously degrades the ability to cool the core by natural convection. In order to preserve the passive cooling capability for combined depressurization and station blackout (no electric power), the containment is normally pressurized at about 20 psig with an inert gas. The peak containment pressure for a depressurization event is 70 psig.

The cooldown transient for combined rapid depressurization and station blackout is shown in Fig. 12 (right) where only natural convection to the two DRACS cooling loops is assumed. The peak clad temperature reaches about 2000°C for a brief period at about 18 minutes into the transient before turning around and declining to shutdown conditions in about 1.5 hours. Since 2000°C is reached by only a small fraction of the fuel for only a period of about 2 minutes, no clad failure is expected and no fission products will be released to the containment.

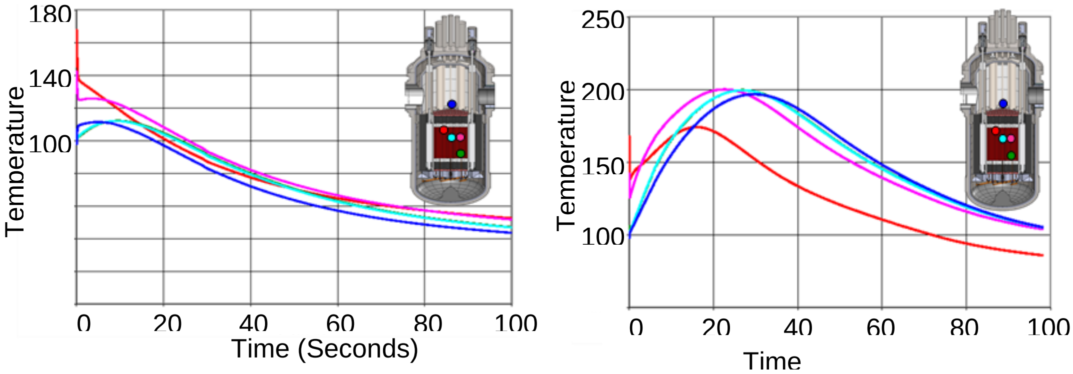

Fig. 12. Pressurized natural convection cooldown on one DRACS loop (left), and natural convection cooldown on 2 DRACS loops following a depressurization accident and station blackout (right)

Beyond Design Basis Heat Removal and Containment Integrity

The MELCOR code was modified for the EM^2 reactor and containment and used to investigate the hypothetical event in which all systems core cooling were lost. This includes the PCU, both DRACS, and both backup circulators. As with LWRs with direct core cooling unavailable, the core will fail. Analyses show that the first fuel failure will occur in about 70 minutes and the molten core will breach the bottom of the vessel in about 12 hours. The reactor chamber floor has a ceramic core catcher to prevent re-criticality of the molten core and increase the heat rejection surface. Natural convection from the core catcher transfers heat to the liner of the reactor chamber which is cooled by natural convection to the atmosphere. This natural convection is sufficient to maintain the liner intact and preserve the integrity of the containment. Without steam present, no explosive gases such as hydrogen are produced that could cause explosive events such as occurred at Fukushima.

FPVS Protection

EM^2 requires the fuel to be vented to the FPVS to prevent over-pressurizing the fuel over its 30-year life. Portions of the system external to the reactor vessels (piping and vessels) must be doubly contained and monitored for leakage because the external pressure will be much lower than the internal pressure. The most serious concern is the potential for a large leak that would depressurize the reactor. Although the reactor could tolerate the depressurization and be adequately cooled to prevent damage, the resulting contamination of the containment would entail extensive cleanup. This part of the system requires careful design and analysis to show that the likelihood of such an event is very remote.

Halides and condensables will be stored in the HTA vessels in the containment. Noble gases will be taken out by the LTA and then stored in gas bottles with guard vessels after LTA regeneration. The rate of gas generation is about 1 standard bottle per year. Depending on the selected accident scenario, the size of the bottle will be selected such that a failure would not constitute a serious accident. Most noble gases would decay to very low levels in about a 1-year period.

5. *Fuel and Fuel Cycle*

SUMMARY FOR BOOKLET (optional)

The baseline concept for the EM^2 fuel cycle is a once-through cycle. At end of cycle the average fuel burnup is 140 GWd/t. The spent fuel assemblies are then placed in stainless steel dry-cooled casks and placed in the spent fuel storage facilities for a cool-off period (5-10 years). The assemblies can then be placed in external dry storage casks for interim storage before placement in a final repository.

The EM^2 fuel cycle can be closed. The end-of-life (EOL) discharge from the 1st core can feed the next 1.2 cores after removing ~60% of fission products and blending with depleted uranium (DU). For the baseline core, low enriched uranium (LEU) is required for the first core, but no fissile addition is needed for follow-on cores, only fertile addition. This recycle process can be repeated indefinitely if the 60% value is applied to all fission product isotopes.

5.1. Fuel Cycle Options

The baseline concept for the EM^2 fuel cycle is a once-through cycle. At end of cycle the average fuel burnup is 140 GWd/t. The spent fuel assemblies are then placed in stainless steel dry-cooled casks and placed in the spent fuel storage facilities for a cool-off period (5-10 years). The assemblies can then be placed in external dry storage casks for interim storage before placement in a final repository.

The EM^2 fuel cycle can be closed via a proliferation resistant process that involves removing only fission products and not separating or removing heavy metal. The EOL discharge from the 1st core can feed the next 1.2 cores after removing ~60% of fission products and blending with DU. For the baseline core, LEU is required for the first core, but no fissile addition is needed for follow-on cores, only fertile addition. This recycle process can be repeated indefinitely if the 60% value is applied to all fission product isotopes.

5.2. Resource Use Optimization

The goal of EM^2 fuel cycle is to significantly reduce waste disposition as an impediment to expansion of nuclear power. Achievement of this goal is correlated with high resource utilization. Improving burnup and closing the fuel cycle in a proliferation resistant manner will substantially reduce the waste burden for EM^2. In addition, increasing the plant generating efficiency will reduce the specific fuel consumption and, hence, the specific waste production.

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

The EM^2 fuel cycle is ideally suited to a dry fission product extraction process such as an enhanced voloxidation to recycle used LWR fuel into EM^2 fuel or recycle EM^2 fuel to new EM^2 fuel with minimal waste. As an example of the voloxiation process, the DUPIC pilot scale voloxidation equipment was constructed by Korea Atomic Energy Research Institute (KAERI) to recycle spent CANDU reactor fuel into LWR fuel. The pilot scale Archimedes equipment was built by GA to demonstrate the electromagnetic separation process. With either process, there is no separation or removal of heavy metals, and it is not necessary to remove all the fission products.

6. Safeguards and Physical Security

SUMMARY FOR BOOKLET (optional)

The safeguards and security system shall follows Chapter I of Title 10 (Energy) of the Code of Federal Regulations (CFR).

6.1. Safeguards

The safeguards system shall follow Chapter I of Title 10 (Energy) of the Code of Federal Regulations (CFR), particularly 10CFR Part 74.

6.2. Security

The security system shall follow Chapter I of Title 10 (Energy) of the Code of Federal Regulations (CFR), particularly 10CFR Part 73.

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

N/A

7. *Project Delivery and Economics*

SUMMARY FOR BOOKLET (optional)

The project is conducted in three phases: high risk development, demonstration module development and prototype operation. The high risk development will have sufficiently progressed to make a decision on going forward with a demonstration module. Successful operation of the demonstration module is required to commence construction of the prototype. Modular design, manufacturing, assembly and construction techniques shall be applied to minimize costs, risks and schedule, plus accommodate sequential deployment of a multi-module plant. Operation and maintenance shall include capabilities for plant monitoring, standardization, maintainability, on-line maintenance, in-service inspection, etc.

7.1. Project Preparation and Negotiation

EM^2 is a high payoff concept but entails a significant amount of front-end development. In order to efficiently retire the development risk, GA has structured a three-phase development program in which the development cost increases in each phase. However, the level of risk decreases in each phase so that the first phase addresses the highest risks but has the lowest cost. A summary description of the risks addressed in each phase is given below. The phases overlap in schedule in order to accomplish the work in the shortest possible time. GA considers total development time a key factor in the attractiveness in the investment.

Phase 1 – High Risk Development

The objective of Phase 1 is to reduce the development risk to a level to justify embarking upon a prototype plant. The highest technical risks associated with EM^2, all of which will be addressed in Phase 1, are as follows:

- Fuel-cladding mechanical interaction due to fuel swelling rate in excess of creep rate
- Fuel-cladding chemical interaction due to U, Pu and fission product affinity for carbon
- SiC-SiC ability to retain essential thermal mechanical properties up to 400 displacement per atom (dpa)
- Release rates of volatile fission products from fuel pellets
- Sufficiently low inner reflector material swelling rates to allow reasonable life
- Passive core cooling under pressurized and depressurized conditions
- Transport of fission products released from fuel through vent system to high temperature adsorber
- Design basis and beyond-design-basis accident analysis
- Plant transient and control system performance for fast reactor
- Concentric duct design has adequate structural strength, heat insulation and low leakage
- First-of-a-Kind (FOAK) design meets requirements
- High speed turbine-compressor generator performance meets requirements

In addition to technical risks, licensing constitutes a major risk. During Phase 1, GA will engage the U.S. Nuclear Regulatory Commission (NRC) in a pre-application licensing review. This review will identify the major licensing issues as well as the approach to resolving these issues.

Phase 2 – Demonstration Module

Because there is no precedent for the EM^2 core and PCU designs, GA believes that a one-unit demonstration module is required to reduce the technical and licensing risk to an acceptable level before embarking upon a commercial plant. The demonstration module can serve several purposes including:

1) Identify unforeseen problems and demonstrate resolution of these problems.
2) Provide a test basis for retiring risks identified in Phase 1.
3) Provide the bases for qualifying the fuel to long life.
4) Provide the bases for a 10CFR Part 52 Design Certification for the commercial unit

Phase 3 – Prototype Development

After the demonstration module has been operating successfully for a number of years, it would be reasonable to commission the first prototype plant rated at full power (265 MWe). The FOAK unit will be licensed by the U.S. NRC under 10CFR Part 52 so the design certification would apply to all subsequent plants within the same design envelope.

The prototype plant will be purchased and operated by a utility or independent power producer, but may require a subsidy to offset FOAK costs. There are several possible strategies for offsetting the cost of the demonstration unit. The lowest outlay would be construction of a single module, but that would have the lowest rate of return on investment to the owner. Another approach would be to construct a module pair with capability to increase the plant size to a full four-module plant based on successful operation of the first pair. This would give the highest rate of return and reduce the amount of FOAK engineering for a commercial enterprise.

EM^2 Development Cost and Schedule

The total time to construction of the demonstration module is 12 years. The key decision points are identified by the milestones. High risk development will have sufficiently progressed in three years to make a decision on going forward with a demonstration module. Successful startup and operation of the demonstration module after Year-7 is required to commence construction of the prototype plant. Two years of successful operation of the demonstration module is required in order to commission the prototype plant. Once the prototype unit receives the Design Certification from the NRC and is operational, the commercial enterprise can begin.

7.2. Construction and Commissioning

A preliminary power generation cost estimate was made and compared to a large advanced LWR. The cost estimate is based a joint effort between an architecture/engineering firm and GA to develop the conceptual plant design and cost estimate. Because the design is at the conceptual stage, it is subject to a high degree of uncertainty. However, it reflects certain technical features that contribute to lower cost relative to other nuclear reactor technologies. These include:

- High net efficiency ~53%
- Compact PCU in a single vessel
- Small component sizes amenable to serial production
- Reduced fuel cycle cost associated with 30-yr core that burns primarily discard ^{238}U.
- Modularized construction resulting in a 42-month on-site construction period
- Reduced site footprint and associated construction cost.

Capital Cost

The overnight capital costs are for a four-module N^{th}-of-a-Kind (NOAK) plant with evaporative cooling. The net output is 1060 MWe. The specific capital cost is $4330/kWe installed.

Fuel Cost

The calculation of fuel cost is based on the June, 2015 spot prices. Because the fuel has a 30-year life, it is treated as a capital investment and the discount rate. The first core cost for the 4-module NOAK plant is $676/kWe. The fabrication cost have a high amount of contingency due to the development stage of SiC composite clad fuel.

7.3. Operation and Maintenance

Levelized Cost of Electricity

The levelized cost of electricity (LCOE) for a 4-module EM^2 NOAK plant is $66/MWh. All costs have been expressed in Year 2012 value. The LCOE for EM^2 is about 40% lower than a comparable sized advanced LWR. The principal reason is in the lower capital cost. This is due to a combination of substantially higher net efficiency (53% vs 33%) and reduced equipment due to the Brayton cycle. Efficiency is the dominant technical factor influencing the power cost followed by the overnight capital cost.

Operations and Maintenance Cost

The annual operations and maintenance cost for a four-module NOAK plant is $94/kWe. The staffing constitutes the major contribution to annual operation and maintenance (O&M). GA and an Architecture-Engineering (A-E) firm estimate that a 4-module plant will require a staff of 377 personnel. The cost estimation does not include property tax, which can vary widely depending on location. The cost of periodic replacement and refurbishment are amortized over the 60 year plant life.