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DESIGN AND DEVELOPMENT OF EM^2

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ABSTRACT

The principal design objectives for EM^2 are to achieve an economically competitive power source that improves resource utilization, reduces waste and meets a self-imposed high standard of safety. In order to meet this challenge, EM^2 departs from traditional nuclear technologies and embraces technical advances in materials, physics design, power conversion, control and passive safety methods. EM^2 is a modular helium-cooled fast reactor with a 265MWe net output. It uses a combined Brayton-Rankine cycle to achieve a net conversion efficiency of 53%. The core design is predicated on the convert-and-burn principle in which fertile material is converted to fissile and burned in situ. This allows the core to achieve a 30 year life without refueling or reshuffling. The combination of high efficiency and convert-and-burn reduces the rate of once-through high-level waste production by 80% relative to an LWR. This principle also enables the core to be multi-fuel capable including LEU, natural and depleted U, Th and spent LWR fuel. The base fuel is in the form of UC pellets with SiC composite cladding. These materials allow a high power density and a core outlet temperature of 850^{o}C for high efficiency. The core outlet helium goes directly to a variable speed turbo-compressor within the primary coolant system. The direct Brayton cycle eliminates costly steam generators and large, steam-condensate system components. The bottoming cycle is a self-contained Organic Rankine cycle (ORC). General Atomics (GA) has a bench-scale fuel fabrication facility for making both EM^2 fuel pellets and cladding. GA cladding materials have been irradiated in ORNL's HFIR to demonstrate the desired irradiation saturation behavior. The design is highly modularized not only reduce cost but also the risks associated with construction cost and schedule.

INTRODUCTION

EM^2 is a privately funded initiative by GA to create a new nuclear plant concept to address the major issues confronting energy demand and supply as related to nuclear power in the 21st Century. EM^2 represents a major departure from previous nuclear reactor projects at GA. Yet, at the same time, it builds upon the 40+ year legacy of gas-cooled reactor development including the High Temperature Gas-Cooled reactor (HTGR), Gas-Cooled Fast Reactor (GCFR) and Gas-Turbine Modular Helium Reactor (GT-MHR). Work on the EM^2 concept was begun in late 2008 with specification of the following goals:

Economics – EM^2 must be economically competitive with other power sources including natural gas in the U.S.

Safety and Licensing – EM^2 shall be licensable in the U.S. by the Nuclear Regulatory Commission (NRC). It shall adopt a standard of safety equal or better than current Generation III+ nuclear plants. This includes a principal reliance on passive safety and improved protection from external threats.

Resource Utilization – The goal is utilization of >90% of mined uranium through high burnup combined with an, economic, proliferation-resistant recycling process. It is anticipated that global competition for energy resources (fossil and ^{235}U) in the 21st century will strongly encourage the deployment of reactors that can burn ^{238}U and thorium in this century.

Waste Disposition – The goal 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 reduces the specific fuel consumption and, hence, the specific waste production.

Non-Proliferation – The goal for the EM^2 fuel cycle is to reduce proliferation risk in the short and long terms over Generation III+ reactors. In the short term, the goal is to reduce access to fissile materials and in the long term to eliminate the need for enriching services and consume all fissile materials through high burnup and recycling.

PLANT ARRANGEMENT AND SPECIFICATIONS

EM[2] 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 MWe. It employs a "convert & burn" core design which converts fertile ^{238}U or ^{232}Th to fissile material and burns it in situ over a 30-year core life. It can also burn spent LWR fuel including higher actinides using only a voloxidation process prior to refabrication.

The reactor is sited in a below-grade sealed containment. It uses passive safety methods for heat removal and reactivity control to protect the integrity of the fuel, reactor vessel and containment. The plant also incorporates a below-grade, passively-cooled spent fuel storage facility with capacity for 60 years of full-power operation.

For electricity production, EM[2] employs a direct closed-cycle gas turbine power conversion unit (PCU) with an R-245fa Rankine bottoming cycle for 53% net power conversion efficiency assuming evaporative cooling. If abundant cooling water is not available, reject heat can be released directly to the atmosphere via dry towers with a 5-point reduction in net efficiency.

The baseline EM[2] plant is composed of four independent modules each consisting of a complete powertrain from reactor to heat rejection such that the modules can be built sequentially and operated independently. Fig. 1 shows the plant layout, which covers 9.3 hectares not including the switchyard. Table 1 gives the principal EM[2] plant specifications.

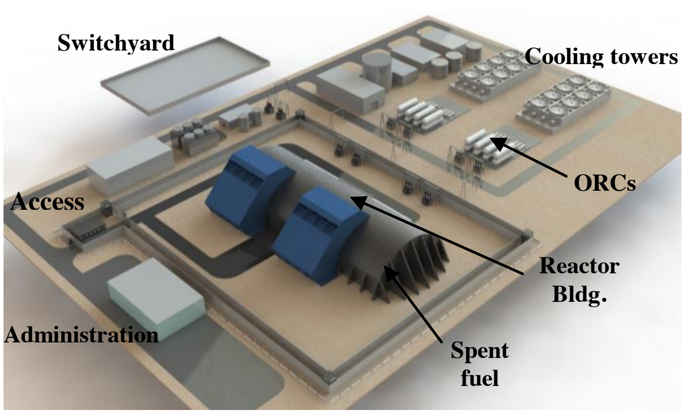

Fig. 1. Baseline plant arrangement with net 1,060 MWe

Table 1 Principal specifications for EM[2] module and plant

Parameters	One Module	Base Plant
Number of modules	1	4
Net power - evap/dry cooling, MWe	265 /240	1,060 /960
Plant design life, years	60	60
Construction time, months	32	42
Reactor power, MWt	500	
Active core height/diameter, m	2.16/2.24	
Average/peak power density, W/cc	58/262	
Initial loading (MT of heavy metal)	42.6	
Primary coolant T_{in}/T_{out} ,°C	549/850	
Primary coolant pressure, MPa	13.3	
Primary coolant flow rate, kg/s	320	
Fuel assemblies per core	85 assemblies with 91 rods	
Fuel enrichment, %	17 – maximum; 6.5 – average	
Average/peak burnup, MWd/kg	146/298	
Refueling interval, years	30	

Fig. 2 shows a cutaway of the reactor building, where he maintenance hall floor is at grade level, and the roof serves as a protective shield structure. The maintenance hall serves all four reactors. The Direct Reactor Auxiliary Cooling System (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 waste handling, electrical distribution facilities and access entry. This allows two modules to be put into operation while the remaining modules are being installed.

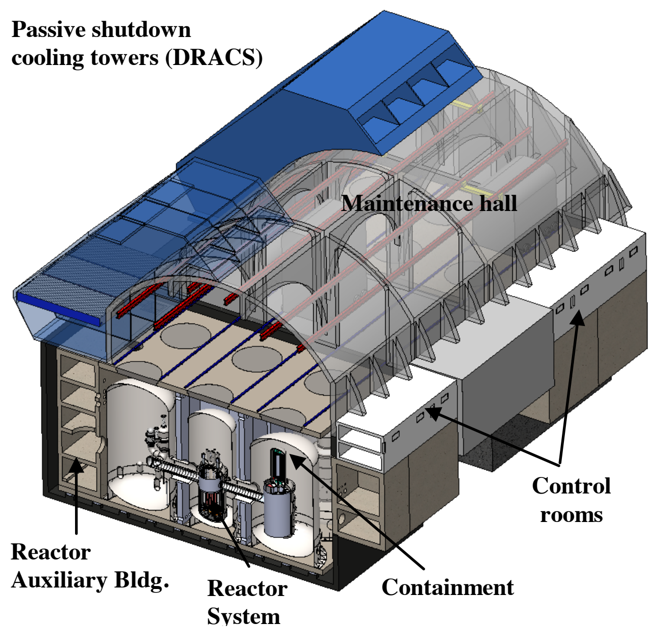

Fig. 2. Four-unit reactor plant with below-grade containments

Fig. 3 shows a cutaway arrangement of two reactor modules with individual containment assemblies mounted on a seismic isolation platform. The Reactor Auxiliary Building is also mounted on the platform. Each primary system is enclosed within a sealed 3-chamber containment, where the chambers are connected by ducts. The central reactor chamber is enclosed in concrete shield structure to enable man-access to the PCU and DRACS containment chambers. 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

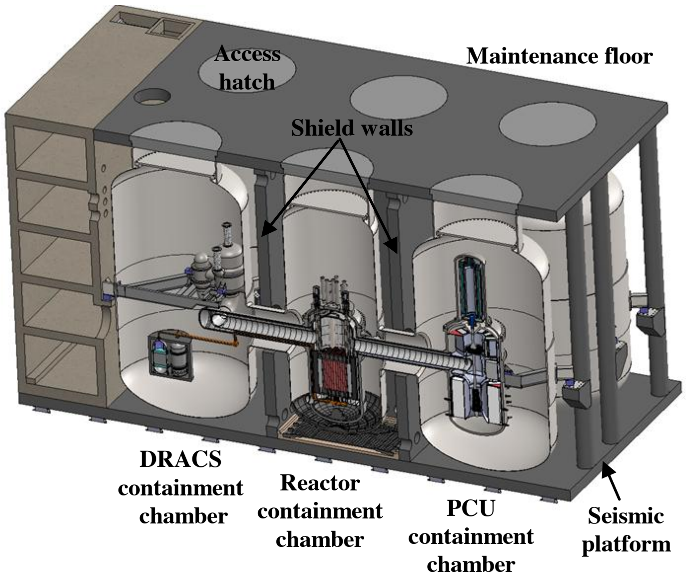

Fig. 3 Reactor module pair on a seismic isolation platform

PRIMARY COOLANT SYSTEM

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. Fig. 4 shows the cutaway elevation view of the vessel system divided into three 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 SA533-Grade B steel and internally insulated.

Fig. 4 shows the flow path in the primary coolant system during normal operation. Hot helium (850^{o}C) 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 from 6.1 to 13.3 MPa in the compressor and returned to the

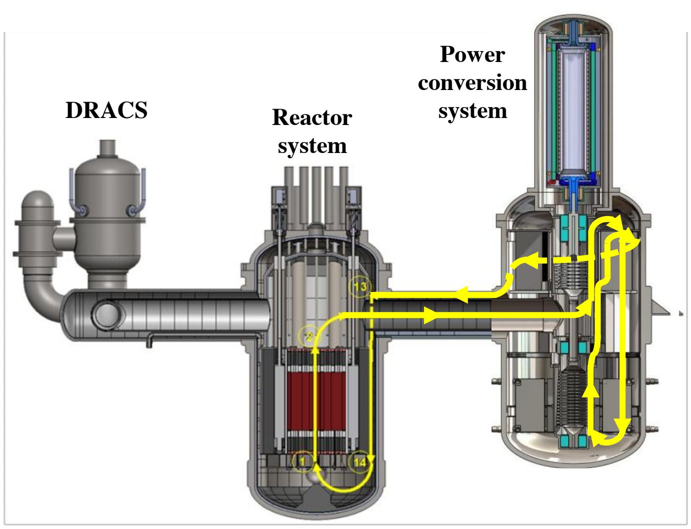

Fig. 4. Primary coolant flow paths for normal operation

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 (550^{o}C) 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.

REACTOR SYSTEM

The reactor system is shown in Fig. 5. 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.

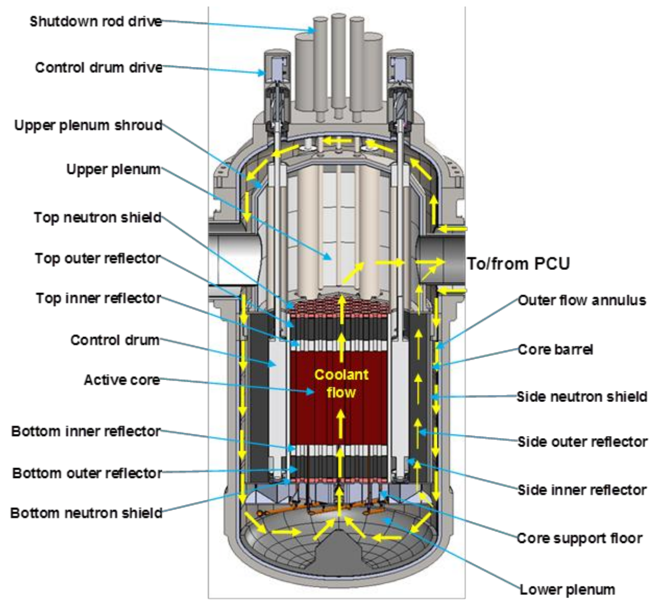

Fig. 5. Cutaway of EM^2 reactor system showing flow path

The reactor has two independent systems capable of shutting down the reactor. Normal reactivity control is by control drums located in the side-reflector. No control elements are in the core during normal power operation. The use of control drums in the reflector is possible because of the low excess reactivity over core life. This preserves a symmetric burn and reduces power peaking factors. The backup shutdown system consists of six B_4C rods that are normally fully redrawn from the core, but are fully released into the core in the event the control drums fail to shut down the reactor. Both the control drums and shutdown rods are fail safe in that they are driven by gravity to the shutdown position in the event of a loss of power.

The core (Fig. 6) is divided into three core sections: starter, fertile, and reflector. The starter section is the "critical" section at beginning of life (BOL). It contains fissile materials to sustain the chain reaction and provide excess neutrons to convert fertile to fissile material. The reflector consists of an inner section of canned Be_2C and an outer section of graphite.

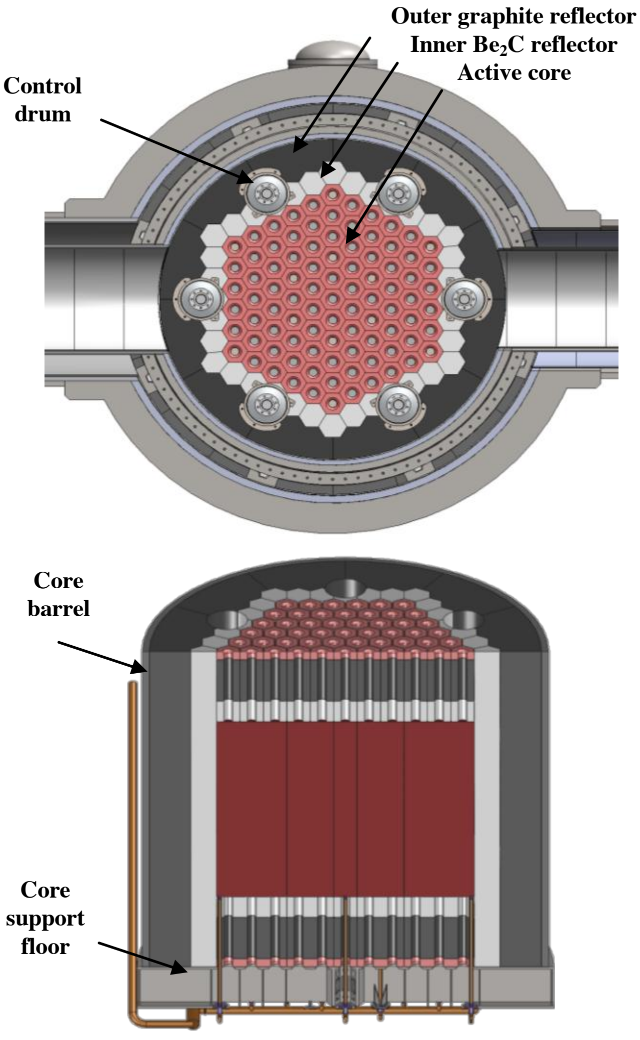

Fig. 6 EM^2 core arrangement

The EM^2 core is designed to:

- Maintain a long fuel cycle length with a power level of 500 MW thermal.
- Provide minimal excess reactivity in the core allowing adequate shutdown margin reflector control drums.
- Minimize the local power peaking to preserve a thermal margin of the fuel.
- Use the same fuel form and elemental composition for the starter and fertile fuels.

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. The active core is divided into two regions, the fissile starter region and the fertile converter region. At the beginning of life (BOL), the critical reaction takes place mainly in the starter region, which contains the initial fissile material. The average starter LEU enrichment is ~12%, but this is radially distributed as suggested by the figure. During operation, excess neutrons from the starter are parasitically captured by ^{238}U, which converts to ^{239}Pu through beta emission. As ^{239}Pu is bred in both the starter and fertile regions, the critical reaction spreads beyond the starter into the fertile area, and the ^{239}Pu is burned. The starter is depleted of the initial fissile material, but the critical reaction is sustained through conversion of ^{238}U to ^{239}Pu. 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. 7 (top) shows the excess reactivity over core life, which never exceeds 3%.

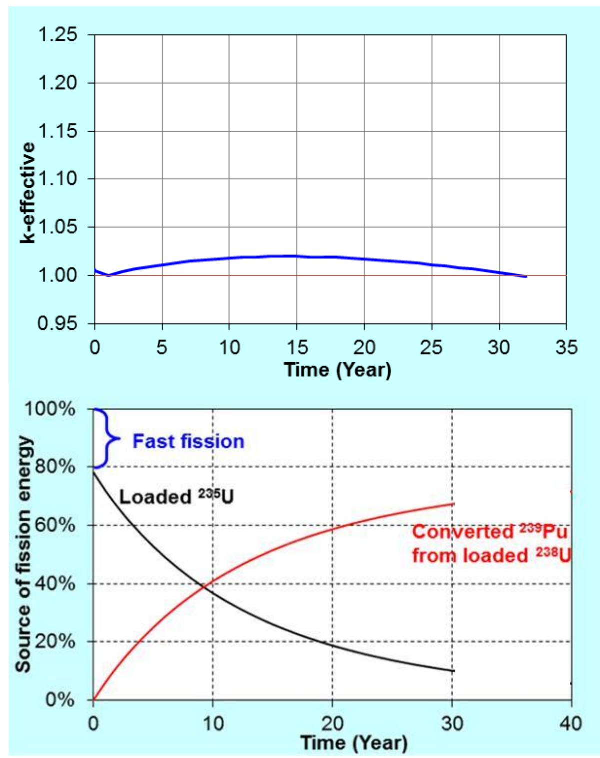

Fig. 7. Excess reactivity (top) and isotopic contribution to core power (bottom) over core life

Fig. 7 (bottom) shows the fractional contributions of ^{235}U and ^{239}Pu fissile inventories to energy production verses core life. Initially, most of the energy comes from fission of ^{235}U in the starter fuel. After ~10 years, the majority of the energy comes from fission of ^{239}Pu, which comes from conversion of the fertile ^{238}U in the starter fuel. By EOL, most of the energy is produced by fission of ^{239}Pu. 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. The fissile starter fuel can be LEU, mixed U/Pu carbide, and/or recycled EM^2 fuel. The fertile fuel can be DU, natural U, spent LWR fuel, and/or mixed Th carbide. Spent LWR fuel can be used directly after clad separation through a voloxidation method without removing fission products.

Fig. 8 shows the energy spectrum of the core as a function of core life. The mean neutron energy is 100 keV. This is due to the Be_2C side reflector which causes an increase in the thermal population at the core edge.

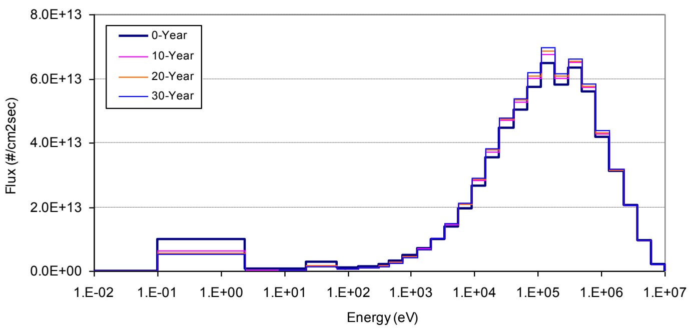

Fig. 8. EM² neutron energy spectrum over the core life

FUEL SYSTEM

The basic building block of the fuel system is the hex-assembly of which there are 85 in an EM² core. Seventy-nine hex-assemblies have 91 fuel rods and six hex-assemblies have 84 fuel rods plus a shutdown rod guide. Eighty-one hex-assemblies are joined into 27 tri-bundles and four remain as individual hex assemblies as shown in Fig. 9.

The fuel for EM² 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. All structural components are made of SiC composite. Each fuel rod is clad in SiC composite with top and bottom end-caps also made of SiC composite. The rod diameter is 21.1 mm and the clad is 1 mm thick. The cladding is chemical vapor infiltrated SiC fiber matrix material (SiC-SiC). The end-caps are hot-pressed composite material. The joining is by a GA proprietary β-SiC hermetic joining method.

The fuel is in the form of UC annular pellets. Each fuel pellet is a sinter "sphere-pac" with a specified interstitial and internal distributed porosity. The internal porosity provides room for solid fission products and the interstitial porosity allow for faster migration of volatile fission products which reduces fuel swelling. A center hole in the annular pellet provides a path for fission gas escape to the vent system. The hole also limits peak fuel temperature and provides additional space for fuel swelling.

A design fuel limit of 2000°C is used for normal operation and 2200°C for accident conditions. The melting temperature of the fuel depends on the amount of converted Pu. The highest concentration of Pu is ~15% at EOL when the corresponding melting temperature is 2350°C. The cladding temperature limit is based on the maximum temperature for which the SiC composite retains its mechanical strength, 1800°C for sustained normal operation and 2000°C for accident conditions.

The calculated highest fuel power density and temperature occurs on the first day of full power operation, when most power is generated in the starter. The peak fuel and clad

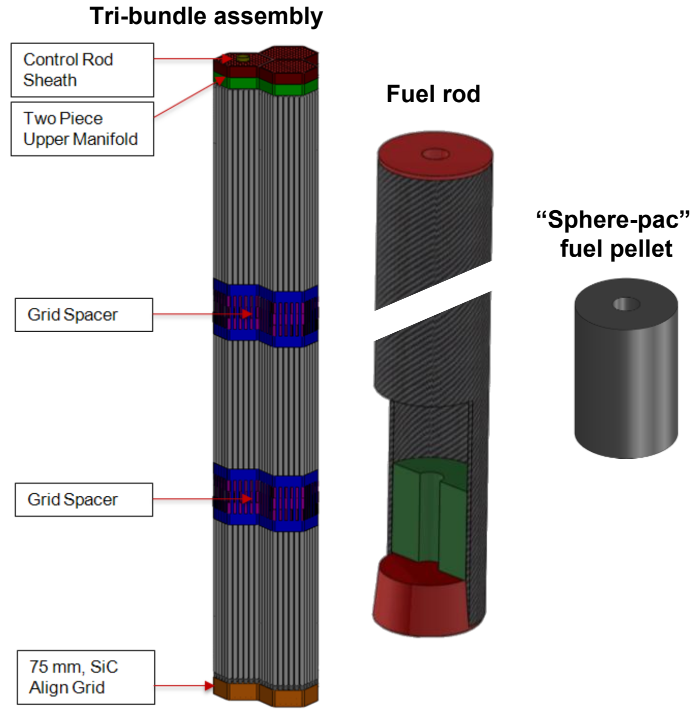

Fig. 9 Components of an EM² tri-bundle assembly

temperatures are 1,670 and 1,179°C, respectively, which are both well under the temperature limits and provide a margin significantly larger than today's reactors.

The gap between the pellet and cladding allows for initial thermal expansion without loading the cladding. Subsequent swelling of the fuel will cause it to mechanically react against the cladding. However, UC fuel has a high steady-state creep rate which allows the "sphere-pac" design to collapse on itself without exceeding the stress allowable of the cladding. [1,2]

In order to prevent a chemical reaction between the fission products and SiC-SiC cladding, excess carbon is added to getter fission products that would attack the SiC clad for their carbon content under the thermodynamic conditions in the fuel. The amount of excess carbon is sufficient to prevent SiC attack under equilibrium conditions up to 30% burnup.

The process for making EM² fuel pellets is illustrated in Fig. 10. Uranyl-nitrate spherical particles containing carbon are made through a sol gel process. After drying and calcining, the particles are in the form of an oxide with carbon. The particles are then sintered to convert them to UC at a diameter of about 200 μm. The particles are then pressed into an annular "sphere-pac" pellet with the selected porosity. The tubular SiC composite clad is made separately. After inserting pellets into the SiC composite tube, end plugs are applied and sealed as shown in Fig. 11.

Fission gas accumulation in the fuel rod will cause unacceptable pressure buildup in the fuel rod unless the gases are safely vented from the rod. Consequently, each EM² fuel assembly incorporates a vent port connected to the Fission

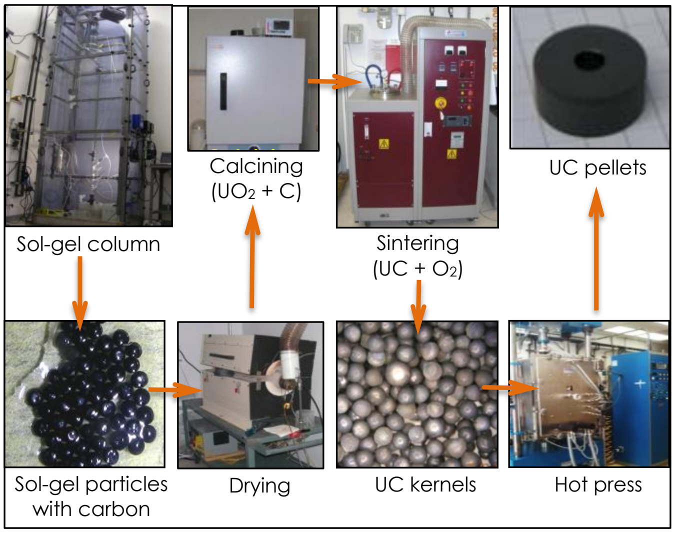

Fig. 10. Process for making EM^2 fuel at GA

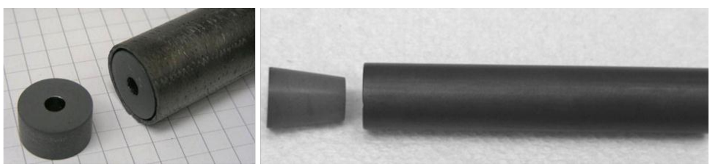

Fig. 11. Finished fuel pellets are inserted in to SiC-SiC cladding and closed with end-caps

Product Venting System (FPVS). Fission gases from the fuel pellets travel 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 high temperature adsorber (HTA) in the DRACS containment chamber as shown in Fig. 12. The HTA vessels are shielded and cooled by natural convection in the containment atmosphere. The HTA is effective in removing halides and metals but not noble gases which are removed subsequently by the helium purification system low temperature adsorber (LTA).

The pressure inside the fuel rod and FPVS is maintained lower than the primary system pressure so that if cracks or pinholes develop in the cladding or transport channels, helium will leak inward rather than fission gases leaking into the primary system.

POWER CONVERSION SYSTEM

The process/flow diagram for the total EM^2 power conversion scheme is shown in Fig. 13. The scheme uses a combined cycle with a direct helium Brayton cycle bottomed by an ORC. The calculation of plant net efficiency has a large impact on plant economics. 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

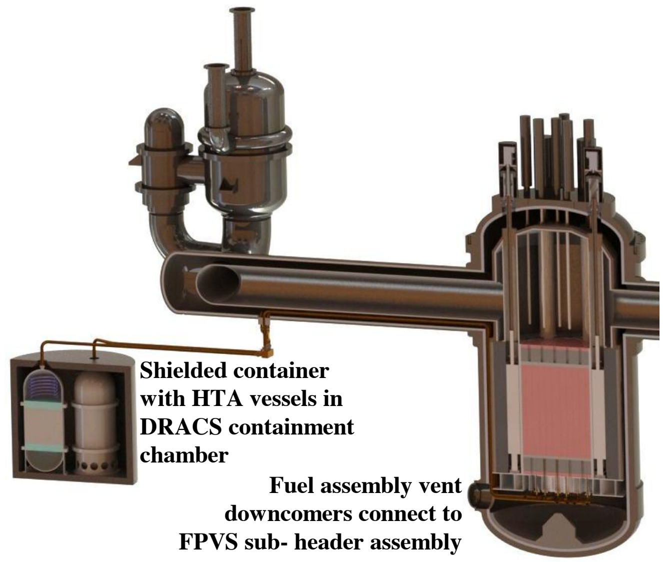

Fig. 12. Transport of volatile fission products from fuel to HTA

temperature (12.2°C) and for dry cooling this is the average annual U.S. dry bulb temperature (20°C). The net efficiency is 53%. For dry cooling conditions the net efficiency is 48%.

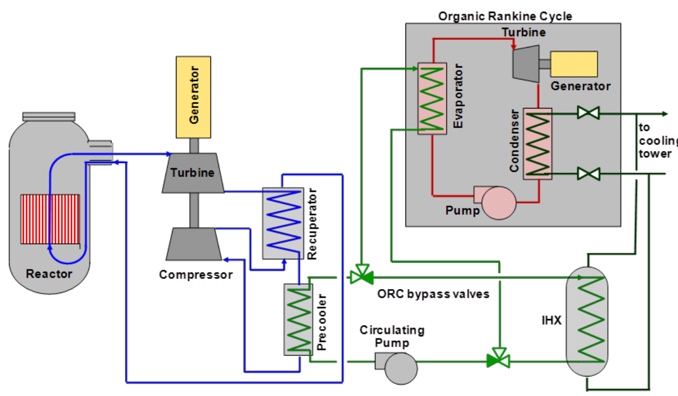

Fig. 13. EM^2 power conversion process/flow diagram

Fig. 14 shows a cutaway of the PCU vessel, which contains all components in contact with primary coolant. The turbine-compressor and generator are mounted on in-line vertical shafts. A shaft seal is located between the turbine and compressor to prevent leakage. The turbo-compressor shaft is suspended on active magnetic bearings. The bearing system is mounted within a stiff cartridge frame that enables it to be removed and re-installed for repairs or replacement.

The PCU incorporates two heat exchangers (HX), a recuperator and a precooler. The recuperator is a helium-to-helium HX constructed from IN617 in a plate-fin configuration. The precooler is a helium-to-water HX constructed from 2.25Cr-1Mo in diffusion bonded configuration. The heat exchanges modules are arranged around the turbine cartridge.

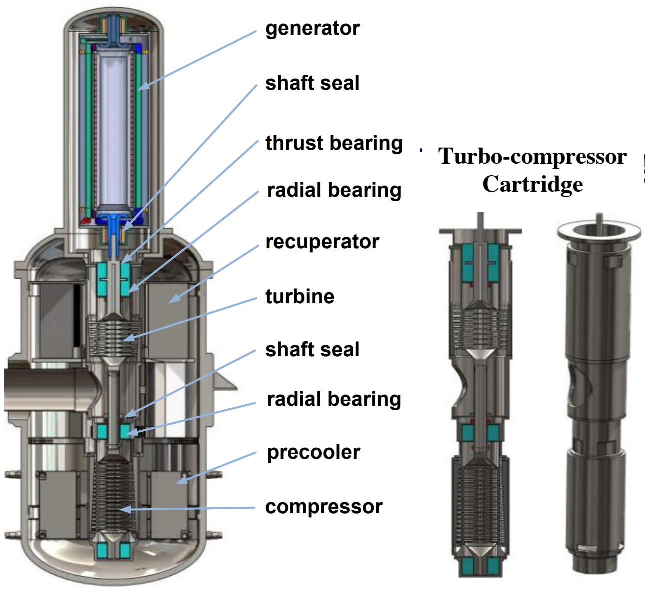

Fig. 14 Principal elements of the power conversion unit

The generator is located in the vertical vessel on top of the PCU. The generator cavity is maintained at lower pressure via a dry-gas seal to reduce windage losses. A spline connects the generator shaft to the turbo-compressor shaft so the generator can be removed for maintenance without having to remove the turbo-compressor. The generator incorporates a permanent magnet (PM) rotor that eliminates the I^2R losses associated with a wound rotor and exciter. The PMs are attached to the rotor by a GA-developed high strength winding.

The turbo-compressor-generator is a variable-speed machine with a top rotational speed of ~6,800 rpm. This is facilitated by GA manufactured power inverter that converts variable input to 50/60 Hz at 99% efficiency. Load changes are accomplished by varying the turbine speed rather than by turbine bypass. This has several advantages. The diameters of the turbo-compressor-generator are reduced so that the overall weight is greatly reduced. The primary system temperatures are maintained at near constant levels over the full turn-down ratio, and the part-power thermodynamic efficiencies are higher.

EM^2 modules can operate in a base-load or load following mode. In the automatic load following mode, the generator speed (hence shaft speed) is set by modulating the generator stator field. A field-oriented control algorithm in the frequency converter controls the generator torque to decrease/increase the generator speed, which in turn increases/decreases helium flow. The reactivity control system maintains a constant core outlet temperature in response to changes in helium flow. The ability to control the turbo-generator speed through field control is a major innovation because it replaces traditional mechanical control elements (e.g. valves) with digital electronic control.

An intermediate loop transfers heat from the Brayton cycle to the ORC. The ORC operates on a supercritical R-245fa cycle. This is a common cycle for geothermal power production and waste heat recovery. The ORC operates in the open loop mode in response to the inlet temperature of the circulating water system. The load to the ORC can be regulated by bypassing the circulating water directly to the cooling towers.

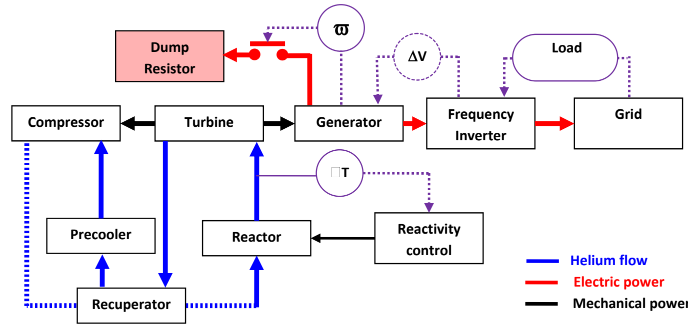

Fig. 15. Plant control diagram for variable generator speed

SAFETY

The EM^2 safety features are designed to meet the NRC requirements for licensing in the U.S. Some of the unique safety features of EM^2 are described below.

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 ATWS by reducing the fission power to zero as the core heats up. No temperature limit is approached during this event.

Shutdown Core Cooling: 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, heat removal can be provided by forced or natural convection flow from the core to the DRACS water-cooled heat exchangers. 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).

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 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.

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 30 psig with an inert gas. The peak containment pressure for a depressurization event is 90 psig. During the cooldown transient for combined rapid depressurization and station blackout, 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 few minutes, no clad failure or fission product release is expected.

ECONOMICS

A preliminary power generation cost estimate was made using a methodology consistent with the literature [3]. The work was a joint effort between the Shaw Group (CB&I) and GA to develop the EM^2 conceptual plant design and cost estimate which reflects the technical features that contribute to lower cost relative to other nuclear technologies including:

- High net efficiency – 53%,
- Compact PCU in a single vessel,
- Small component sizes amenable to serial production,
- Reduced fuel cycle cost from 30-yr core,
- Modular construction for 42-month on-site construction,
- Reduced site footprint and associated construction cost.

The equilibrium overnight capital cost is estimated at $4,500/kWe and the first core cost is $970/kWe. Fuel is a capital item because it is a 30-year investment. The O&M cost accounts for staffing, fees, projects, replacement, training, decommissioning and consumables. The total annual O&M cost is $100 M for a 4-unit plant. Staffing is the major cost and is based on a 377 personnel for a four unit plant

The levelized cost of electricity (LCOE) for a 4-module EM^2 NOAK plant was computed as a function of the cost of money (COM). The results are shown in Fig. 16 for COM values of 5% and 8.7%. The former value is consistent with natural gas-fired units while the latter value reflects a risk premium associated with nuclear power [4]. The COM is the most sensitive parameter affecting the LCOE, which accounts for the significant difference between the two cases. Nevertheless, the chart shows the potential for EM^2 to be competitive with natural gas if performance of the initial EM^2 units can justify reduction in the "nuclear risk premium".

DEVELOPMENT STATUS AND THE PATH FORWARD

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.

Phase 1 – High Risk Development. The objective of Phase 1 is to reduce the development risk to a level to justify

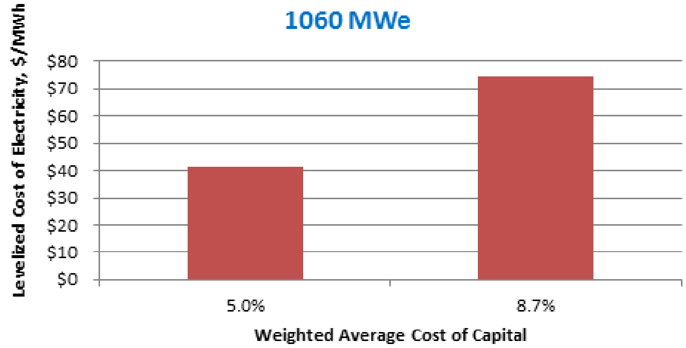

Fig. 16. LCOE for a 4-unit EM^2 plant for 5% and 8.7% COM

embarking upon a prototype plant. The key risks are associated with fuel performance including effects of high fluence on cladding and pellet-clad mechanical and chemical interaction. To-date, GA has demonstrated the ability to manufacture pellets and clad to required specifications and has begun the irradiation program with SiC composite cladding materials and joints in HIFR at ORNL. During Phase 1, GA will irradiate rodlets to the design burnup level. GA will also build a quarter-scale PCU and perform validation experiments on key systems including the DRACS, FPVS, reflector material, and control drums. During Phase 1, GA will engage the U.S. NRC in a pre-application licensing review to identify the major licensing issues as well as the approach to resolution.

Phase 2 – Prototype development. Because there is no precedent for the EM^2 core and PCU designs, GA believes that a one-unit prototype plant is required to reduce the technical and licensing risk to an acceptable level before embarking upon a commercial plant. The purpose of the prototype includes:

1. Identify and resolve unforeseen problems,
2. Provide a test basis for retiring residual Phase 1 risks,
3. Provide the bases for qualifying the fuel to long life,
4. Provide the bases for a 10CFR52 Design Certification.

Phase 3 – Demonstration module. After the prototype core has been operating successfully, GA foresees commissioning the first demonstration 4-unit plant. 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.

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