The Holos Reactor: A Distributable Power Generator with Transportable Subcritical Power Modules

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Abstract

Holos is a distributable modular nuclear power generator with enhanced safety features. Holos design objectives include production of affordable pollutant-free electricity and process heat with the safest melt-tolerant and proliferation resistant fuels. The design leverages commercial technologies utilized for the conversion of thermal energy into conditioned electricity. Holos can operate as a stand-alone electric island at sites with no power grid infrastructure and can be scaled-up or clustered to meet local electric demands. Specialized configurations of Holos generators can be airlifted and timely deployed to supply emergency electricity and process heat to disaster areas and to inaccessible remote locations. The proposed distributable electric generator is comprised within dimensions and weight requirements compatible with International Standard Organization (ISO) transport containers, and is formed by subcritical power modules protected from shock stressors during transport. Holos coupled core becomes critical and enables power generation only when multiple subcritical power modules are positioned near one another. Cooling of Holos fuel relies only on environmental air during operations with passive decay-heat removal. Depending on configurations, Holos fuel cycle is 12-20 years, with 8%-15% enriched nuclear fuel sealed at all times and contained within replaceable fuel cartridges. At the end of the fuel cycle, the fuel cartridges fit within licensed transport and storage canisters for long term storage with low decommissioning cost. Holos power conversion components can be reconditioned when the fuel cartridges are replaced at the end of their fuel cycles and the generator can be re-licensed to resume operation for a total generator life-span of 60 years. In this design, the thermodynamic cycle utilized to convert the core thermal energy into electricity is based on the Brayton power cycle. In some configurations, the design integrates and couples a bottoming Rankine power cycle operating with organic fluids to enhance efficiency, convert decay thermal energy into electricity and support process heat applications. Holos waste heat recovery and conversion feature also relaxes thermal loading requirements at underground spent fuel repositories. The power conversion components utilized in this design are off-the-shelf, with power ratings comparable to those forming aviation jet engines and gas turbines commercially available worldwide. This approach simplifies the design and enables factory certification following the regulatory and quality assurance programs applied by the aviation industry. Holos innovative architecture provides the means to support a distributable power source satisfying various applications' requirements with enhanced safety and substantial cost reductions, thus making Holos generators competitive, and synergetic with technology sourced on renewable energy.

Keywords: Nuclear Power; Energy; High Temperature Gas Reactor; Small Modular Reactor

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ISO	International Standard Organization
MWe	Mega Watt-electric
UHS	Ultimate Heat Sink
TRISO	Tristructural-Isotropic
ORC	Organic Rankine Cycle
FEPY	Full Effective Power Years
MWth	Mega Watt-thermal
B-ORC	Brayton-ORC
LOCA	Loss of Coolant Accident
DBA	Design Basis Accident
HTGR	High Temperature Gas Reactor
MTC	Moderator Temperature Coefficient
IGBT	Insulated-Gate Bipolar Transistor
AMPS	Automatic Module Positioning System
SMR	Small Modular Reactor
PCU	Power Conversion Unit
BoP	Balance of Plant
SSCs	System Structures and Components
AGC	Automatic Generation Control
FERC	Federal Energy Regulatory Commission
LWR	Light Water Reactor
EPZ	Evacuation Planning Zone
AOOs	Anticipated Operational Occurrences
DBA	Design Basis Accident
DBT	Design Basis Threat
BDBA	Beyond Design Basis Accident
NRC	Nuclear Regulatory Commission
HTR	High Temperature Reactor
TRLs	Technology Readiness Levels
PRA	Probabilistic Risk Assessment
MHTGR	Modular High-Temperature Gas-Cooled Reactor
GT-MHR	Gas Turbine Modular Helium Reactor
PBMR	Pebble Bed Modular Reactor
LEU	Low-Enriched Uranium
EOL	End-of-Life
EIA	Energy Information Administration
EDGs	Emergency Diesel Generators
NPPs	Nuclear Power Plants

SBO	Station Black Out
LCOE	Levelized Cost of Electricity
IEP	Integrated electric propulsion
MDO	Marine Diesel Oil
NPX	Neo Panamax
TEU	Twenty-foot Equivalent Units
O&M	Operations and Maintenance
ECA	Emissions Control Area

1 Introduction and Brief Design Overview

Holos is a nuclear powered electric generator concept designed to address and satisfy the requirements of transportability and encapsulation. The reactor is distributable and can be configured to supply from 3 Mega Watt-electric (MWe) up to 81 MWe of load-following electricity. The design features an innovative architecture centered on subcritical fuel cartridges enabling lowered production costs and rapid deployment through standard transport containers. In addition to electric power at various power ratings, the design is equipped with isolation heat exchangers to support process heat applications and can operate as a stand-alone power source or "electric island". The generator is equipped with interfaces for automatic connection to power-grid/switchyard stations and can provide electric power and process heat to remote areas with underdeveloped or absent power grid infrastructure. The fuel cartridges are scalable, hardened and permanently sealed throughout the fuel life cycle from factory to temporary or permanent repository. Holos configurations with power ratings below 10 MWe (e.g. emergency-power applications) can be airlifted to timely provide electricity and process heat to emergency responders in disaster areas. The distributable generators can supply electric power for 12-20 years without refueling and can be clustered to match local energy demands and/or support industrial processes. Versions of the distributable generators can be employed as power plant for off-shore rigs and marine applications (e.g. supplying power to electric propulsion systems). Figure 1 illustrates general configurations and applications of the proposed electric generator fully comprised within transport containers for rapid deployment and electric connection.

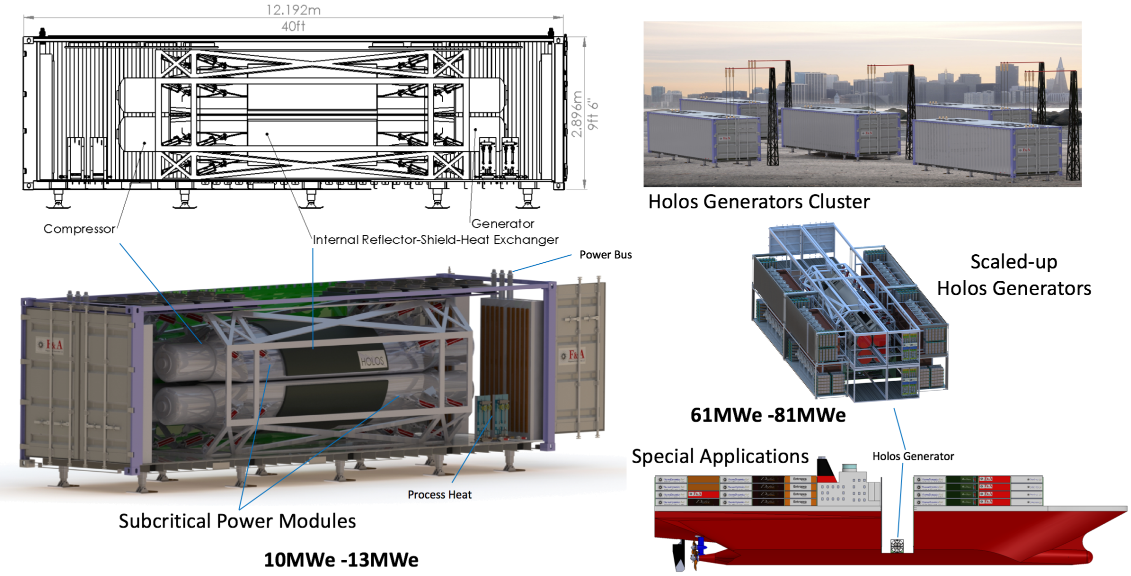

Figure 1: Holos generators general footprint and applications

The name *Holos* comes from the Greek for "*whole*" as the core is formed by subcritical power modules sealed in independent steel pressure vessels. The resulting coupled core becomes critical (able to sustain a nuclear chain reaction) and produces electric power when multiple Holos subcritical power modules are brought together, thus forming the *whole* core. Neutrons couple fuel cartridges through controlled leakage. The fuel cartridges house the nuclear fuel and perform safety functions including containment, ballistic shielding, and heat transfer functions via passive thermal coupling with the environment as the Ultimate Heat Sink (UHS) surrounding the generator. From a heat transfer viewpoint, the fuel cartridges can be represented by a “tube-shell” heat exchanger, wherein the shell-side is preferentially loaded with melt-resistant fuels, for example, TRIstructural-ISOtropic (TRISO) fuel, while the tube-side is thermally coupled to a cooling primary fluid (e.g. He or CO_2), internally flowing through pressure tubes. The moderator is formed by materials that simultaneously satisfy neutronics and thermal-physical properties. For example, graphite, silicon-carbide (SiC), beryllium and other materials in various combinations and mixtures can be utilized to form fuel matrixes compatible with Holos fuel cartridges requirements. The fuel cartridges can be cost effectively manufactured with components housing low-cost “fuel-bricks” (as discussed in detail in Section 3.3).

One of the enhanced safety features offered by Holos is represented by multiple pressure boundaries separating the working fluid from exposure to the fuel cartridges internals. This feature inherently inhibits transport of radionuclides through the power conversion components and segregates potential radionuclides released by the fuel within the reinforced fuel cartridge structures. In all of Holos fuel cartridges’ configurations, the fuel is contained within multiple redundant and independent containment structures, pressure boundaries, radiation and neutron shields and ballistic shields.

1.1 Combined Brayton and Rankine Thermodynamic Cycles

In the Holos reactor concept, the conversion of thermal-to-electric energy is based on the Brayton thermodynamic cycle, wherein all of the components are housed, sealed and shielded within each subcritical power module. To increase efficiency, the Brayton intercooler and precooler heat exchangers are configured to be thermally coupled to components forming a bottoming Organic Rankine Cycle (ORC)[1] also comprised and sealed within each subcritical power module with no physical exposure to the fuel cartridges internals. Holos nuclear generators can operate at 97% capacity with efficiency varying between 45.5% when thermal conversion is executed by the Brayton cycle, and 60% when the Brayton cycle components are coupled with the ORC components. The UHS for both Brayton and Rankine cycles is represented by environmental air. Both thermodynamic cycles are operational at power rates proportional to electric power and process heat demands. Only the ORC remains operational after the subcritical power modules are in shutdown configurations. This feature enables electricity production at power rates proportional to the core decay heat rate when the generator is shutdown.

1.2 Full Effective Power Days, Refueling Cycles and Power Ratings

The refueling intervals vary between 12-to-20 Full Effective Power Years (FEPY), utilizing fuel cartridges with nuclear elements enriched between 8%-15%, depending on application requirements. Holos sealed subcritical power modules fully comprise the refuelable fuel cartridges and power conversion components which can be refurbished to extend operational life. Holos architecture supports power rating scaling under various configurations, for example “Holos Quad” is formed by 4x subcritical power modules, each with fuel cartridges producing 5.5 MWth (Mega Watt-thermal). For Holos applications requiring higher power ratings, “Holos Quad Titan” repre-

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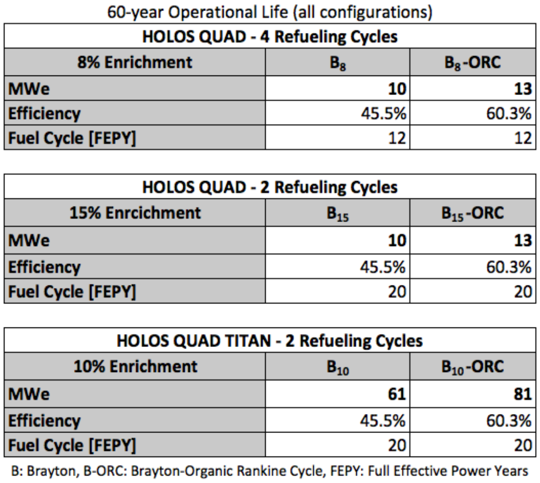
[1] The Organic Rankine Cycle is a thermodynamic process where heat is transferred to a fluid at a constant pressure. The fluid is a low vapor pressure fluid vaporized and then expanded in a vapor turbine that drives a generator, producing electricity. The low-energy vapor discharged at the turbine is condensed to liquid and recycled back, thus resetting the cycle.

sents a design configuration with larger subcritical power modules and correspondingly scaled up fuel cartridges. In the Quad Titan configuration 4x scaled-up subcritical power modules are loaded with proportionally larger fuel cartridges producing 32.9 MWth each. As the neutronic efficiency of the Holos Quad Titan subcritical power modules is enhanced, 10% fuel enrichment can support up to 20 FEPY between refueling cycles.

1.3 Holos Quad 10MWe-13MWe and Holos Quad Titan 61MWe-81MWe

Holos design architecture enables application-specific power rating and FEPY. Table 1 groups three exemplary configurations. As shown, Holos generators operating with coupled Brayton-ORC (B-ORC) power cycles increase the total power rating from 10 MWe to 13 MWe while maintaining the same FEPY and enrichment conditions. In these configurations, the electric power rating increases without increasing fuel burnup. The B-ORC configurations shown represent Holos generators with Brayton precooler and intercooler heat exchangers thermally coupled to the Rankine cycle heat exchangers. Under the B-ORC configurations, Holos recovers a portion of the unavoidable Brayton heat rejection to the environment and converts otherwise wasted thermal energy into electricity, while boosting efficiency from 45.5% to 60%. As the B-ORC configurations reject lower amounts of thermal energy to the environment, the power module's thermal pollution and signature is reduced.



60-year Operational Life (all configurations)

HOLOS QUAD - 4 Refueling Cycles		
8% Enrichment	**B_8**	**B_8-ORC**
MWe	**10**	**13**
Efficiency	45.5%	60.3%
Fuel Cycle [FEPY]	12	12

HOLOS QUAD - 2 Refueling Cycles		
15% Enrcichment	**B_{15}**	**B_{15}-ORC**
MWe	**10**	**13**
Efficiency	45.5%	60.3%
Fuel Cycle [FEPY]	20	20

HOLOS QUAD TITAN - 2 Refueling Cycles		
10% Enrichment	**B_{10}**	**B_{10}-ORC**
MWe	**61**	**81**
Efficiency	45.5%	60.3%
Fuel Cycle [FEPY]	20	20

B: Brayton, B-ORC: Brayton-Organic Rankine Cycle, FEPY: Full Effective Power Years

Table 1: Application-specific Holos configurations (subscripts indicate enrichment levels**)**

1.4 Low Core Power Density and Off-the-shelf Technologies

With reference to the Holos Quad generator operating with fuel cartridges 8% enriched and Brayton cycle (B_8 in Table 1), the thermal-to-electric power rating is 22 MWth-to-10 MWe respectively. Accordingly, the maximum thermal-to-electrical power rating per individual subcritical power module in this configuration is 5.5 MWth-to-2.5 MWe respectively. This relatively modest power rating produced by each subcritical power module enables utilization of off-the-shelf power conversion components based on reliable turbojet technologies employed worldwide. For example, the compressor and power turbines of the turbojet model General Electric CJ-610 operate at 6 MWth and similar components can be utilized to support Holos power conversion turbomachinery. More generally, low volumetric power generation and relatively low operating temperatures, further support utilization of non-exotic materials in the high-temperature regions of the fuel cartridges and for the turbomachinery components. A similar approach is applied to the scaled-up version of the subcritical power modules employed by the Holos Quad Titan configuration. The design ability to utilize off-the-shelf components and non-exotic materials enables substantial cost reductions while assuring reliability proven by decades of commercial operations.

1.5 Enhanced Safety

The working fluid utilized in the Holos Brayton thermodynamic cycle is Helium (He) or Carbon dioxide (CO_2); however, other working fluids with adequate thermal-physical and neutronics properties can be utilized. Safety is inherently enhanced by core architecture as Holos nuclear core is formed by coupling multiple independent subcritical power modules, each containing sealed fuel cartridges that do not rely on emergency cooling systems even under total loss of coolant accident (LOCA). As the subcritical power modules are thermally coupled to the surfaces forming the walls of the standard transport container, the fuel cartridges are passively cooled by environmental air. As a result, the design does not require inventories of water and balance of plant. Additionally, as the fuel cartridges are relatively small, fuel elements are sealed within multiple pressure boundaries further hardened with ballistic shields to work towards satisfying safety requirements addressing Design Basis Accident (DBA) scenarios, as well as Design Basis Threat and Attack scenarios for civilian and military applications (see Section 3 for in-depth Holos passive safety features).

One of the preferential fuels loaded in the fuel cartridges can be represented by TRISO fuel with proven radionuclide retention even under prolonged exposure to temperatures exceeding 1,600°C (2,912°F) [1]. Tests on High Temperature Gas Reactors (HTGR) conducted by U.S. and international programs demonstrated that under LOCA accident scenarios the maximum temperature reached by the core is substantially below safety thresholds. HTGR cores are much larger than Holos coupled core, thus temperature transients deep inside the HTGR cores induce higher maximum temperatures when compared to Holos smaller coupled core (multiple fuel cartridges). Heat transfer analyses focused on establishing the maximum temperature reached by Holos fuel cartridges under total loss of coolant accident scenarios produced temperature peaking at 1,400 Kelvin (1,127°C or 2,060°F see Section 3.6). As the fuel cartridges represent very small heat transfer systems compared to HTGR core designs, the distance from the center of the fuel cartridge to the passive heat transfer surfaces is lowered by a factor of 15-20, thus thermal energy is naturally and more effectively transferred by thermal conduction from the fuel cartridge internals to the UHS represented by environmental air.

Neutronic computations determined that Holos moderator-to-fuel ratio ensures a negative Moderator Temperature Coefficient[2] (MTC). The subcritical power modules cannot become critical even under the scenarios considering flooding of the transport ISO container with neutron moderating fluids (e.g. submerging the Holos retrofitted transport container by dropping it into a body of water).

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[2] The moderator temperature coefficient (MTC) is defined as the change in reactivity per degree change in moderator temperature. This coefficient should be negative for safe operation.

Overall, the fuel loaded within Holos fuel cartridges is not thermally challenged even under worst-case accident or attack/sabotage scenarios as the fuel cartridges are formed by reinforced structures with multiple containment and pressure boundaries to ensure radionuclides remain sealed and confined within the fuel cartridges at all times.

1.6 Scalable Power Rating while Satisfying Mobility Requirements

For electric power demand up to 13 MWe, a single transport container comprises the whole operational generator as shown in Figure 2 and Figure 3, wherein each subcritical power module is independently supported within an exoskeletal structure. For simplicity, the modules shown in these Figures have been stripped of auxiliaries, shielding and passive air-cooling heat transfer systems. Figure 2 shows the frontal-, side-, top- and perspective-view of a fully operational Holos Quad generator. The power conditioning electronics is mainly formed by pre-fabricated modular enclosures equipped with three-phase inverter bridges or power modules (e.g. IGBT[3]). Auxiliary equipment supporting the Automatic Module Positioning System (AMPS), formed by redundant hydraulic, electromagnetic and control systems, is also housed inside enclosures integrated within the transport container. Holos fast actuating hydraulic system operates similarly to hydraulic flight-control systems with redundant safety and architecture similar to those employed by the aviation industry. For example, landing gears, flaps, and flight-control surfaces are actuated by highly reliable redundant systems with decades of operational experience. Load following, three-phase, electric power is provided by actuating the AMPS to regulate core criticality, which, in turn, increases/decreases the fuel cartridges' thermal rating and induces the power conversion unit in each subcritical power module to proportionally produce electric power.

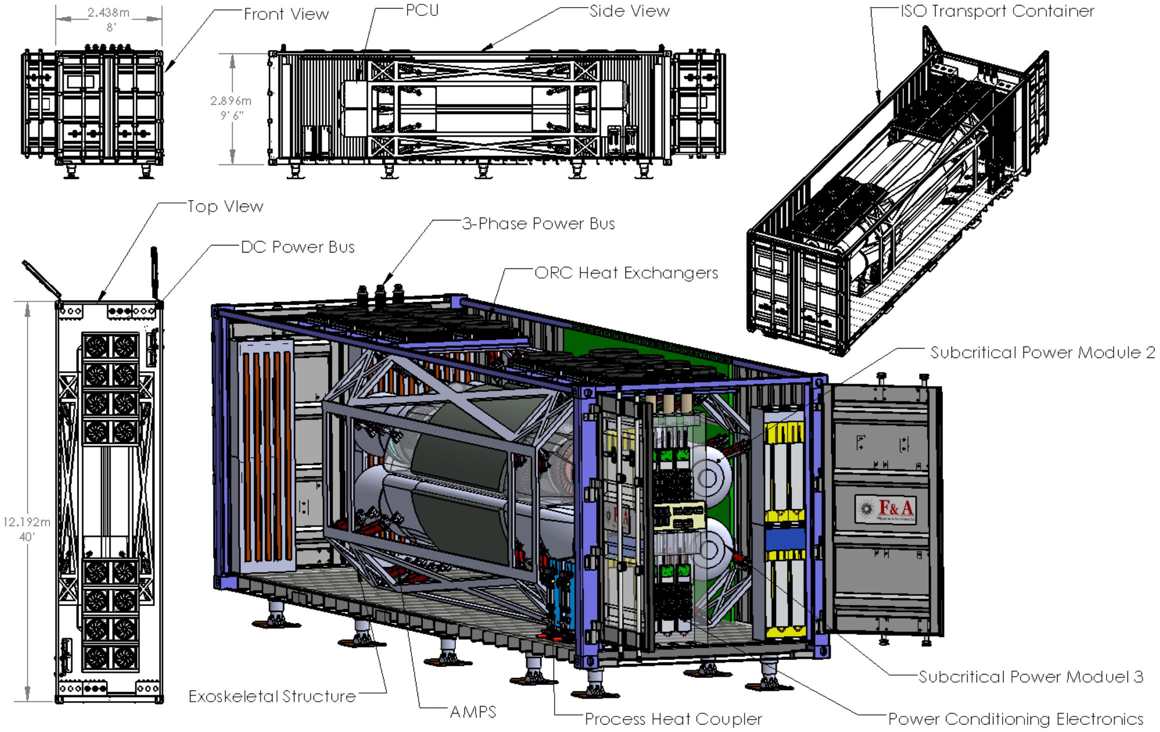

Figure 2: 13 MWe Holos Quad (4x subcritical power modules) in transport ISO container

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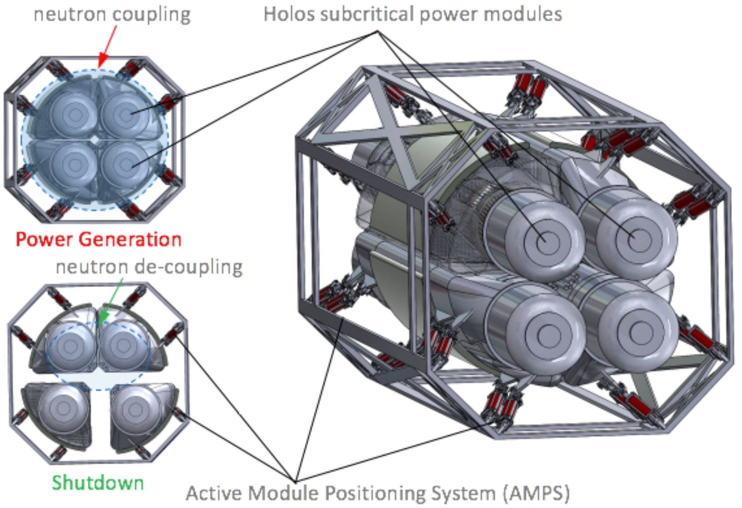
[3] Insulated-Gate Bipolar Transistor (IGBT) generally formed by a three-terminal power semiconductor device used as an electronic switch which, as it was developed, came to combine high efficiency and fast switching.

Neutron coupling among multiple subcritical power modules is determined by core geometry-mass changes resulting from active positioning of the subcritical power modules relative to one another (Active Module Positioning System shown in Figure 2, Figure 3 and Figure 4).



- Distributable/Transportable
- 3-13MWe Quad configuration
- 60-81MWe Titan configuration
- 12-20 Years refueling
- Enrichment 8% - 15%
- He/CO_2-cooled
- 60% Brayton & ORC efficiency
- Air as Ultimate Heat Sink
- Sealed fuel cartridges
- Decommissioned via licensed casks

$75M/13MWe NOAK	20 FEPY
LCOE QUAD	$0.0532/kWh
LCOE Titan	$0.0249/kWh
Overnight cost Quad	$4,404/kWe
Overnight cost Titan	$1,863/kWe

Figure 3: Holos Quad generator general characteristics

The fuel cycle for Holos Quad generators is driven by application requirements. For example, Holos generators dedicated to support rapidly deployable emergency power can supply electric power and process heat at a power rating <5 MWe, with a 6-year fuel cycle. For this specialized application, the generator size and weight is reduced and fully comprised within transport ISO containers measuring 20ft (6m) in length instead of 40ft (12.2m), to comply with total generator weight air-lifting and cargo-bay dimensional requirements. For these applications, the generators are not utilized at full power at all times, therefore the 6-year fuel cycle is practically extended proportionally to the generator utilization or duty cycle, which is dictated by the emergency power demand and the frequency of emergency operations.

For applications requiring power ratings up to 81 MWe, the overall size of the subcritical power modules is increased to house proportionally larger fuel cartridges. The scaled-up versions of the design comprise and seal all of the components within each subcritical power module. For these configurations, a single 40ft (12.2m) transport ISO container may comprise only one scaled-up subcritical power module and the AMPS. Figure 4 illustrates an operational power station based on the Holos Quad Titan electric generator. As shown in this figure, multiple larger subcritical power modules are comprised within independent transport containers clustered near one another to form the variable whole core geometry system. As for the Holos Quad configuration shown in Figure 2, to simplify the visual representations, the Holos Quad Titan generator modules represented in Figure 4 have been stripped of auxiliaries, shields, reflectors and passive air-cooling heat transfer systems. In this configuration, to further increase radiation shielding, the process heat components coupled to the ORC heat exchangers can be housed in independent ISO containers positioned and stacked as shown in this illustration. Holos generators can be clustered to meet different power demands by electrically coupling multiple fully operational generators. Depending on market characteristics at the deployment site, cost-effectiveness of Holos generators can become more advantageous when considering the scaled-up version of Holos Quad Titan generators as an alternative to clustering multiple Holos Quad generators. For example, 1x Holos Quad Titan generator can more cost-effectively provide 81 MWe at higher FEPY, compared to 6x Holos Quad generators producing 13 MWe each.

The fully operational 81 MWe power station shown in Figure 4 utilizes the Organic Rankine Cycle (ORC) modules to provide additional shielding. In these configurations, the ORC modules are thermally coupled to the scaled-up subcritical power modules without exchanging or mixing the ORC working fluid and the fluids utilized to support process heat applications. The ORC modules are equipped with the components forming the closed loop organic Rankine power cycle (e.g. organic fluid reservoir, heat exchangers, pumps, and turbo-generator). Additionally, depending on application requirements, battery banks can populate the ORC modules, to support start-up and load-following operations.

To summarize, each transport container can be configured to house a fully operational Holos Quad generator with 10-13 MWe power rating as shown in Figure 2, or it can house individual, comparatively larger, Holos Quad Titan subcritical power modules aligned and clustered to form the full core as shown in Figure 4.

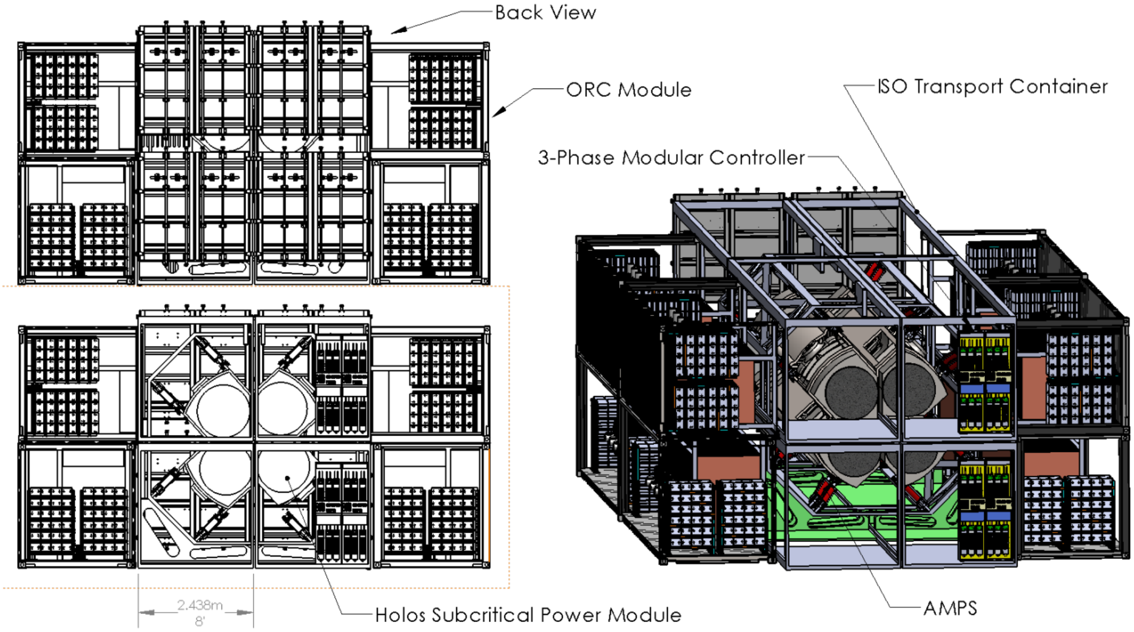


Figure 4: 81MWe Holos Quad Titan generator

1.7 Melt-resistant fuels and fuel neutrality

The preferential type of fuel loaded in each subcritical power module is melt- and proliferation-resistant TRistructural-ISOtropic (TRISO) fuel (see Section 3.8). Fuel performance evaluations under various operational and accident scenarios have been executed through programs supported by the U.S. Department of Energy and private industry [2]. Additional validation on fuel performance is supported by international advanced nuclear fuel programs with full-scale testing mainly executed in Germany, U.S., Japan, and Russia, with China currently constructing two high-temperature gas reactors loaded with TRISO fuel for commercial operations. Holos fuel cartridges can operate with nuclear fuels developed for Generation III and Generation IV advanced nuclear reactors, and can be cooled by gaseous and non-gaseous fluids (see fuel cartridges configurations shown in Figure 9). More generally, the fuel cartridges enable “fuel neutrality” as the working fluid does not mix and is not in physical contact with the fuel-moderator matrix (fuel cartridge internals), and its impact on neutronics (e.g. moderation) is factored in the design of the fuel-moderator matrix or mixture. As the fuel cartridge pressure boundary does not affect the turbomachinery pressure boundary, the fuel can be pressurized or maintained at atmospheric pressure.

1.8 Innovative Approach

The Holos concept enables several technological innovations with respect to large reactor and small modular reactor (SMR) designs considered in Generation III, III+ and IV. The fuel utilized by Holos represents a first containment and pressure boundary, contained within fuel cartridges with multiple discrete pressure boundaries and independent containments to further prevent migration of radionuclides to turbomachinery components. As part of the Holos approach, the fuel elements can remain sealed within the fuel cartridges at all times throughout the fuel cycle, from factory to permanent repository. Another innovative aspect is represented by the integration of the turbomachinery and electrical machines, forming the components of the Power Conversion Unit (PCU), all together with the fuel cartridge and within the same pressure vessel. This eliminates the Balance of Plant (BoP) and the total number of System Structures and Components (SSCs) forming the generator.

Transportability with conventional transport platforms of fully operational Holos generators is another innovative feature. The generators can be configured to produce power even while being transported, for example, to rapidly deploy emergency power or to provide electric propulsion (see marine applications in Market and Deployment Applications Section 4). This feature supports deployment of the generators at electric distribution nodes to support power grids operating near full capacity.

The distributable generators can be coupled to renewable energy sources (e.g. wind, solar). Holos Quad generators can be operated with duty cycles that compensate for the power production intermittence and refurbishing downtime typical of technologies based on non-dispatchable renewable energy systems.

Another innovation is represented by Holos generators configured with ORC components. These components continue to convert thermal energy into electricity even after the subcritical power modules are shutdown. Electricity will be continuously produced proportionally to the fuel cartridges natural decay thermal energy. This feature provides passive and automatic cooling of the fuel cartridges while in shutdown conditions, and lowers thermal loading requirements at spent fuel storage and permanent repository facilities. As decay-heat power is converted to electricity the Holos Quad generators can be rapidly retrieved from the site of deployment.

Real-time load-following capabilities is another innovative feature of this design. Most SMR designs inefficiently discharge excess thermal energy to the condenser in order to comply with load following electric requirements. As the power ratings of the Holos subcritical power modules are relatively low and their power conversion systems are based on turbojet technologies, the AMPS executes quasi-instantaneous criticality adjustments and Holos generators are real-time load followers. As a result, nuclear fuel utilization is increased as it is only consumed to produce electricity based on electric demand.

Finally, the fuel cartridges comprise innovative enhanced safety features to address beyond design basis accident scenarios, and design basis attack/sabotage scenarios by segregating the fuel, separating the working fluid from the fuel and moderator components, while reinforcing the fuel cartridges' structures with multiple shields.

Overall, the key innovations in the Holos reactor concept are represented by the thermal-hydraulic architecture enabled by the integration of the fuel cartridges with turbomachinery-components, thermal coupling of Brayton and ORC components, BoP elimination, passive air-cooling, transportability and retrievability by fitting standard transport containers, real-time load-following capabilities, with components fitting licensed standard spent fuel storage casks, thus inducing simplified decommissioning activities and lowering decommissioning costs.

1.9 Full-scale Testing Capability

As the non-nuclear components are represented by commercial/operational systems (e.g. all of the subcritical power module components, with the exception of the fuel cartridge), the hardware required to satisfy the various Holos configurations with Brayton or Brayton-ORC power conversion systems can be rapidly constructed and full-scale tested. Full-scale testing can be executed through utilization of surrogate fuel cartridges utilizing non-nuclear heat sources. Surrogate heat sources and test rigs have been developed to support testing and performance validation of multi-megawatt Brayton and ORC based waste heat recovery systems applied to large diesel-engines. These testing facilities, without substantial modification, enable full-scale performance validation of the Brayton and Rankine cycle components adapted to support Holos Quad configurations. Therefore, fully assembled Holos subcritical power modules can be cost-effectively tested at normal and off-normal operating conditions to optimize the design and provide real-life thermal-hydraulic data to increase accuracy of coupled neutronic simulations. The ability to execute full-scale subcritical power module testing under all operational, off-normal, design basis and beyond design basis accident scenarios, as well as design basis attack/sabotage scenarios, enables validation of safety performance parameters to accelerate licensing processes and lower costs.

2 Overview of Holos Design Features

Table 1 provided in Section 1, summarizes six selected configurations of the Holos design to support application-specific requirements. For example, the subcritical power module power rate depends on the fuel cartridges' composition, size, and core geometry formed by actively positioning multiple subcritical power modules. The efficiency of the power conversion components is mainly dependent on the thermal-physical properties of the working fluid, the coupled Brayton-Rankine cycles components and the elimination of the BoP outside of the sealed pressure vessels surrounding each individual subcritical power module. As the generator produces electricity, it also produces thermal energy normally rejected into the environment with portions of this energy recovered to support process heat applications. These features further convert waste thermal energy into electricity (ORC components). This Section provides an overview of Holos design features.

2.1 Waste Heat Recovery and Process Heat Capabilities

Holos modules equipped with combined Brayton and Organic Rankine Cycle (B-ORC) components integrate a secondary loop wherein an organic working fluid circulates. Organic fluids are characterized by high-molecular mass with liquid-to-vapor phase change (e.g. boiling) occurring at relatively low temperatures.

All thermodynamic cycles unavoidably reject a portion of the thermal energy source to the environment. Holos waste thermal energy sources are represented by the Brayton intercooler and recuperator heat exchangers, normally rejecting thermal energy to the UHS (environmental air surrounding the generator). Another source of thermal energy is represented by the decay heat generated when Holos fuel cartridges are shut down after a period of power production. In the Holos thermal-hydraulic system, a primary fluid is represented by the gas (He or CO_2), a secondary working fluid is represented by the organic fluid circulating in the ORC system.

As the ORC heat exchangers transfer thermal energy to support process heat application, a third fluid is utilized to further separate from the primary and secondary fluids to transport thermal energy to process heat applications. Because of the multiple physical separations between the various fluids and the physical isolation of the fuel cartridges, radionuclides cannot be transferred to the process heat equipment under all operational, off-normal and accident scenarios. Process heat can be provided with high- and low-temperature depending on applications' requirements.

Figure 5 illustrates the general position of hydraulic couplers providing access to the third fluid (3^{rd} fluid circulating through Process Heat Hydraulic Ports shown in this Figure) and supporting process heat applications with respect to the generator layout.

In this representation, four subcritical power modules are comprised within a transport ISO container (see also Figure 2 and Figure 3), all together with power inverters to control and condition the electrical power generated.

Shielding and passive heat transfer systems coupled to the ISO transport container structures and surfaces are not shown in these illustrations. The ORC radiators, shown on the top portions of the transport ISO container, support active air-convection heat transfer during normal operation and become part of the passive heat transfer mechanisms transferring decay thermal energy to the UHS when the subcritical power modules are shutdown.

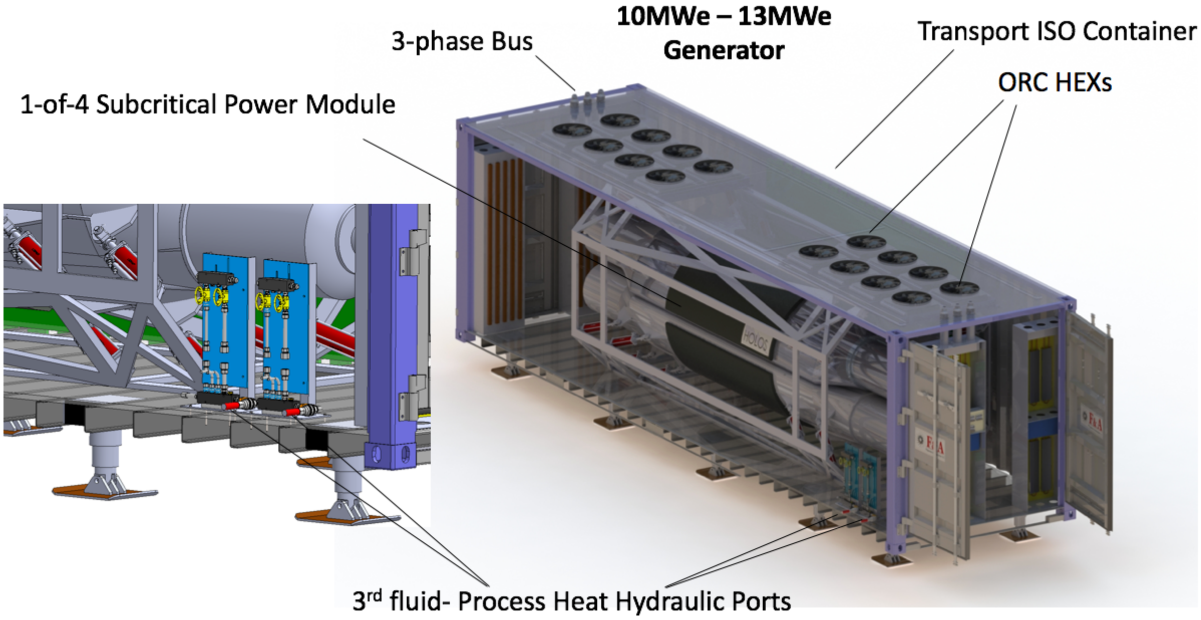


Figure 5: Holos Process Heat Capability via Isolation Heat Exchangers

2.2 Grid Connectivity and Ancillary Services Markets

Holos generators can be clustered to match electric demand. Connection to grid is obtained by interfacing the generators 3-phase AC power bus to power grid substation equipment. The Power Conversion Unit (PCU), integrated with each Holos subcritical power module, regulates electronic multi-level inverters to provide high-resolution, near real-time load-following electric power automatically synchronized with grid/substation equipment. Load following and regulation ensure that, under normal operating conditions, a control area is able to balance generation and load. Regulation is intended as the use of on-line generation, storage, or load that is equipped with automatic generation control (AGC) and that can rapidly change output (MW/minute) to track fluctuations in customer loads, and to correct for the unintended fluctuations in generation. Regulation helps to maintain interconnection frequency, manage differences between actual and scheduled power flows between control areas, and matches generation to load within the control area [3]. Ancillary services are defined as functions performed by the equipment and people that generate, control, and transmit electricity in support of the basic services of generating capacity, energy supply, and power delivery. The Federal Energy Regulatory Commission (FERC) has defined such services as those "necessary to support the transmission of electric power from seller to purchaser given the obligations of control areas and transmitting utilities within those control areas to maintain reliable operations of the interconnected transmission system." Hourly markets for regulation and the contingency reserves (as opposed to long-term contracts) in most independent system operator regions, are advantageous proportionally to a resource ability to supply these services near real-time (as the hourly energy market varies).

As Holos reactivity-to-thermal-to-electricity production can be changed near real-time, the generator can provide fast response services, command higher prices and provide distributed contingency power for generators based on renewable energy sources. For example, wind generators produce fluctuating electricity as a result of wind conditions. To ensure grid stability, other generation resources have to be employed. Figure 6 is reproduced from reference [3] and shows variations in wind speed and power output over a two-day period from a wind-plant with a total of 138 turbines spread over four interconnection points indicated from A to D in this Figure.

Power output variability is directly proportional to wind speed changes. From a grid operation stand point, the adoption of distributed Holos generators can be seen as AGC generators that can supply MW/min proportionally to grid operator needs. In this example, assuming a hypothetical demand requiring steady power generation at 75 MW for the first 12 hours, and 60 MW for the last 36 hours, a single Holos Quad Titan can supply the demand near real-time.

Regulation requirements change in agreement with the independent system operator regions (as a result of total generation capacity in the controlled area). For the example shown in Figure 6, the wind-plant regulation requirement is 4.8 MW, therefore, in this specific control area, a single Holos Quad generator could satisfy the regulation requirement without need for power storage equipment.

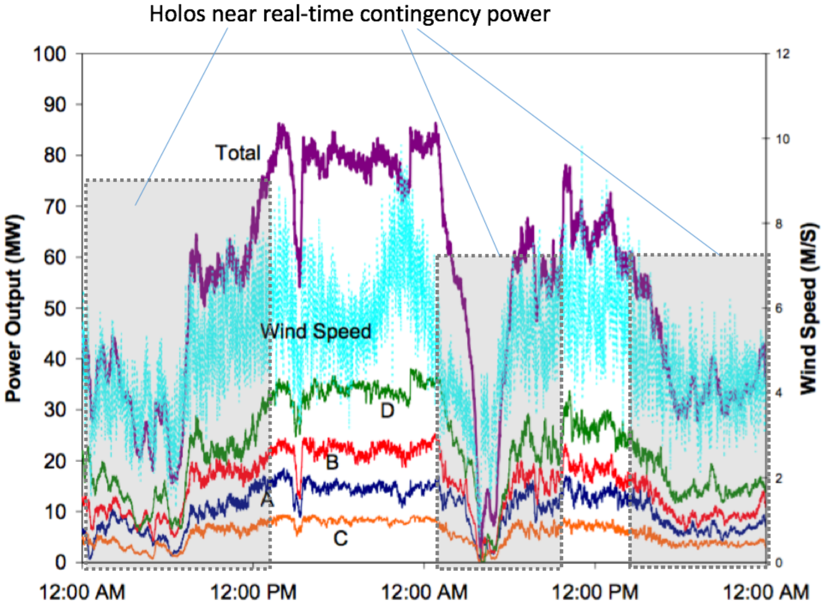


Figure 6: 48-hour Midwestern wind-plant power output (source Hudson, Kirby, and Wan, 2001)

Figure 7 provides an example of 5x Holos Quad generators clustered to obtain a total power rating of 65 MWe. The *source term*[4] represented by the proposed generators is substantially reduced when compared to light water reactors (LWRs) and Generation IV advanced and SMRs. Accordingly, the evacuation planning zone[5] (EPZ) normally characterizing nuclear power plants, and mostly depending on the total quantity of radioisotopes that can be released into the environment, can be reduced. This enables deployment/distribution of the generators at various locations.

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[4] Types and amounts of radioactive or hazardous material released to the environment following an accident. (https://www.nrc.gov/reading-rm/basic-ref/glossary/source-term.html)

[5] https://www.nrc.gov/about-nrc/emerg-preparedness/about-emerg-preparedness/planning-zones.html

Figure 7: 5x Clustered Holos Quad generators, 65 MWe total generation
Each generator is positioned to ensure adequate passive air-flow, external shields not shown

Clustering Holos Quad Titan generators, representing power ratings up to 81 MWe per individual generator, results in proportionally larger power plant footprint as shown in Figure 8.

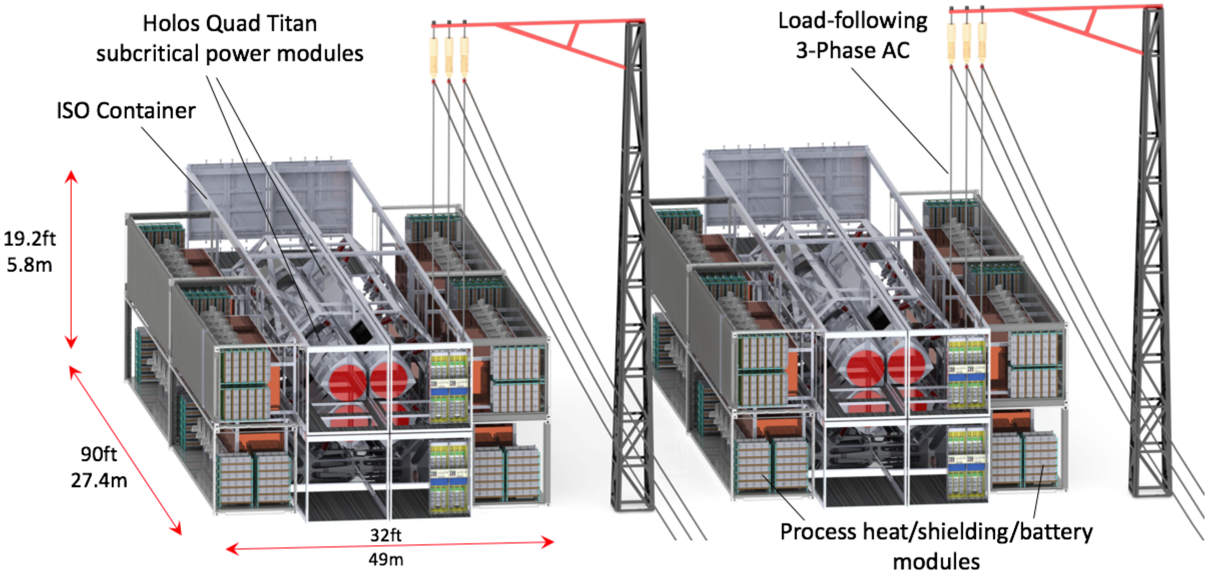

Figure 8: 2x Clustered Holos Quad Titan generators, 162 MWe total generation

While in the Holos Quad configuration each transport ISO container comprises all of the subcritical power modules, under the Holos Quad Titan configuration, each scaled-up subcritical power module occupies the entire volume represented by a single transport ISO container.

In this case, the variable core geometry characteristic of the Holos concept is executed by clustering multiple transport ISO containers, each retrofitted with scaled-up subcritical power modules. Shields and ORC modules can be integrated with specialized transport containers assembled and positioned as shown. For all configurations, the retrofitted transport ISO containers can be clustered above or underground or integrated with industrial equipment, for example, on board marine vessels (e.g. see Figure 30).

2.3 Fuel Cartridges and Fuel Neutrality

Holos design is “neutral” with respect to fuel composition and neutron moderation. Fuel neutrality is enabled by the fuel cartridge architecture as it contains the fuels and moderators while including the features of a “shell-tube” heat exchanger. Accordingly, the fuel-moderator components are constrained within the shell-side of the heat exchanger. As the fuel-moderator cooling mechanisms are thermally coupled to the working fluid without physical contact, the fuel cartridge can be loaded with different fuels and moderators (see Section 3.3 for in-depth information about the fuel cartridges features). Generally, the fuel loaded in the fuel cartridges can be represented by solid fuel particles (e.g. TRISO micro spheres), compacts, pellets, monolithic fuel elements, or homogenous mixtures moderated by various materials in liquid and solid forms mixed with or constrained by moderator materials. The shell-side of the fuel cartridge does not need to be pressurized to satisfy thermodynamic cycle requirements (see Figure 10). Therefore, the fuel cartridge merely represents a thermal source coupled to high-pressure tubes for the working fluid to increase its energy content as it flows through the tube-side, without mixing and physical contact with the fuel cartridge’s internals.

Figure 9 illustrates multiple subcritical power modules containing fuel cartridges (A and B) possibly loaded with different types of fuel arranged within fuel-moderator matrices with moderators formed by the same or different compositions.

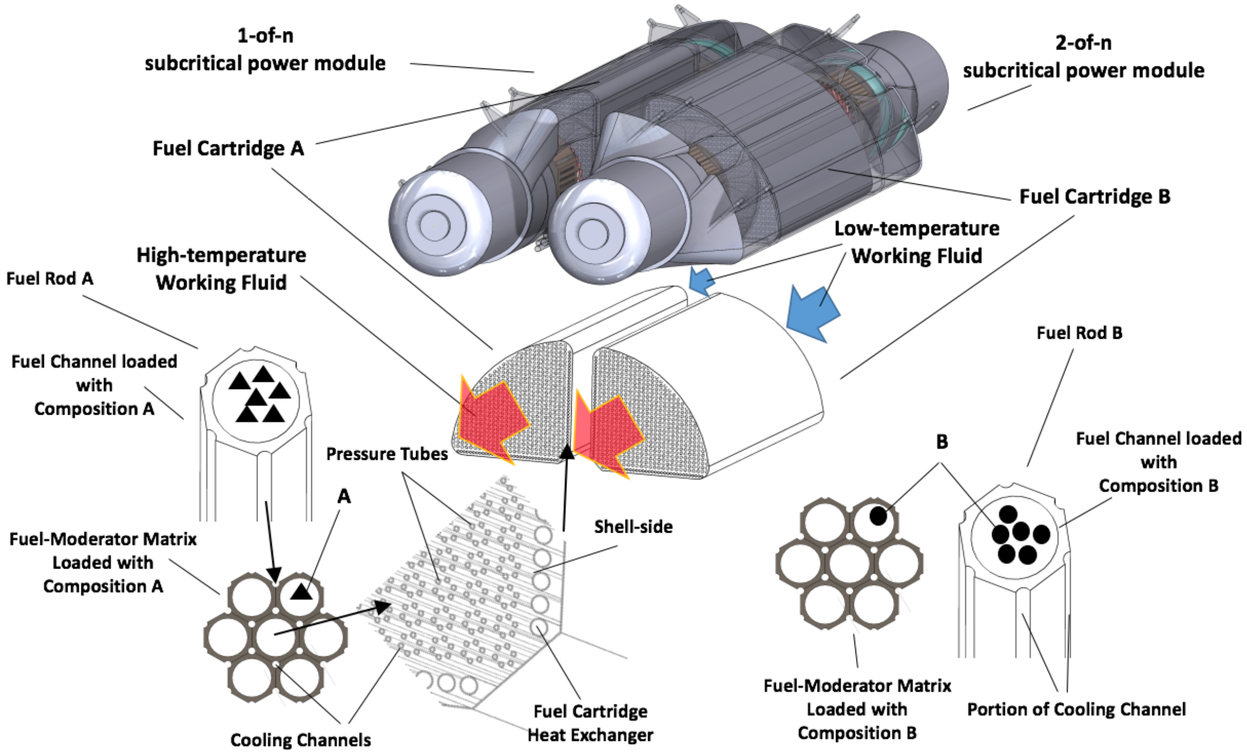

Figure 9: Subcritical power modules loaded with various fuel and moderator compositions

Once the subcritical power modules are positioned near one another, they enable sustained chain reactions. As shown in this Figure, the fuel channels in one of the fuel cartridges equipping the subcritical power module, can be loaded with multiple fuel compositions to optimize performance. Criticality is achieved through neutron leakage control. The coupled whole core becomes critical, leading the PCU equipping each subcritical power module to produce electricity, as long as the type of nuclear fuel, enrichment, total mass of fuel, moderator and coupled geometry satisfy geometric and mass buckling requirements to sustain chain reactions. With reference to Figure 9, fuel cartridge A is formed by a fuel-moderator matrix loaded with one type of fuel (as represented by the triangular symbols). The fuel-moderator matrix is then inserted by sliding the pressure tubes through the fuel-moderator matrix cooling channels, which thermally couple the fuel-moderator matrix to the working fluid circulating within the pressure tubes. The fuel cartridge is then permanently sealed, thus trapping all fuel elements in its internals. Under this configuration, relatively low-temperature working fluid inlets the fuel cartridge tube-shell header on one side, flows through the pressure tubes, and exits the pressure tube header on the other side with increased energy content. In another configuration, the fuel-moderator matrix can be formed by "fuel bricks" as shown in Figure 10. Other fuel cartridge configurations can be represented by monolithic fuel bricks, wherein fuel elements (e.g. microspheres) can be embedded altogether with the moderator matrix through various manufacturing methodologies.

2.4 Balance of Plant (BoP) Elimination

LWR as well as Generation IV advanced and SMR designs are generally characterized by a reactor pressure vessel comprising the core and in some cases heat exchangers. For the great majority of these designs, the turbomachinery components dedicated to the thermal-to-electricity conversion are often housed in different locations within dedicated buildings equipped with firewalls, isolation structures, and redundant BoP. In these configurations, thermal-hydraulic coupling of the components between the reactor pressure vessel and the power conversion equipment is executed through networks of piping, valves, fittings, and electric conduit to provide hydraulic connections as well as motive, emergency and control power to auxiliary equipment. Holos fully integrated thermal-hydraulic, turbomachinery and electricity producing components sealed within the subcritical power modules all together with the fuel cartridge represents a diverging approach when compared to LWR, SMR and Generation IV designs.

While Brayton cycle conversion to electricity is often executed through gear reductions to match the optimum turbine rotational speed with the generator's speed, Holos integral PCU is directly driven – the turbine-generator assembly is directly coupled, with voltage and frequency satisfying power grid requirements through electronic control via power modules. Holos design requirements solely rely on operationally proven technologies, therefore the components forming Holos PCU are derived from commercial off-the-shelf turbomachinery and generator equipment normally utilized to support turbojet-engines for aviation and power generation applications. Direct-drive electric generators are available from waste heat recovery applications. Similar components are also utilized to support operations of conventional and advanced fossil-fuel combustion turbines. Holos power conversion system operates on the same principles applied to commercial jet engines and gas turbines for power generation, wherein the "combustor" utilized to increase the working fluid thermal energy is replaced by Holos fuel cartridges. As the thermal-hydraulic system is integrated within each subcritical power module, there are no external networks of piping, valves, fittings and electrical conduits normally required by LWR and Generation IV designs. Eliminating the BoP induces significant hardware simplifications and costs reduction, while increasing the overall system reliability, robustness and safety performance.

3 Safety and Detailed Design Features

3.1 Enhanced Shielding

The total power level and amount of fuel represented by each fuel cartridge are small compared to both traditional power reactors and SMR designs. As a result, further protecting the radionuclide inventory inside Holos reinforced structures with additional external shields (e.g. inside and outside of the ISO container housing the generator) can leverage adoption of ballistic shielding technologies developed and mass-produced for armored vehicles. In these configurations, the extra shields can also be coupled to the ISO container heat transfer surfaces to support heat transfer functions in addition to ballistic shielding.

Holos shields simultaneously execute the following functions: 1) neutron reflection; 2) heat transfer to the ORC working fluid without physical contact between the primary working fluid and the fuel-moderator elements; 3) heat transfer to the UHS (ISO container surrounding air); 4) radiation shielding; 5) ballistic shielding; and 6) structural support.

3.2 Engineered and Inherent Safety Features

Holos has extensive application requirements guiding the reference design. These requirements cross all aspects of safety and performance, from temperature limits for fuel failure to mass and volume restrictions for transport.

Core/fuel cartridge design and architecture ensures fuel temperature remains below 1,620°C[6] under all Anticipated Operational Occurrences (AOOs), Design Basis Accident (DBA), Design Basis Threat (DBT), and Beyond Design Basis Accident (BDBA) scenarios. The core achieves a maximum fuel temperature less than 1,200°C (2,192°F) under total loss of coolant with no volatile radionuclides release from TRISO particles up to the fuel limit (see Section 3.6 for supporting analysis). Radionuclides are retained in the fuel in compliance with the Nuclear Regulatory Commission (NRC) requirements (10CFR 50.34/10 CFR 52.79) for HTGR with TRISO fuels.

Decay heat is passively removed via thermal conduction, convection and radiation heat transfer from the fuel-moderator elements, comprised by the fuel cartridge, to the fuel cartridge integral heat-exchanger-housing. This thermal-hydraulic structure is configured to transfer the decay heat energy to the reflectors substantially surrounding the fuel cartridge. The reflectors are thermally coupled to the ballistic and radiation shields which further transfer the decay heat energy to the air (UHS) surrounding the ISO container. As a result, the fuel cartridges internals are thermally coupled to the heat transfer surfaces represented by the ISO container.

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[6] High Temperature Reactor (HTR) module data on TRISO fuel elements wherein at 1,620°C minimum release of volatiles through SiC layer can occur.

Holos has the required negative temperature coefficients of reactivity, which are essential for safe operation to ensure intrinsic reactor shut down during a temperature excursion – as core temperature exceeds threshold limits (e.g. due to off normal operating scenarios), reactivity decreases independently of malfunctions of the AMPS controls.

Fuel cartridges remain factory sealed, thermally coupled and physically independent with respect to the Brayton and ORC working fluids and from other fuel cartridges sealed within surrounding subcritical power modules. There is a low working fluid inventory: no mixing and no working fluid contamination (no physical contact), no coolant purification systems are required, and there is no coolant loading at deployment site. The power conversion systems comprising compressor and power turbine are thermally coupled to the fuel cartridges with no physical contact with the fuel-moderator elements. Finally, there is no transport pathway from the shell-side of the fuel cartridge heat exchanger through the pressurized working fluids operated by the Brayton and ORC components supporting core cooling, thermodynamic cycles and process heat functions.

Because of the simplified design architecture, the SSCs in the Holos design are substantially reduced compared to LWRs, HTGRs, and Generation IV reactors, including non-light water SMR designs with relatively high Technology Readiness Levels (TRLs). Fuel cartridges and portions of subcritical power modules fit standard fuel casks for remotely executed loading and sealing into spent fuel disposal casks for transport to temporary or permanent repositories.

The reduced number of SSCs for the Holos design implies a proportionally reduced number of events to be modeled and verified by full-scale testing. This supports the reduction of the Probabilistic Risk Assessment (PRA) event tree/fault models, as well as licensing processing time and cost.

More generally, the design leverages safety basis approaches [4] [5] [6] developed for HTGR with implementation of safety inherently in the subcritical power modules architecture and components. The result is a partitioned core engineered with each subcritical partition contained and representing highly reduced source terms. Each core partition is independently passively cooled and inherently subcritical with radionuclides sealed at all times during the lifecycle of the generator from factory to temporary storage or permanent repositories. Decay heat energy is passively removed by air even under worst case scenarios, including loss of coolant accidents (LOCA), Brayton and/or ORC components failure, and core breach resulting from attack/sabotage scenarios.

Active protection against threats of nuclear power plants is the responsibility of federal organizations, and "*…nuclear power plants owners have no obligation to defend against air attacks, including terroristic attacks*[7]". However, as Holos generators are distributable and can be deployed at an array of non-traditional sites, Holos safety features address active protection to enhance the generator safety performance under various types of threats. For example, DBTs involving missiles, air-crash, mortars and other means of delivering explosives are integrally addressed in the design to ensure containment and control of radionuclides resulting from various attack scenarios leading to damage of one or multiple fuel cartridge(s).

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[7] Final Rule in Docket RIN 3150-AH60 – Design Basis Threat, 72 Fed. Reg. 12,705 -12,727 (2007).

To summarize, the design factors the NRC regulatory requirements developed for LWRs, and integrates lessons learned from the development and operations of the HTR, the modular high-temperature gas-cooled reactor (MHTGR), the gas turbine modular helium reactor (GT-MHR), and the pebble bed modular reactor (PBMR). To validate Holos safety performance, all of the components forming the subcritical power modules can be tested at full-scale, individually, or operating as a whole system (i.e. 4x coupled subcritical power modules – Holos Quad configuration), under normal and off-normal operating conditions. Given the modest dimensions of the fuel cartridges, ballistic shields and TRISO mockup fuel particles ejection/transport due to DBT scenarios can also be tested at low-cost for validation of radionuclide containment effectiveness within controlled areas surrounding the generator.

3.3 Fuel Elements Thermally Coupled while Physically Isolated

To illustrate the different pressure boundaries and key features of Holos fuel cartridge, an analogue utilized to test temperature-induced expansions and heat transfer characteristics, as well as to increase accuracy of manufacturing costing, is illustrated in Figure 10. For simplicity, only a portion of the pressure tubes are shown in the fuel cartridge analogue containing only one of multiple fuel bricks forming the fuel cartridge. Accordingly, the working fluid (e.g. inert coolant helium) compressed by the compressor, inlets the fuel cartridge at the inlet header and flows internally to the fuel cartridge through the high-pressure tubes at elevated pressure. In this configuration, the fuel-moderator forming the fuel matrix or "fuel brick" is thermally coupled with the working fluid through the walls of the pressure tubes, as they are inserted through the cooling channels and further thermally coupled via thermal couplers (not shown in this Figure) to enable expansion and contraction during start-up, load-following operation and shutdown.

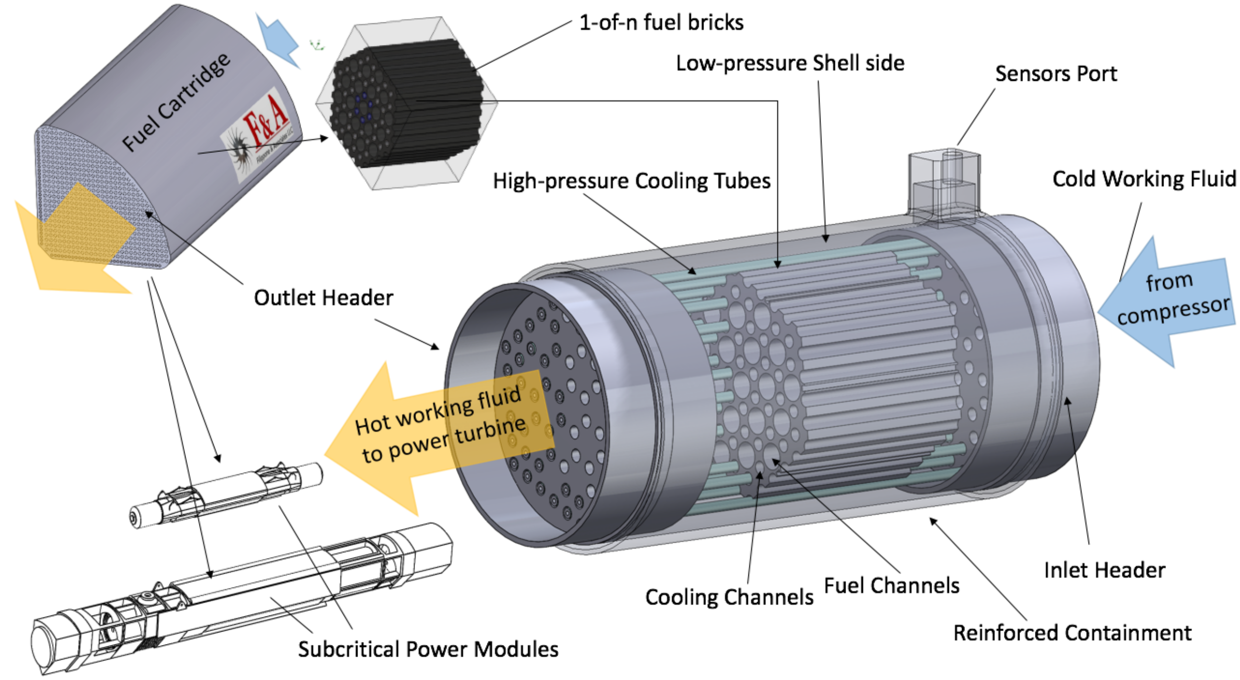


Figure 10: Holos' "single fuel brick" and fuel cartridge analogue

As shown, the working fluid circulates through the heat generating portion of the fuel cartridge without physical contact with the fuel and moderator materials, and exits through the outlet header with increased energy content. Accordingly, turbomachinery components can operate at relatively high pressures (e.g. to satisfy thermodynamic efficiency requirements), while the fuel and moderator can be operated at different pressures (e.g. atmospheric).

Overall, for applications utilizing melt-resistant fuels, the inherent high temperature characteristics and proven radionuclides retention of the TRISO fuel particles, combined with the passive decay heat removal and containment design features of the fuel cartridges, supports meeting of regulatory requirements for dose limits at substantially reduced exclusion area boundaries (leading to reducing the Emergency/Evacuation Planning Zone radius).

Figure 11 summarizes Holos fuel cartridges features wherein TRISO particles are placed and sealed within the fuel channels inside each fuel brick. As shown in this Figure, the fuel bricks are thermally coupled to the high-pressure tubes inserted within the fuel brick cooling channels. In this example, the fuel channels are loaded with TRISO fuel microsphere, thermally coupled through a thermal coupler and sealed within each fuel brick. Alternatively, TRISO fuel compacts can be inserted within the fuel bricks fuel channels. The loaded fuel bricks are then assembled by sliding them through the pressure tubes to form any subcritical or critical core shape (see Figure 11 top-right). Each layer of fuel bricks is then stacked to form a complete fuel cartridge which seals the fuel bricks (fuel and moderator). Finally, the sealed fuel cartridge is thermal-hydraulically coupled to the turbomachinery components of the subcritical power module and surrounded by reflectors and shields (not shown).

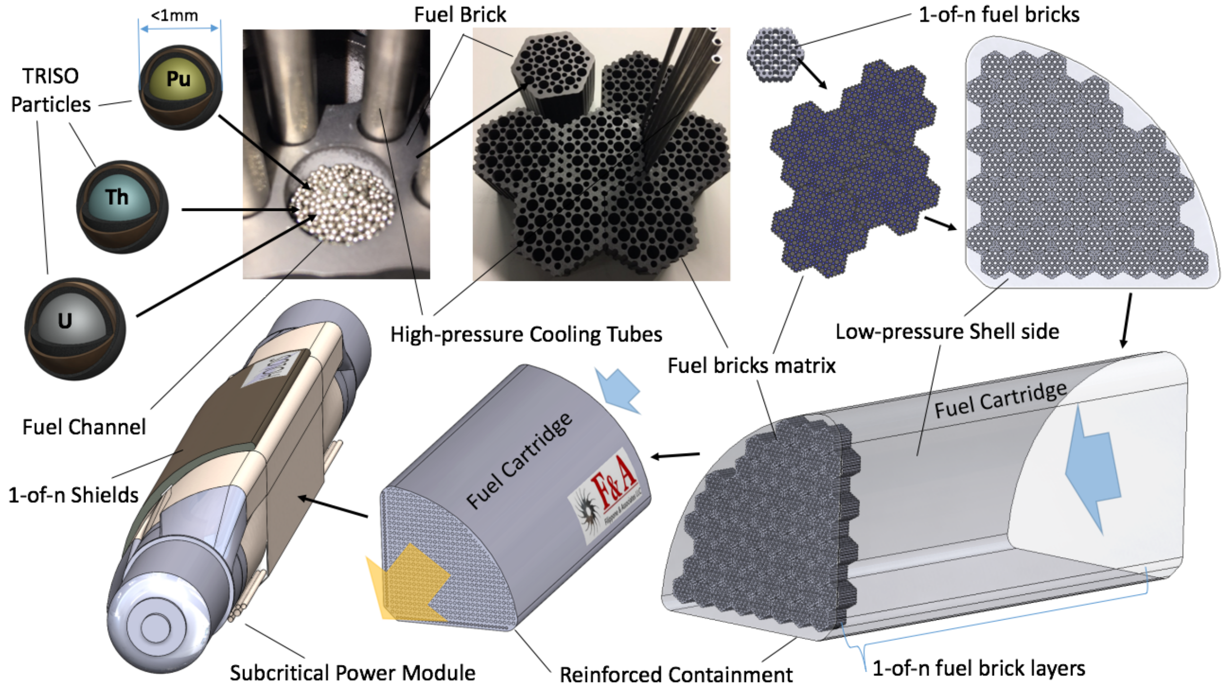


Figure 11: Holos fuel cartridge and containment configuration

3.4 Thermal-hydraulics and Power Conversion

As discussed in previous Sections, energy transfer from the fuel elements to the primary working fluid occurs without physical contact. During this process, the working fluid maximum temperature remains at values that are lower than temperatures characteristic of commercial turbojet and turboshaft combustion systems. As a result, metallurgical stresses of the turbomachinery components equipping Holos PCUs are less challenging than those represented by similar systems employed, for example, for aviation applications. Figure 12 illustrates the estimated working fluid temperatures and pressures at selected locations from the compressor inlet to the power turbine outlet. Depending on the ORC and process heat configurations, the Brayton intercooler and recuperator heat exchangers are coupled to the ORC evaporator and the process-heat intermediate heat exchangers.

The Brayton cycle thermodynamic efficiency is approximately 45% with an assumed environmental temperature set at 50°C (122°F). The efficiency increases to 60% for Holos subcritical power modules configured with ORC components. For these configurations, Holos thermal rejection to the environment and relative thermal signature are reduced, while the nominal total electric power produced by, for example the Holos Quad generator (4x subcritical power modules), increases from 10 MWe to 13 MWe, with unchanged fuel burnup rate.

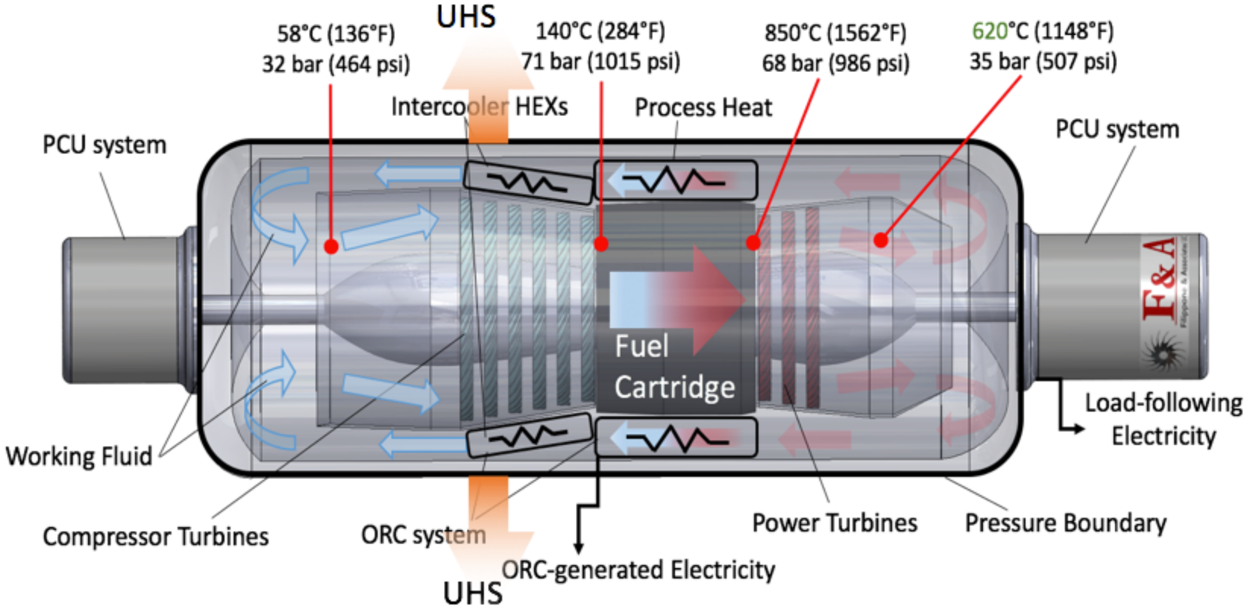
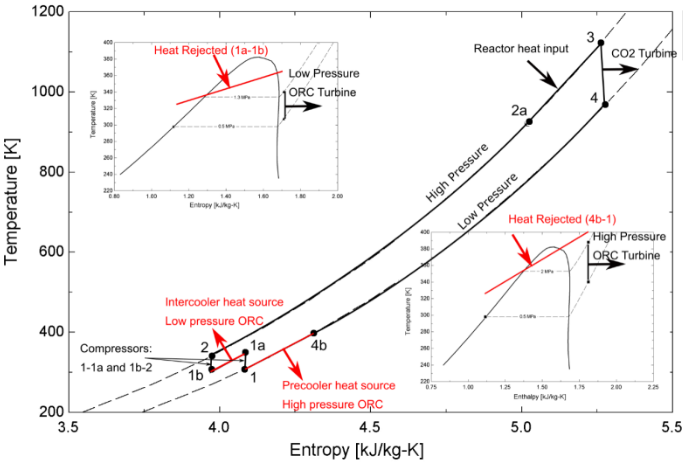


Figure 12: Holos full-Brayton closed loop thermodynamic parameters

3.5 Brayton Cycle Intercooler and Precooler Coupled to ORC

Figure 13 illustrates the temperature-entropy diagram of the Brayton cycle coupled to an Organic Rankine Cycle (ORC) configured to recover the otherwise wasted thermal rejection to the environment from the precooler and intercooler heat exchangers. The fuel cartridges provide thermal power (e.g. 22 MWth Holos Quad configuration) to the system (process 2a-3), which increases the working fluid energy content. Helium or CO_2 undergo expansion processes through the power turbine (process 3-4), thus providing mechanical energy converted to electricity by the PCU generator. In a standard Brayton cycle, thermal energy is rejected to the environment through process 4b-1. However, by coupling the precooler and intercooler heat exchangers to the closed-loop organic Rankine cycle heat exchangers, the cooling energy required to reset the Brayton cycle represents the heat source for a bottoming ORC cycle with a specialized ORC expansion turbine coupled to an electric generator (independent of the PCU generator), thereby resulting in the generation of electricity. The averaged environmental temperature assumed in the estimates summarized in Figure 13 (right) is 35°C. The net result of recovering the otherwise wasted Brayton thermal energy manifests into enhanced generator efficiency, with increased power rating without increasing fuel burnup. These preliminary analyses were performed for working fluids represented by Helium and CO_2 with different turbine inlet temperatures and pressure ratios. The results show that by coupling the full Brayton cycle to a bottoming ORC Holos could generate 5%-8% additional electrical energy compared to the standard Brayton cycle with no waste heat recovery features. Under the assumptions, the highest efficiency is 60.3%. As the subcritical power modules architecture is formed by relatively small pressure vessels, further reinforced to execute radiation and ballistic shielding protection, high-temperature and high-pressures can be employed without significantly increasing components costs. Furthermore, the analysis shows that efficiency up to 59% can be achieved even with relatively lower pressure ratios (see case represented by Brayton and ORC, Helium as working fluid, $T_{\text{inlet turbine}}$ = 1,123K (850°C or 1,562°F) and pressure ratio 70/35.

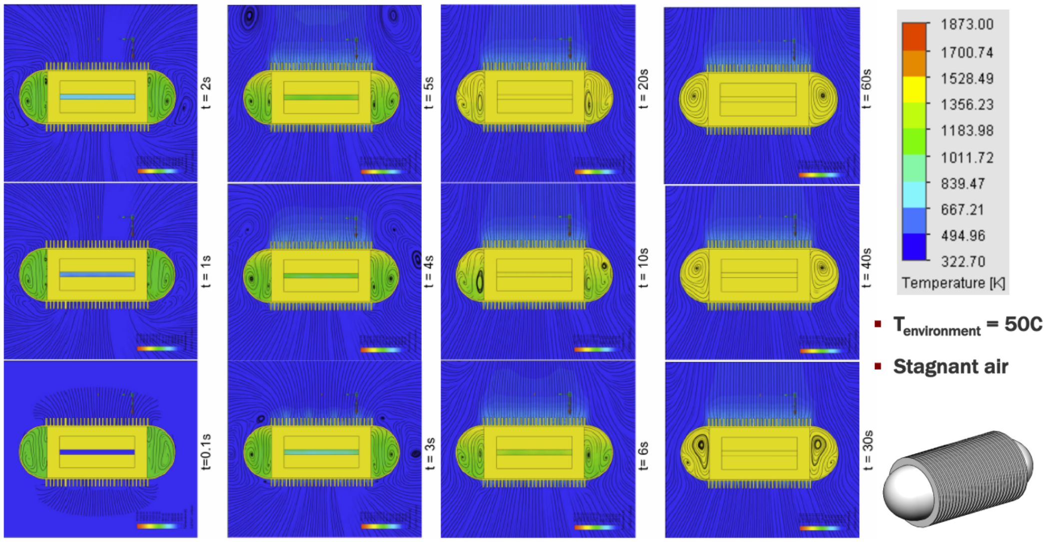


Working Fluid	Thermodynamic Cycle	$T_{\text{IN Power Turbine}}$			P_{in}/P_{out}		Efficiency
		°C	°K	°F	bar	psi	%
Helium	Brayton	650	923	1202	200/70	2900/1015	46.95
					70/35	1015/508	45.51
		850	1123	1562	200/70	2900/1015	55.60
					70/35	1015/508	53.70
	Brayton & ORC	650	923	1202	200/70	2900/1015	50.11
					70/35	1015/508	51.85
		850	1123	1562	200/70	2900/1015	60.30
					70/35	1015/508	59.10
CO_2	Brayton	650	923	1202	200/70	2900/1015	42.70
		850	1123	1562			50.45
	Brayton & ORC	650	923	1202			49.62
		850	1123	1562			56.30

Figure 13: Brayton Coupled to ORC Temperature-Entropy Diagram and Efficiency

3.6 Maximum Core Temperature under Loss of Coolant Accident (LOCA)

Figure 14 illustrates thermal transient estimates under total LOCA. The assumptions adopted for these preliminary projections are conservative with the environmental air temperature set at 50°C (122°F), and zero air velocity at start of event (stagnant air conditions) inducing negligible natural convection cooling. Additionally, the decay-heat power generation rate was selected according to core thermal power history prior to shutdown. Accordingly, after less than one hour from shutdown the decay heat power naturally reduces to 1.12% of the nominal power produced prior to the shutdown event. To simplify this preliminary analysis, the subcritical power modules were merged into a single pressure vessel (cylindrical core) with heat transfer mechanisms mainly dictated by thermal conduction from the fuel bricks to the fuel cartridge containment structures and from the containment to the external shields with fins thermally coupled to environmental air. At 0.1s post shut down (Figure 14, bottom left), the blue central area of the core indicates the central region or space between Holos subcritical power modules. As pressurized Helium or CO_2 gas is assumed to be suddenly lost due to pressure boundary breach, environmental air or air and air-helium mixtures take its place at atmospheric pressure. The thermal conductivity of SiC at the projected temperatures was utilized for the computation of heat transfer from the central regions of the simplified core to its outermost periphery. The maximum temperature reached under the assumptions is 1,400 Kelvin (1,127°C or 2,060°F), and starts to decrease exponentially after 60s (proportionally to the exponential decrease in decay heat power).



- $T_{environment}$ = 50C
- Stagnant air

Figure 14: Maximum temperatures reached under LOCA scenarios

Additional transient simulations were performed with environmental air temperature set at 80°C (176°F) resulting in negligible increase of core temperature. The driving heat transfer mechanism, under the assumptions, is radiative heat transfer. As the event progresses and the external surfaces heat up the air, the initial stagnant air conditions change into modest convective heat transfer induced by increasing air velocities driven by change in air density as air is "wetting" the external fins. The total air-cooling surfaces represented by the fins considered in this simulation lead to conservative results as the subcritical power modules are thermally coupled through reflectors and shields to surface areas equivalent to those characterizing the ISO transport container surfaces, thus, the total heat transfer surface area is actually extended by a factor of 4.5 when compared to the surface area represented by the fins utilized in the simulation.

These preliminary results were compared with data from testing of the MHTGR [7], where peak fuel temperatures remain under 1,523 Kelvin (1,250°C or 2,282°F) under similar transients. When the fuel cartridges are loaded with TRISO fuel particles, the resulting core is substantially smaller than the cores characterizing HTGR designs. Accordingly, the fuel cartridges comprised in each subcritical power module inherently induce lower maximum fuel temperatures under off-normal conditions when compared to maximum temperatures reached by larger cores under similar off-normal conditions.

3.7 Core design

Holos innovations are in the power conversion features that enable the identified use cases. A prototype core design has been developed for Holos to accommodate this innovative application. The main reactor core element of the Holos concept is the fuel cartridge which provides fuel sealed containment and can be loaded with different types and mixes of nuclear fuel and moderators. Figure 15 provides an exemplary simplified illustration of a single Holos fuel cartridge and coupled fuel cartridges. The choice of materials is restricted by the design constraint of geometry of the Holos subcritical power modules concept under movement by the AMPS controls. The fuel design used in the initial Holos core system is high-temperature TRISO fuel. The reactor core utilized for the simulation consists of an array of fuel subassemblies. Each fuel subassembly consists of a lattice of individual fuel cells and coolant channels surrounded by a steel layer serving as the primary fuel cartridge containment and pressure vessel. The coolant is helium gas.

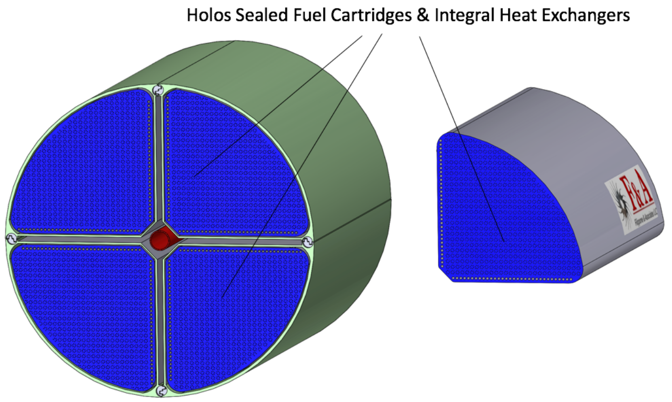


Figure 15: Simplified Holos Subcritical Fuel Cartridges

Table 2 provides an overview of the Holos operating parameters. MCNP 6.1 (a Monte Carlo radiation transport code) was used to construct a computational model of the reactor core and calculate initial physics parameters. Individual fuel channels are arrayed in a lattice as described above. Coolant channels were placed at the hexagonal vertices of the fuel channel. The subassemblies are placed in a hexagonal lattice structure surrounded by helium coolant. These fuel elements are shown with dimensions in Figures 16 and 17. To simplify the computation, four Holos fuel cartridges (Holos Quad configuration) were merged and the core was homogenized as shown in Figure 18.

Table 2: Holos Overview

Reactor Properties		
Operating Power	MW_{th}	22
Operating Lifetime (FEPY)	y	10-20
Mass of Heavy Metal	kg	2,562
Enrichment Range	%	8-15%
Mass of U-235	kg	384
Whole Core Volume	m^3	6.9
Whole Core Mass	kg	10,732

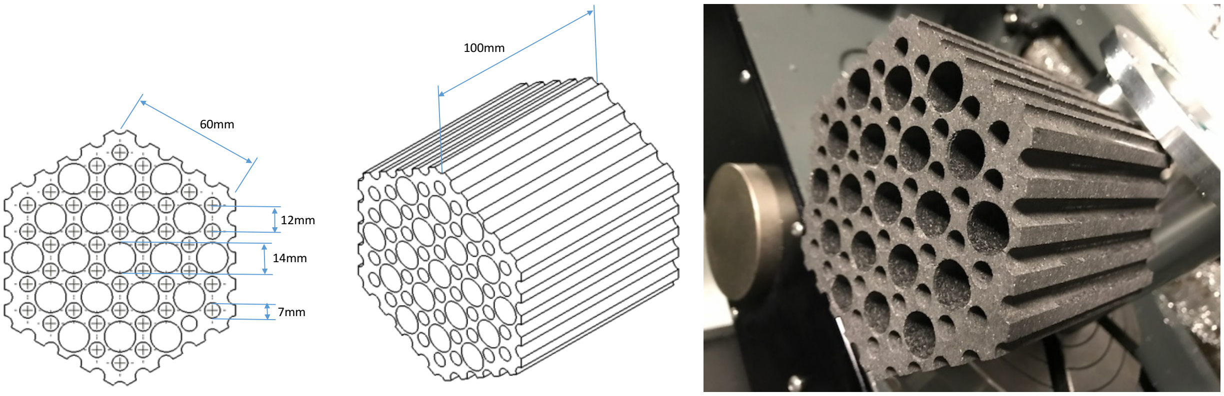


Figure 16: Individual graphite fuel brick dimensions (left) and as fabricated (right)

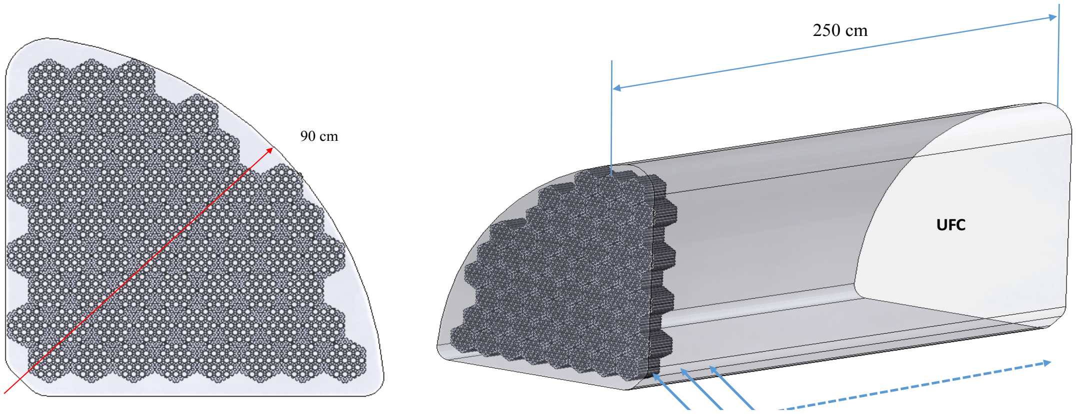


Figure 17: Single brick layer (left) inside of a Holos fuel cartridge (right)

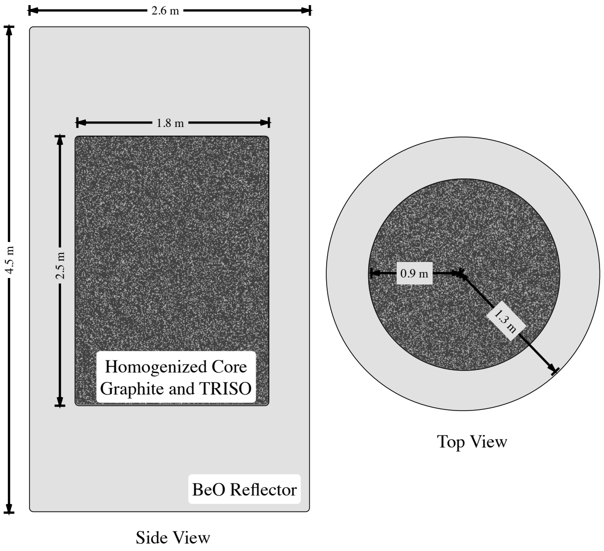


Figure 18: View of the Holos reactor homogenized computational model

TRISO fuel fills the channels of the graphite bricks. TRISO is a fuel design wherein fissile fuel is coated in layers of silicon and carbon which provide both moderation and containment of the fuel. For the model, the fuel is assumed to contain low-enriched uranium (LEU), uranium dioxide (UO_2), silicon carbide (SiC), and pyrolytic carbon (PyC), homogenized with the graphite moderator. The geometry and composition of the core used for construction of the homogenized model is presented in Table 3, Table 4, and Table 5 below.

Table 3: Geometry and composition of one Holos UFC

UFC fuel single module (1/4 Core)		
Fuel Channels		19
Fuel Channel Diameter	cm	1.4
Coolant Channels		54
Coolant Channel Diameter	cm	0.7
Brick Graphite Density	g/cm^3	2.23
Brick Edge Length	cm	6
Brick Height	cm	10
Brick whole volume	cm^3	889.13
Brick layers		25
Total bricks/layer		77
Fuel Channel Volume Individual	cm^3	15.4
Fuel Channel Volume Per Brick	cm^3	292.5
Coolant Channel Volume Individual	cm^3	3.8
Coolant Channel Volume Per Brick	cm^3	207.8
Brick subtracted volume		388.8

Table 4: Holos core composition

Holos Core		
UO_2 Density	g/cm^3	10.8
Kernel Diameter	cm	0.05
Buffer Layer Thickness	cm	0.01
SiC, IPyC, OPyC Thickness	cm	0.012
TRISO Sphere Diameter	cm	0.094
Total core bricks		1,925
Packing Fraction	%	70%

Table 5: Fuel loading calculation for homogenization

TRISO Inventory		
Volume of TRISO sphere	cm^3	$4.35x10^{-4}$
Volume of Kernel (EUP)	cm^3	$6.54x10^{-5}$
TRISO spheres in Fuel Channel		24,778
TRISO spheres in 1 brick		470,777
TRISO spheres in core		$3.62x10^{9}$
Total volume of kernels in core	cm^3	237,255
Void volume in Fuel Channel	cm^3	4.62

The homogenized core model at 1,200K was used for kinetics and burn-up calculations. Analysis was conducted to determine the lifetime of the reactor at continuous full rated power. A burn simulation in MCNP calculates the effective multiplication (k_{eff}) value of the reactor at specified time steps, adjusting the composition of the reactor at each step to reflect changes in quantities of fuel and decay products, some of which are reactor poisons.

This simplified core model assumes no reactivity control and burnable poisons, as a result this method generates a conservative underestimate of the true full lifetime of the core. Fuel supply is depleted in this model without dynamic flux balancing, until such time that there is no excess reativity. The effects of dynamic control, burnable absorbers, and variable enrichment patterns to flatten the flux profile over time and extend the life of the reactor core are not included. Factoring in these gains from fully heterogenized core design, the calculated lifetime estimate for Holos is in excess of 12 years of full-power operational years at 22MW.

Safety and kinetics parameters were computed from the homogenized model and are presented in Table 6. The delayed neutron fraction is typical for a LEU-fueled thermal reactor system.

Table 6: Reactor safety and kinetics parameters

Parameter	Value	Name
ρ_T	-8 PCM $\frac{\Delta k}{K}$	Temperature Coefficient of Reactivity
$\boldsymbol{\beta}_{\mathbf{eff}}$	733 PCM	Delayed Neutron Fraction
Λ	233 μs	Generation Time

The temperature coefficient was computed by varying the temperatuçre of the design and recording the resultant multiplication. A trend line can then be fit to the plot of data. The temperature coefficient is the slope of this trend line, as shown in the figure below. For this calculation, the temperature was varied between 300K and 1,200K by changing the cross-section libraries referenced by the fuel and moderator materials. A negative temperature coefficient of reactivity is a prerequisite requirement for safe operation.

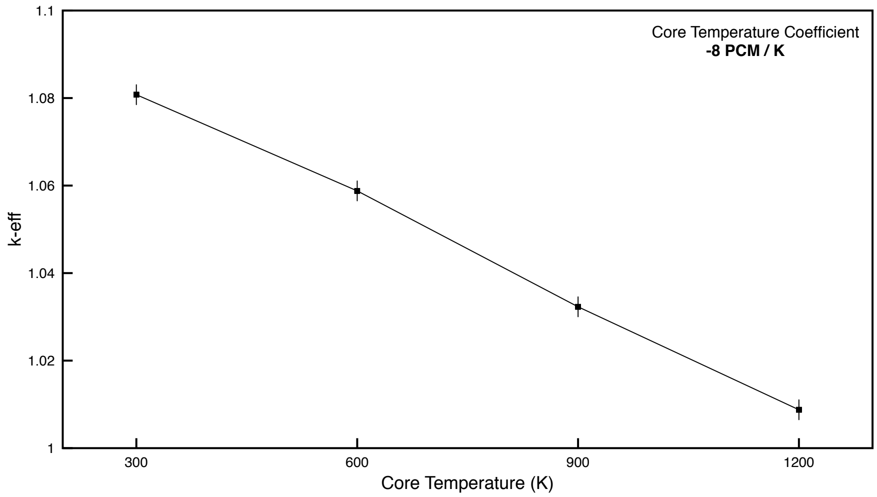


Figure 19: Reactor temperature coefficient calculation

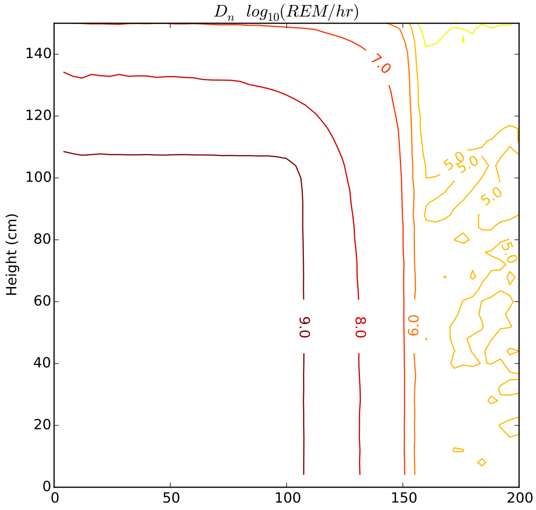
3.8 Radiation Protection and Shielding

Neutron production rate for dose calculations based on core power relates the total neutron population to the number of fissions for a given operation power. This is the proportionality constant in the dose assessment relating power to neutron and gamma dose field in (REM/h):

$$S(n/W) = \frac{P(W)\ \bar{\nu}}{1.6{*}10^{13}\frac{J}{MeV}{*}200\frac{MeV}{fission}}$$

This relation is used to scale the dose field calculations at operation, which are a function of power and not dependent on the burn-up level of the reactor. The gamma and neutron dose fields for these operating reactors are shown below in Figure 20. Each dose contour is one order of magnitude of dose in (REM/hr), i.e. 6.0 = 10^6 REM/hr at that point in the field. Shielding requirements can then be computed from these field strengths.

The surface gamma dose during operation is 10^6 REM/hr. Neutron emission is of a similar intensity, but the spectrum of emitted neutrons is thermal, so shielding can be achieved through better reflector design, addition of neutron absorbing layers such as cadmium, and use of water tanks if needed. Gammas are the primary shield driver, and emit over a wide-spectrum of energies.



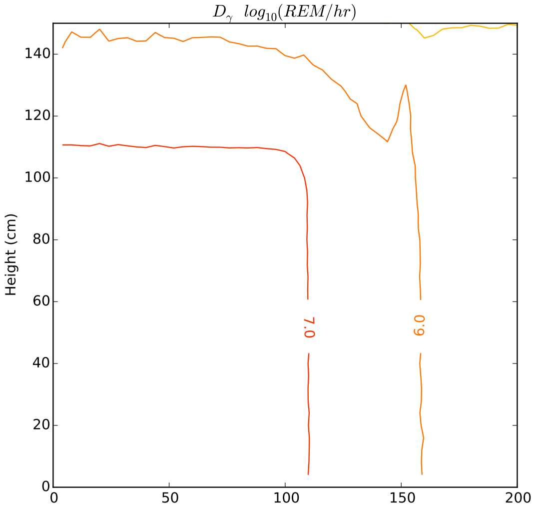


Figure 20: Gamma (left) and neutron (right) dose fields for the 22 MWth operating reactor

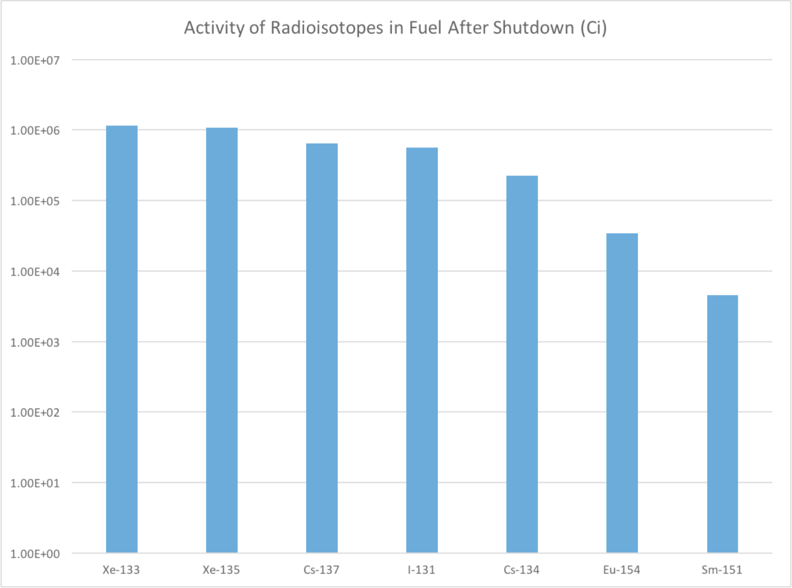


Figure 21: Radioisotope inventory at End-of-Life (EOL)

For calculation of isotopic inventory at end of life, and subsequent dose, both actinide and non-actinide concentrations are traced, including the most relevant radioisotopes for shielding (for example, ^{137}Cs). Figure 14 shows the primary radioisotope inventory. Of the seven isotopes with significant activity, only ^{137}Cs, ^{134}Cs, and ^{154}Eu are gamma emitters, and of those three, only ^{137}Cs has a high specific yield. The source can be approximated using ^{137}Cs gammas, which emit at 662 keV and are of primary radiation protection concern in spent nuclear fuel. For ^{137}Cs, 7.2 cm of steel will reduce the dose by an order of magnitude. Buildup factors are suppressed for thick shields so this can be approximated as a true exponential process, as seen in Figure 22.

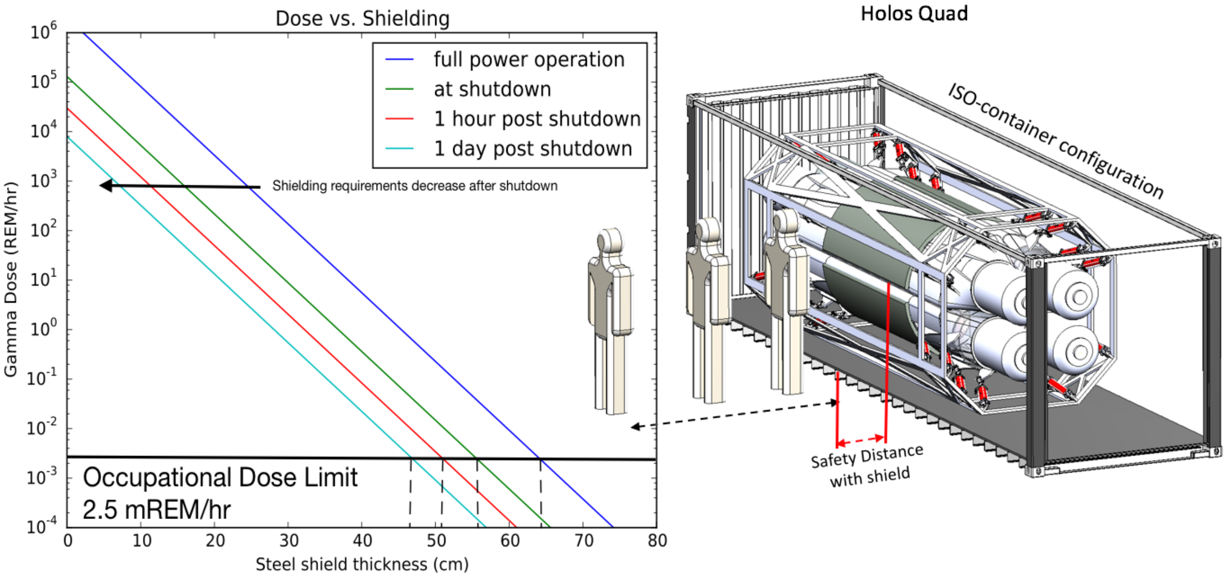


Figure 22: Shielding requirement during operation

Occupational dose limits are 5 REM/yr, so for assumed 2,000 working hours of exposure, the maximum dose rate must be less than 2.5 mREM/hr, indicating (with a conservative engineering factor included for streaming and other leakage effects) a 65 cm steel shield for operator exposure at the surface, however this requirement will be lessened by the reality that operators will be working at some offset from the unit and Holos adoption of composite shields.

After shutdown of the reactor, dose emissions drop sharply (levels fall to 6.5% of operating power), and continue falling to 1.5% after an hour, and 0.4% after a day as dictated by neutron kinetics and decay heat production. Shielding will still be required even after shutdown, but transport will not necessarily require the full assembly remain intact, with the outer 25 cm being removable while remaining in dose limits.

4 Market and Deployment Applications

Holos nuclear generators can be deployed fully operational to supply electric power and process heat to support a large spectrum of industrial terrestrial, off-shore, marine and military applications. Analyses and presentations of two Holos applications are discussed in this Section. A case is presented for the economic advantages of utilizing Holos as a distributable power source for mining and remote operations currently relying on diesel-electric generation, and as power plants enabling marine electric propulsion.

4.1 Disaster Preparedness and Emergency Support

As Holos is formed by independent transportable subcritical power modules, each module can be configured at the deployment site, or the whole generator can be deployed fully operational. For rapid response/emergency applications, the subcritical power module size and power rating can be further decreased to satisfy aerial transport lifting capacity.

For an example of Holos Quad configured to provide approximately 3-4 MWe (7 MWth) output with process heat capability, Holos generators represent cost savings, and potentially lives saved by being able to quickly restore electric power to critical facilities. The ability to deploy a generator that does not require refueling with universal electric connection for emergency power distribution ensures continuity of disaster management and operations. Holos generators configured to support emergency power can be deployed in areas where seismic, flooding, high-wind hazards are present. The generator is not an air-breathing engine (e.g. diesel-generator, gas-turbine generator), therefore it cannot be impaired by ingesting debris (as is the case for conventional emergency generators). With special provisions addressing electrical insulation at the three-phase AC power bus, Holos generator is not affected by water flooding (e.g. fuel cartridges are sealed and insensitive to neutron moderating fluids potentially flooding and submerging the subcritical power modules). The generator load-following capability also ensures voltage and frequency stability in an environment where electric loads may severely fluctuate (e.g. multiple pumps, connections/disconnections).

Holos Quad generators configured to support emergency power applications can be rapidly deployed at undamaged power distribution locations or at locations dedicated for emergency power sources. Multiple generators can also be clustered to supply power to emergency and fire protection responder facilities, law-enforcement and water pumping stations, water purification plants, sewer pumping stations, critical healthcare and government facilities. In addition to supporting emergency response in areas where power grid and infrastructures have been severely damaged, 3-4 MWe Holos Quad generators can provide electric power to restore power grid stability and mitigate otherwise unavoidable sympathetic tripping of base-load grid generators.

As an example, in 2012 Superstorm Sandy impacted over 90% of Long Island Power Authority's customers with outages that lasted up to two weeks. [8] In similar emergency situations, Holos generators could have been deployed to provide emergency power to critical facilities affected by the outages.

Overall, versions of Holos power generators with power ratings <10 MWe can be air-lifted for deployment in remote or generally inaccessible areas. For emergency support applications, Holos ORC features can provide process heat to intermediate heat exchangers to support high- and low-grade process heat in addition to electricity to support, for example, water desalination and urban heating.

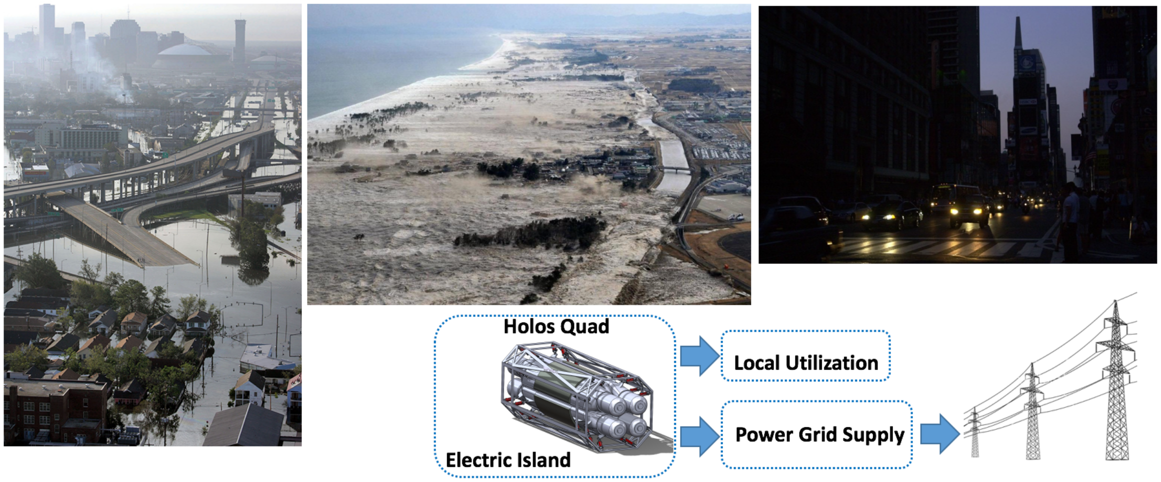


Figure 23: Rapidly deployable Holos Quad generators, disaster and emergency responders support

4.2 Decommissioned Nuclear and Coal Power Plant Replacement

Holos modular generators can be clustered to meet local energy demand. Nuclear and coal power plants being decommissioned conserve switchyard and power grid connectivity. Clustering Holos generators by the switchyard of decommissioned power plants allows maintaining power grid supply at minimum power grid connection costs. The decommissioning cost of nuclear power plants include energy activities dedicated to the removal of potentially contaminated equipment with staggering costs. Holos generators deployed at these sites can continue to supply electricity to the grid and to crews/equipment dedicated to decommissioning activities. Providing substantial electric power capability at these locations accelerates power plant decommissioning activities, thus reducing decommissioning costs. Decommissioned power plants based on non-nuclear energy sources often conserve switchyard infrastructures and possibly operational equipment. These sites generally represent large base-load generator nodes with medium to large transmission line rating.

Clustering of Holos generators at these sites does not involve costs associated with uprating transmission lines. Additionally, the number of Holos generators to be clustered (Quad or Titan) can be selected so as to match the transmission line power rating. Figure 24 illustrates the aerial view of the switchyard at the Crystal River (CR) decommissioned nuclear power plant. This power plant was producing 838 MWe (2,435 MWth at 34% Rankine cycle efficiency) at 95% capacity factor. The Crystal River Energy Complex is located in Citrus County, Florida. The site consists of approximately 4,700 acres with the nuclear unit sharing the site with 4 fossil-fueled electric generators. In this example, 10x Holos Quad Titan generators would provide the electric power capability provided by CR-3, at an estimated cost of \$2.19B with Payback Period of 2.71 years by selling electricity at \$0.1031/kWh, based on the 2016 Energy Information Administration (EIA) average price of electricity in the United States [9]. Under these conditions Holos generators would operate at 97% capacity factor with the power rating of the fossil-fueled generators connected to the same switchyard regulated so as to demand full loading of Holos generator during the payback period. As shown in Figure 24 top right, a cluster of transport ISO containers provides visual scaling indicating the size of the switchyard and the ability for this site to accommodate 10x Holos Quad Titan generators.

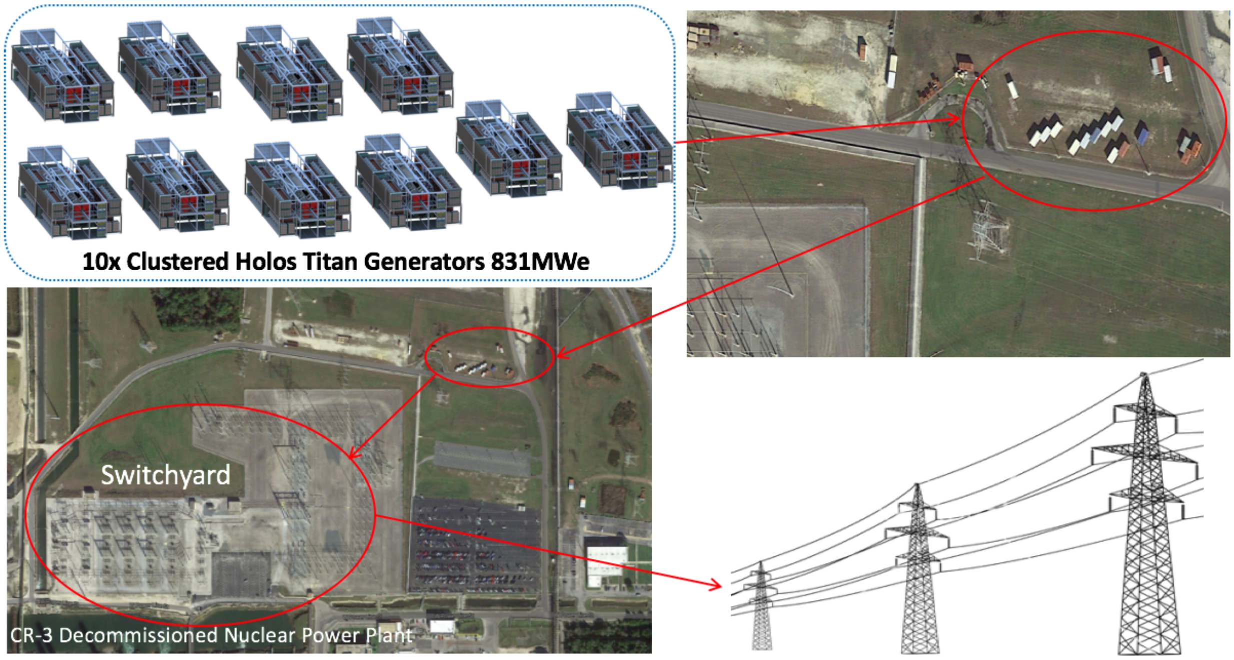


Figure 24: Clustered Holos generators to replace decommissioned power plants

4.3 NPP LWR Fleet Emergency Support

Holos modular generators can be stationed at currently operating power plants and replace fleets of aged emergency diesel generators (EDGs). During severe nuclear accidents, diesel fuels can become contaminated, or the diesel engines providing emergency AC power to run reactor cooling systems and vital equipment may fail under a variety of start-up and accident scenarios. Holos can be deployed at Nuclear Power Plants (NPPs) sites and provide emergency power without need for refueling. Holos generators dedicated to supply emergency power can last the whole life of the power plant as the "emergency-power duty-cycle" does not deplete Holos fuel cartridges. Emergency power only uses a fraction of the fuel cycle computed at FEPY wherein, for example, the configuration operating with Brayton-only power cycle at 8% fuel enrichment supports a fuel cycle of 12 years. Redundant emergency diesel generators at the Fukushima Daiichi nuclear plant failed because of fuel contamination and debris ingestion through the fuel distribution system and the air-breathing components (air-filters and turbochargers). This resulted in a prolonged Station Black Out (SBO) event which led to core meltdown, hydrogen explosion and radionuclides release from multiple units at the same site. Holos Quad generators would have provided uninterruptable AC power for all LWR units operating at this site for as long as needed.

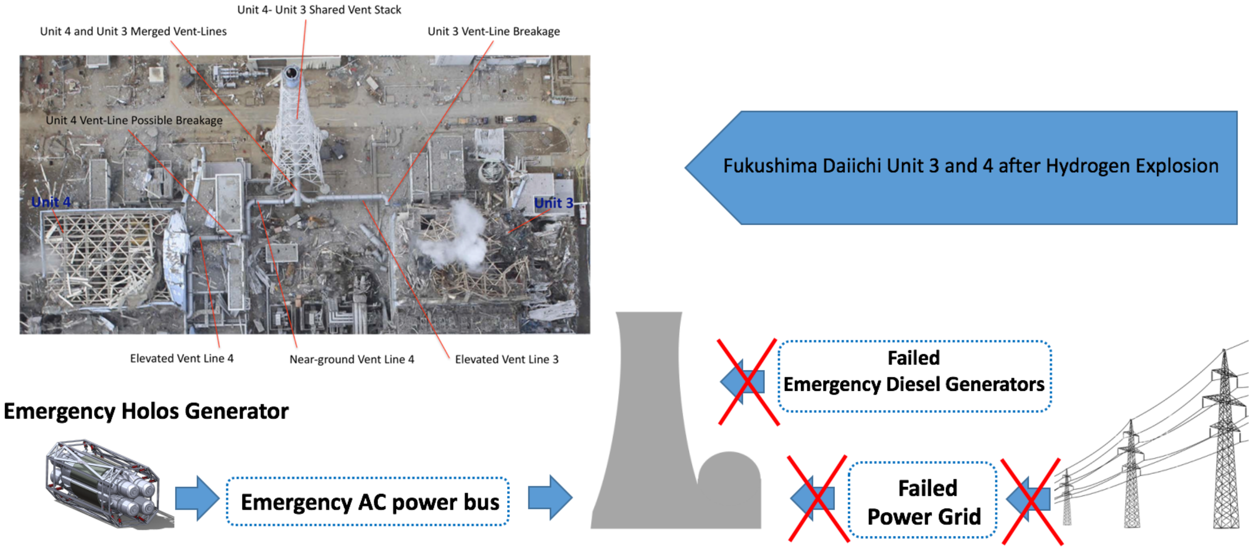


Figure 25: Emergency Diesel Generators (EDGs) replacement

Figure 26 shows a typical EDG engine-generator block at NPPs and the Holos Quad generator.

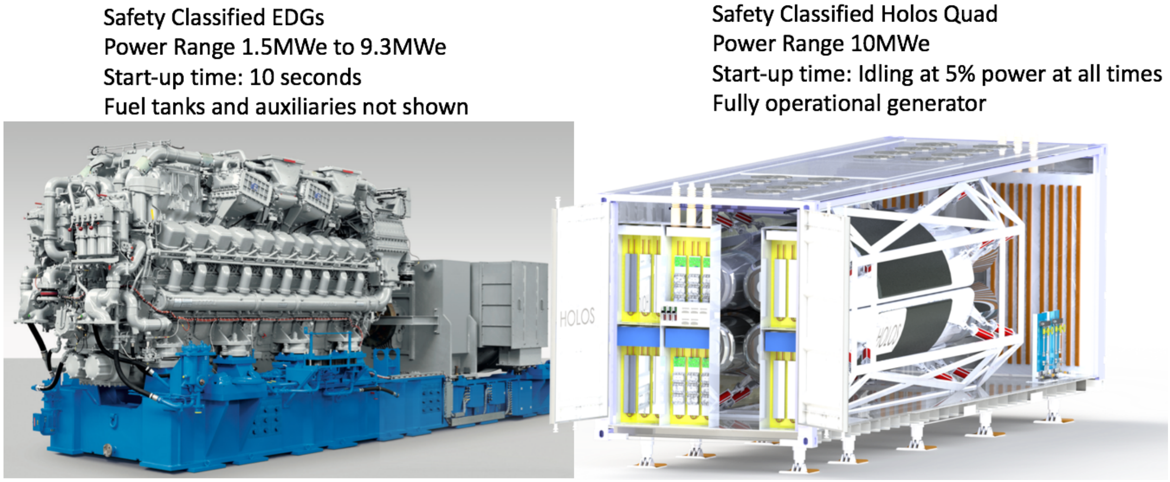


Figure 26: EDGs vs. Holos Quad Brayton-8% enriched configuration

As PRAs executed on EDGs SSCs produce non-negligible probabilities of system failure under various scenarios, each NPP is equipped with redundant EDGs. The PRAs generally focused on establishing risks associated with this safety-sensitive equipment are normally addressing the equipment itself rather than the whole network of BoP supporting the EDGs and enabling execution of their safety functions (e.g. the EDGs at the Fukushima NPP failed mainly through failure of their BoP SSCs). EDGs maintenance programs involve periodic activation of the diesel-generator with requirements to provide full power rating emergency power only a few seconds from emergency signal activation. To enable these air-breathing diesel engines to be loaded so rapidly from start-up, the whole equipment is maintained "hot" at all times by circulating hot water through their cooling jackets. Compounding the costs associated with the EDG and auxiliary supporting equipment, EDGs redundancy requirements and maintenance programs, even the least economically performing configuration of Holos Quad generators becomes very attractive for this application. While EDGs have to be periodically started, loaded and their emergency diesel fuel tanks and plumbing monitored with entire inventories of diesel fuel frequently replaced[8], Holos generators can remain at idle power (e.g. 5%) and quasi-instantaneously ramp-up to full power rating (e.g. upon emergency signal), without refueling for the whole licensed life of the NPP (e.g. 60 years).

Under the tsunami-triggered accident scenarios in 2011 at the Fukushima Daiichi power station in Japan, the station experienced prolonged SBO and unrecoverable damage to the emergency diesel generators and to the electric power grid. Battery powered emergency system can cope with these scenarios only for a few hours. Under these scenarios rapid deployment of Holos generators could provide AC power supply to ensure cooling of the reactors and spent fuel pools for extended time durations, thus preventing or mitigating the severity of similar accident scenarios.

Figure 27: Rapid deployment of Holos generator to disaster areas

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[8] Diesel fuel is a carbon based petrochemical, starting the process of oxidization as soon as it departs the refinery, with formation of sediments and gums. Without diesel fuel additives, diesel fuel deteriorate in as little as 30 days before this oxidization process becomes unwieldy, creating deposits that can damage fuel injectors, fuel lines, and other EDG system components. Water contamination is also a major issue. With additives, diesel fuel can be stored without significant fuel degradation for 6-12 months.

4.4 Holos Utilization to Enhance Large Reactor Safety

As Holos is transportable, a utility with a number of reactor sites could utilize a minimum number of Holos generators to execute emergency power supply functions as well as fine-tuned load following operations. Utilities with multiple sites owning a small-fleet of Holos generators could rapidly deploy Holos generators to sites at risk and/or during the development of accident scenarios to provide an uninterruptable source of electric power. As a variation of this Holos application, a consortium of utilities could invest in Holos generators and timely move them where needed. For example, Japanese utilities owning multiple power plants in high seismic sites could prevent future earthquake-tsunami induced SBO at their stations by timely deploying Holos generators in the hours following these extreme events. The minimum SBO coping time for most NPPs is 8 hours, thus enabling deployment and connection of Holos Quad emergency AC power bus to the station internal grid. As a result, supply of AC motive power (e.g. cooling pumps) and vital power to control of reactor and spent fuel pool cooling systems is ensured under Beyond Design Basis Accident scenarios.

4.5 Large Reactors Construction Support and Selling Point

As Holos is rapidly deployable, a large reactor vendor could utilize Holos to supply on-site electric power during single or multiple reactor construction, thus expediting site-preparation, first concrete and components assembly, while reducing construction costs. As the large reactors are connected to the grid, Holos can be left at the site to provide uninterruptable emergency power to essentially represent the selling point: “Buy our LWRs and we (vendor) also supply you (utility) with Holos generators to support, expedite and reduce construction costs while enhancing safety as the LWRs are connected to the power grid for commercial operations”.

4.6 Increase Spent-fuel Storage Capacity at Permanent Storage Facilities

As Holos fuel cartridges become depleted they can be replaced. Alternatively, portions of the subcritical power module comprising the spent fuel cartridge can be disposed of at temporary and permanent storage facilities. As the ORC is thermally coupled to the fuel cartridges, Holos continues to produce electricity by converting the naturally generated core decay-heat into electricity. As thermal energy is converted, a lower amount of thermal energy is rejected by the spent fuel cartridge to the surrounding environment. As a result, multiple spent fuel cartridges can produce electricity to support active-cooling at permanent repositories while decreasing thermal loading to the repository structures. By decreasing thermal loading, Holos effectively extends the repository storing capacity.

4.7 Case Study 1: Alternative to Diesel Generators in Mining/Remote Operations

Holos Quad generators provide a cost-effective solution to continued use of diesel generators in remote locations where there is little or no access to an established electrical grid and logistic/storage of diesel fuel represents substantial economic challenges. Both mining operations and remote/forward operating military installations are generally located in remote areas and currently rely on multiple sets of diesel generators to provide electricity for personnel and equipment. Lazard’s Levelized Cost of Energy Analysis reports levelized cost of electricity (LCOE) for Diesel Reciprocating Engines (2 MWe output) between $212/MWh and $281/MWh assuming a diesel price of $2.50/gallon [10]. Of the energy producing technologies reported by Lazard, diesel generators are the most expensive for continued use; however, in these types of remote operations there exists few cost-effective options.

A 2016 Study by Hatch titled "Feasibility of the Potential Deployment of Small Modular Reactors (SMRs) in Ontario" [11], reported the potential benefits of using small modular nuclear reactors for remote mining operations in Ontario. This study found that mines in this area typically have a power requirement of 10MWe-20MWe for a lifetime of 15-25 years and use multiple diesel generators to meet this demand. The estimated cost of using diesel generation for remote mines located in Ontario, Canada as reported by Hatch is $345/MWh. While this amount is considerably higher than Lazard's estimated LCOE, the higher cost can be attributed to the remoteness of the location and the increased cost and difficulty in transporting fuel for the generators. Similarly, a 2016 Defense Science Board report, "Task Force on Energy Systems for Forward/Remote Operating Bases Final Report", reports that remote and forward operating bases experience significantly higher diesel fuel costs, between $10 to $50 per gallon [12]. Holos generators are self-contained modules equipped with fuel cartridges lasting 12-20 years between refueling; and therefore, can immediately reduce operating costs by eliminating the costs associated with fuel consumption and transport. Figure 28 shows the average LCOE for Holos Quad configurations with ORC, using 8% enrichment (12 FEPY) and 15% enrichment (20 FEPY) compared to LCOE for diesel generators reported by Hatch and Lazard (converted from $/MWh to $/kWh). This chart shows the economic benefit represented by adopting Holos Quad as electric power generators over diesel generators.

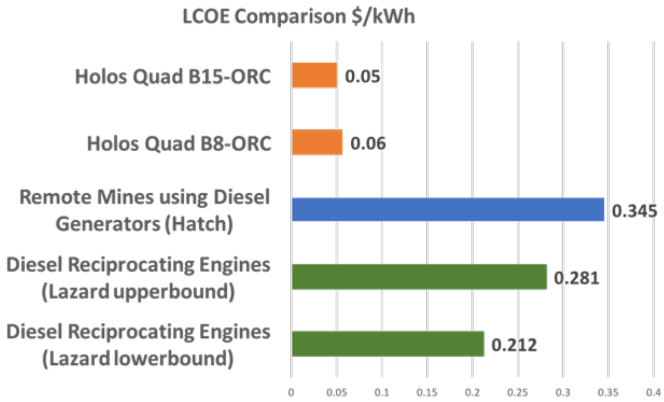


Figure 28: Comparison of Holos Quad LCOE with Diesel Generators in Remote Applications

4.8 Case Study 2: Electric Propulsion for Container and High-performance Ships

Propulsion systems using AC or DC electric motors coupled to propellers have come to play a dominant role for marine applications worldwide. Ships can be equipped with multiple electrically-driven propellers to reduce operating cost and increase maneuverability. Ships represents the same characteristics of an electric power station, a fuel storage and a utility company with several additionally restricting requirements addressing noise, heat generation within enclosures, emissions and fuel consumption directly affecting the overall economic performance. Weather and maintaining maneuverability are additional aspects that affect energy demand and management at the ship's propeller drives.

Naval ship propulsion systems based on integrated electric propulsion (IEP) generally represents power generators utilizing diesel engines or turbines to produce electricity. These propulsion systems can be retrofitted with Holos generators and replace their fossil-fueled energy source by interfacing the IEP main electric power buses to the AC or DC Holos generator power bus. Under these configurations, the distribution of electric power is regulated by an integrated power management system which modulates power to increase operating efficiency through at least one electric motor coupled to a propeller. Ships with propulsion systems entirely based on diesel engines directly coupled to propellers generally represent the lowest capital cost but also the least efficient configuration – leading to the highest operating cost.

Combining Holos generators with electric-drive propulsion can modernize or renew obsolete fleets by retrofitting ships with submerged electric motor-propeller systems or "propulsor pods". Figure 29 (left) provides an example of a propulsor pod formed by an electric motor and thruster system coupled to propellers. The propulsor pod is generally formed by a variable speed electric motor inside the submerged pod shown. The electric motor can drive fixed or variable pitch propellers, and, in some configurations, the pod can rotate 360° around its vertical axis, thus enhancing maneuverability. Figure 29 (right) provides an example of high-performance IEP on board of the USS Zumwalt (DDG 1000). In this application, a total power rating of 80 MWe is required to satisfy current speed and weapons requirements, and to support potential expansion to drive directed energy/laser and electro-magnetic railgun weapons. As shown in Table 1, a single Holos Quad Titan generator can support the power requirements of the USS Zumwalt with lower real-estate/foot-print represented by currently utilized turbine- and diesel-generators when considered all together with their unavoidable fuel tanks. Installing Holos generators to supply electric power as replacement or in tandem with the current electric power plant equipping modern ships with IEP systems would require seamless interfacing. For these applications Holos generator retrofitting would consist of coupling the integrated ship power management system with Holos power bus, and thermally couple Holos passive heat transfer surfaces to the ship structure. Additionally, for Holos generators positioned under the water line, the requirements for shielding can be substantially relaxed.

Figure 29: (left) Electric propulsor, (right) USS Zumwalt (DDG 1000) with Integral Electric Propulsion (IEP)

In one exemplary retrofitting configuration developed to satisfy container ship applications, a relatively small portion of the cargo bay could be dedicated to house the Holos generator comprised within standard transport ISO containers. Container ships' cargo real-estate is generally configured to accommodate containers below and above the main deck, thus Holos can leverage the container ship existing infrastructure. Holos Quad Titan assembly containers can be positioned below or above deck through the equipment normally utilized to position transport containers. Figure 30 illustrates one of multiple configurations in which a single Holos Quad Titan generator is retrofitted by locating its subcritical power modules below the main deck. In this retrofitting configuration, additional shields and the ORC modules can be positioned in a manner that minimally impacts the cargo-bay real-estate. Once the Holos generator is secured aboard the ship, electric power can be distributed by high-voltage, high-power cables to the electric propulsors by the ship power management system.

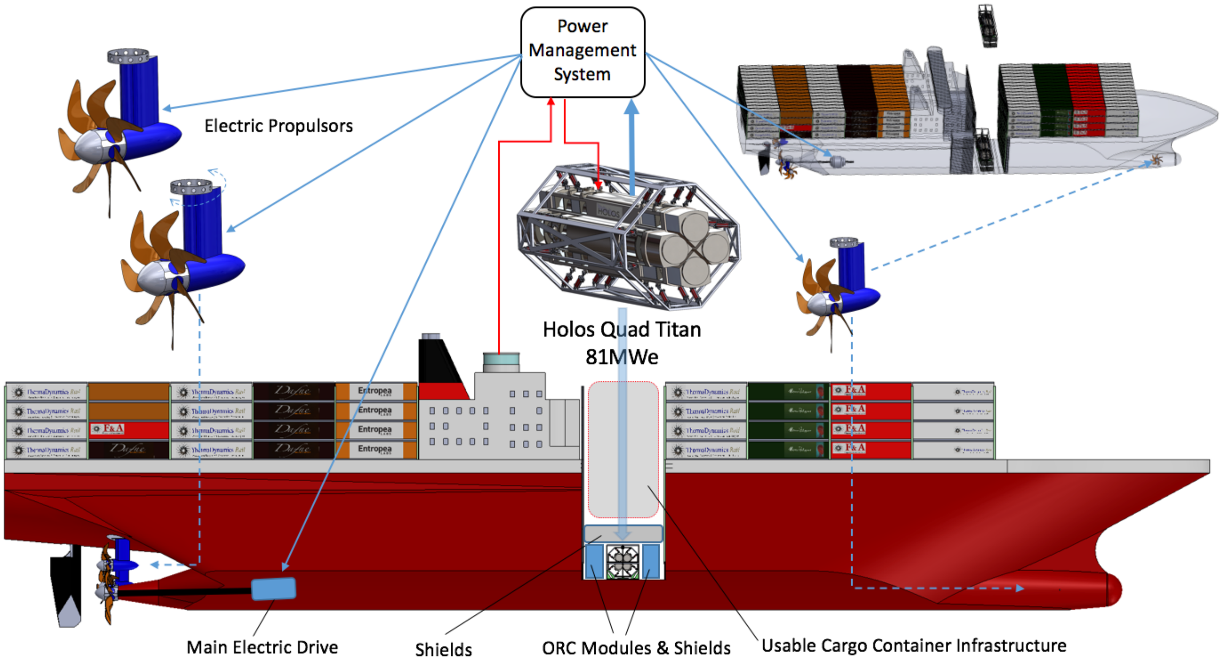


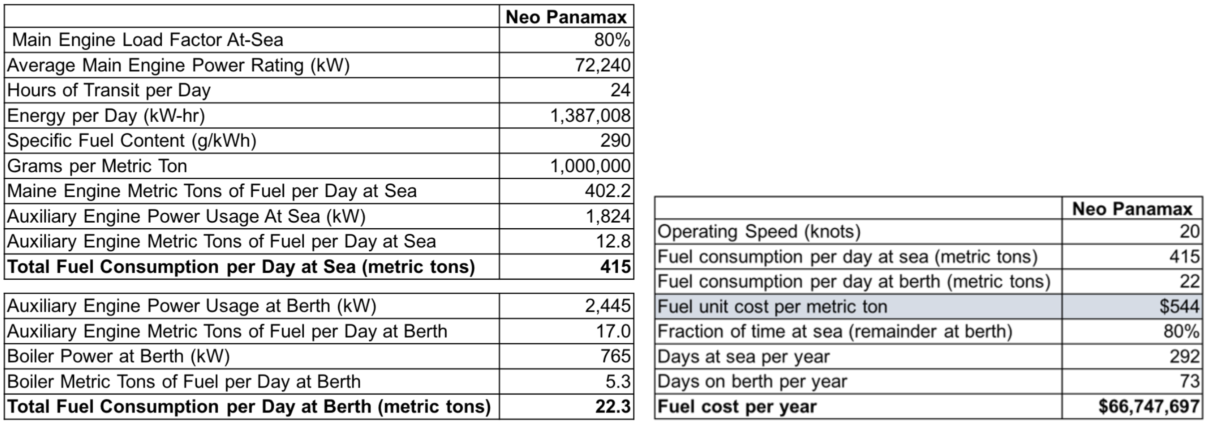
Figure 30: Retrofitting Holos Quad Titan 80 MWe generator within container-ships infrastructure

To summarize, retrofitting Holos Quad Titan (or multiple Holos Quad) generators as a power source for container ship applications would generally consists of:

- Securing the Holos ISO transport containers subcritical power modules above or below the main deck;
- Surrounding the subcritical power modules with the ORC modules and shields;
- Electrically coupling the Holos generator power bus to the ship's main power bus;
- Thermally coupling Holos heat transfer surfaces to the UHS (air or water);
- Thermally coupling the process heat ports to provide the ship's auxiliaries with high- or low-temperature process heat;
- Distributing power to retrofitted electric propulsors and electric drives for aging ships – this step in not necessary for ships with IEP systems on board;
- Restoring a separating floor at the appropriate deck level above the Holos generator

As these Holos configurations include ORC features, the generator continues to produce electric power after the subcritical power modules are shutdown. This is the decay-heat-to-electricity conversion feature offered by the design. As a result, electric power at a relatively low-power rating is available for days after Holos subcritical power modules are induced by the AMPS into shutdown configurations. Therefore, ship vital systems and low-power propulsion can continue to be provided for days even with the Holos generator in a shutdown configuration.

Marine Diesel Oil (MDO) is the largest operating cost for containership operators, making up approximately 50% of annual operating charges [13]. A typical Neo Panamax (NPX) cargo ship capable of carrying 12,000 TEU (Twenty-foot Equivalent Units) requires approximately 74 MWe for propulsion and ancillary systems. Based on a 2012 NC Maritime Strategy Report [14], Table 7 (left) shows the average total fuel consumption for NPX containerships. Table 7 (right) summarizes the annual fuel costs. The original chart from the report used $700/metric ton for fuel unit cost; however, Table 7 (right) updates this figure to the 2016 year-end Bunker Index price for MDO [15] to update costing figures to 2016 values.



	Neo Panamax
Main Engine Load Factor At-Sea	80%
Average Main Engine Power Rating (kW)	72,240
Hours of Transit per Day	24
Energy per Day (kW-hr)	1,387,008
Specific Fuel Content (g/kWh)	290
Grams per Metric Ton	1,000,000
Maine Engine Metric Tons of Fuel per Day at Sea	402.2
Auxiliary Engine Power Usage At Sea (kW)	1,824
Auxiliary Engine Metric Tons of Fuel per Day at Sea	12.8
Total Fuel Consumption per Day at Sea (metric tons)	**415**
Auxiliary Engine Power Usage at Berth (kW)	2,445
Auxiliary Engine Metric Tons of Fuel per Day at Berth	17.0
Boiler Power at Berth (kW)	765
Boiler Metric Tons of Fuel per Day at Berth	5.3
Total Fuel Consumption per Day at Berth (metric tons)	**22.3**

	Neo Panamax
Operating Speed (knots)	20
Fuel consumption per day at sea (metric tons)	415
Fuel consumption per day at berth (metric tons)	22
Fuel unit cost per metric ton	$544
Fraction of time at sea (remainder at berth)	80%
Days at sea per year	292
Days on berth per year	73
Fuel cost per year	**$66,747,697**

Table 7: Fuel Consumption per Day and Fuel Cost per year (at 2016 conditions)

Using a constant fuel price and adjusting for inflation, a NPX could incur fuel expenses of over $1.6B during a 20-year operating period. Holos Quad Titan with ORC coupling can be used to retrofit NPX containerships supplying up to 81 MWe of propulsion and ancillary power. Capital Costs, including fuel for Holos Quad Titan with ORC is $151M. There are additional unknown costs associated with the electric motor and propeller pod as previously described. These costs depend on various parameters including power rating and dimensions, and can vary significantly. However, even with the additional costs of retrofitting the ship with electric propulsors and $24M in operations and maintenance (O&M), which could be reduced by redundancies in the marine vessels' current O&M, Holos represents significant cost savings over fuel consumption. Figure 31 shows the total cost of Holos Quad Titan with ORC, including fuel, O&M, and de-commissioning compared to the total costs of MDO fuel over the equivalent 20-year period based on the information in Table 7. For ships not equipped with Integral Electric Propulsion (IEP), the costs for cabling, power management system, and electrically-driven propellers has to be added.

Figure 31: Holos Titan Costs vs. NPX Fuel Costs

At the end of the first Holos Quad Titan fuel cycle, the vessel owner has to pay only fuel and refurbishing for the next 20 years compared to additional 20 years of MDO fuel costs. Holos Quad Titan ensures the vessel produces zero pollutants, which makes it an ideal alternative for shipping routes within Emissions Control Areas (ECAs), representing areas which have set control standards for SO_x, NO_x and particulate matter emissions. The EIA reports that ECAs in North America typically extend 200 nautical miles from ports [16]. In these areas, vessels are required to burn fuel with lower sulfur content or use scrubbers to remove the emissions which raises operating costs. Using Holos Quad Titan instead of diesel engines reduces not only costs over equivalent fuel use, but also the costs associated with mandatory pollutant emissions reduction technologies.

4.9 Market Considerations

The Holos design allows for multiple configurations enabling a variety of applications and markets. Holos can be used to supply electric power and process heat for terrestrial and marine industrial and military applications where the cash inflows from the sale of electricity is not the end goal. Holos can be used to provide routine and emergency electric power during a disaster, support construction of LWRs and reduce cost of existing power plants (nuclear and non-nuclear) shutdown or decommissioning, or in place of other power generating systems. In these applications, Holos represents the amount of cost savings over current or next-best options.

Holos Quad represents a significant cost savings over continued diesel generator use in mining and remote operations, including military installations. One Holos Quad can replace multiple sets of generators and eliminate costly refueling transports. Costs per kWh for Holos are significantly lower than reported costs per kWh for continued diesel generator use. For military applications, reducing fuel transports also reduces personnel casualties, a greater incentive over fuel savings.

Large containerships and other marine vessels can be retrofitted with Holos Quad Titan to provide electric power as replacement or in tandem with current electric power in ships with IEP systems. Holos Quad Titan can also be combined with electric-drive propulsion systems to modernize older fleets. One Holos Quad Titan with B-ORC configuration can provide 81 MWe continuously for 20 years at a significant savings over MDO fuel. Additionally, using Holos in place of fossil fueled generators allows for pollutant elimination and is an attractive feature for ships travelling through ECAs. Other applications include off-shore installations and any application requiring high power densities for prolonged amounts of time.

5 Conclusions

An overview of the Holos reactor concept has been presented in this paper. The novel power generation architecture is the strength of this concept. The power generation design is equipped with thermal-hydraulic interfaces to support full-scale testing through non-nuclear heat sources. This feature enables low-cost safety performance validation of multiple applications.

Holos is transportable, sealed, self-controlled, highly-efficient, affordable, and load-following, thus providing a generator as a distributable power source. Its thermal-to-electricity conversion equipment is represented by proven jet engines components and its reinforced fuel cartridges are loaded with melt-resistant proliferation-resistant fuels that remain safe under worst-case off-normal operational scenarios. By integrating turbo-machinery and power generation components, all together with the fuel cartridges, Holos does not require Balance of Plant (BoP). Holos presents an extremely compact and simplified architecture, fully contained within sealed pressure vessels enabling factory certification to reduce licensing costs. Factory certification eliminates design dependencies associated with site-specific requirements. Holos relies on commercially proven components developed for waste heat recovery systems and jet-engine turbo-machinery at comparable power ratings and thermodynamic conditions. Holos components costing is based on detailed engineering non-recurring, labor and materials costs associated with specialized hardware developed for waste thermal energy recovery.

Basic reference core design analysis has been performed using homogenized, generic reactor physics analysis. The basic low-enriched uranium requirements, power, lifetime, and safety parameters have been estimated and shown to be consistent with further development of the Holos concept. Future work will focus on a detailed core design, with the goal of developing a true reference loading, determining the most effective method of reactivity control, and confirming reactor core safety parameters.

As Holos is rapidly deployable via standard transport platforms, it can support several emergency functions, for example, to enhance safety of current nuclear reactor fleets, as a distributable power source at remote sites, or as an emergency power generator at disaster sites with severely damaged infrastructures. Holos concept produces electricity and process heat with reduced thermal pollution as the total heat rejection to the environment is lower than that represented by conventional fossil-fueled and nuclear power plants. At the end of the fuel cycle (e.g. 12-20 years) Holos fuel cartridges can be stored all together with the submodule power conversion unit, wherein the ORC components continue to produce electricity by converting the fuel decay-heat. This feature lowers permanent and temporary repositories thermal loading limits, thus enabling expansion of storage capacity at these facilities.

Holos costs are minimized by eliminating the BoP, solely relying on air as the Ultimate Heat Sink, enabling factory certification and utilizing proliferation resistant fuels further enhancing safety performance. Holos represents a truly innovative approach to nuclear generated electricity, through a highly integrated system sealed and contained within pressure subcritical modules inherently safer and less expensive when compared to well-known and advanced reactor concepts.

The technologies integrated within each Holos module are supported by three decades of design, manufacturing and testing experience in the fields of power electronics, heat-transfer, thermal-hydraulics and optimized thermodynamic cycles applied to fossil-fueled and renewable-energy electricity producing systems. Holos Brayton cycle is formed by operational components utilized in commercial gas turbines and jet engines. Holos ORC components are the result of optimizations in the field of non-invasive heat recovery systems developed to convert waste thermal energy produced by large internal combustion engines into electricity. Holos costing estimates are based on components developed for high-speed turbo-machinery applications operating at power ratings comparable with Holos module PCUs, and on compact low-backpressure heat exchangers developed for waste heat recovery systems.

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