



Original Article

Design of an Organic Simplified Nuclear Reactor

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ABSTRACT

Numerous advanced reactor concepts have been proposed to replace light water reactors ever since their establishment as the dominant technology for nuclear energy production. While most designs seek to improve cost competitiveness and safety, the implausibility of doing so with affordable materials or existing nuclear fuel infrastructure reduces the possibility of near-term deployment, especially in developing countries. The organic nuclear concept, first explored in the 1950s, offers an attractive alternative to advanced reactor designs being considered. The advent of high temperature fluids, along with advances in hydrocracking and reforming technologies driven by the oil and gas industries, make the organic concept even more viable today. We present a simple, cost-effective, and safe small modular nuclear reactor for offshore underwater deployment. The core is moderated by graphite, zirconium hydride, and organic fluid while cooled by the organic fluid. The organic coolant enables operation near atmospheric pressure and use of plain carbon steel for the reactor tank and primary coolant piping system. The core is designed to mitigate the coolant degradation seen in early organic reactors. Overall, the design provides a power density of 40 kW/L, while reducing the reactor hull size by 40% compared with a pressurized water reactor while significantly reducing capital plant costs.

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1. Introduction

The need for low-cost near-zero emission sources for base-load electricity generation has driven resurged interest in nonlight water reactor (LWR) nuclear reactor designs. While LWR technology dominates the current nuclear power market, high capital costs and extended construction times for

advanced LWR plants make nuclear power unattractive and unable to compete with natural gas from an economic perspective. In addition, while Gen III+ LWR designs boast improved safety and operation, with some having core damage frequencies as low as 10^{-9} per reactor year, recent events at Fukushima have tarnished the perceived safety of LWR technology in general.

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In the past decade, numerous non-LWR designs have been proposed to supplant LWR technology, nearly all of which are iterations on or copies of designs previously explored in the 1950s to 1980s. The majority of these designs focus on increasing operating temperature to improve plant thermal efficiencies and, in theory, the economics for electricity generation. While fuel and operating costs are not insignificant (approx. 30% of total levelized cost for a modern LWR), failure to effectively address the prohibitive capital costs and construction times will prevent market penetration of advanced nuclear designs. Many advanced reactor concepts were previously ruled out as impractical for power generation due to material limitations at elevated temperatures. While advanced alloys (Inconel, Hastelloy, etc.) may offer the potential to overcome these material challenges, they are by no means affordable and drive costs higher compared to LWR designs.

One reactor concept that has received little attention in the latest resurgence is that in which the moderator and/or coolant is an organic liquid. The organic moderated and organic cooled reactor (OCR) concepts were considered highly attractive options for baseload electricity generation [1]. The advantages of using an organic coolant were clear to low operating pressure, mitigation of corrosion, the ability to use low-cost materials for the primary system, all while achieving thermal efficiencies similar to those of pressurized and boiling water reactor designs. The organic concept was so attractive that the U.S. Atomic Energy Commission (AEC) undertook an aggressive program in the mid-1950s to explore organic nuclear reactors for baseload electricity generation. Many other countries followed suit, including Canada, Italy, Denmark, and the Soviet Union. In addition to showing promise for baseload electricity generation, the organic concept was viewed as an ideal candidate for small modular reactor (SMR) plants, as demonstrated by the Soviets with Arbus. Despite some difficulties encountered in early reactors (OMRE and Piqua), operational simplicity turned out to be a key highlight gained with all the organic reactor designs.

In summary, some of the key advantages of the organic nuclear concept include [2]:

- 1) Low vapor pressure of the organic coolant, enabling high temperature operation near atmospheric pressure.
 - i) Eliminates the need for heavy forgings for pressure vessels, fittings, and pipe.
 - ii) Reduces probability and severity of a loss of coolant accident.
- 2) Coolant compatibility with low-cost materials and virtually no corrosion potential enabling use of plain carbon steel and aluminum.
- 3) Low activation of coolant and corrosion products, reducing biological shielding requirements and allowing for on-line maintenance of the primary system.
- 4) Flexibility in fuel used [UO₂, uranium carbide (UC), U alloys, etc.] due to elimination of fuel-coolant interaction potential in the event of cladding breach.
- 5) Use of slightly enriched uranium due to enhanced moderation.

However, the use of an organic coolant presents some difficulties, including:

- 1) Thermal and radiolytic degradation of organic coolants may lead to volatile organic compounds and/or polymerization.
 - i) Requires removal of volatile products.
 - ii) Polymerization may lead to increased viscosity and film formation on cladding if the core is not designed properly and the coolant is not purified.
 - iii) Necessitates coolant make-up, either through hydrocracking/reformation or introduction of fresh coolant.
- 2) Historically, the most promising class of organic coolants (terphenyls) are moderately toxic and slightly flammable.
 - i) Requires use of inert cover gas and care to prevent introduction of air in the coolant system.
- 3) Organic coolants under consideration have mediocre heat transfer relative to water, requiring special fuel element design to avoid high film temperatures.

In this paper, we provide a historical overview of organic nuclear reactor technology, and present an advanced core design moderated by graphite and cooled by an organic liquid. The design builds on the past operating experience of organic reactors, and addresses the key concerns encountered when using an organic coolant. In particular, our design employs a graphite moderator, reducing coolant damage fivefold while improving heat transfer characteristics from the fuel to coolant. We also explore the use of alternative organic fluids that are nonflammable and nontoxic. Advances in hydrocracking and reforming technology in the oil and gas industries may also allow for improved coolant reclamation. Neutronic, thermal hydraulic, and chemical thermodynamic analyses are presented. Results indicate the new organic reactor can achieve thermal efficiencies comparable to or greater than advanced LWR plants while providing inherent safety and advanced economic potential through significantly lower capital costs.

2. Historical review

Enrico Fermi and Leo Szilard [3] first proposed the possibility of using a diphenyl as a coolant and/or moderator in a nuclear reactor in 1944. However, it was not until 10 years later that the idea was first explored seriously. The organic concept initially gained traction in the U.S. when calculations showed that organic coolants, particularly those consisting of benzene rings, could provide superior moderating capability compared with light water. At the time, uranium enrichment was still viewed as a key challenge in making nuclear power generation economical, so the ability to operate with natural or slightly enriched uranium was viewed as a distinct advantage. In 1955, authorization to build an Organic Moderated Reactor Experiment (OMRE) at the National Reactor Testing Station in Idaho marked the start of an ambitious U.S. program to study the organic concept. OMRE was a plate-type reactor, building on experience from the Materials Test Reactor, fueled with UO₂/stainless steel cermet fuel clad in stainless steel. OMRE achieved criticality in 1957 and initially operated at 5–6 MW(th). Operation with the first two cores had essentially no provisions for coolant purification and the hot organic coolant was often exposed to the atmosphere during refueling operations. Not surprisingly, fouling and at least one case of coolant channel

blockage occurred due to polymerization of the terphenyl coolant (Santowax OM, later Santowax R). As a result of these observations, the third core instituted more robust on-line coolant purification processes, including glass spool filtration, activated clay adsorption, and a high throughput distillation system. In addition, care was taken to minimize coolant exposure to the atmosphere during refueling. As a result, fuel fouling and channel plugging were not observed, indicating these detrimental aspects of organic coolant usage could be mitigated by maintaining the purity of the terphenyl coolant.

The Piqua Nuclear Power Facility was a landmark power demonstration project, commissioned at the request of the AEC and designed and built by Atomics International in the city of Piqua, Ohio, building off the experience of OMRE. The Piqua organic moderated nuclear power plant first went critical in June of 1963 and operated at 45.5 MW(th) with 11.4 MW(e) net electric generation. The core used an annular fuel design clad in finned aluminum to improve heat transfer. Some initial problems, unrelated to the organic coolant, involved secondary side corrosion of steam generator tubes (due to steam) and control rod drive mechanism problems. However, when the reactor was opened it was noted that “carbonaceous material,” likely formed by coolant degradation, was preventing fuel elements from seating properly. In addition, there were buckled fuel elements, but this was most likely attributable to fuel handling and not the organic coolant. Later analyses of the “carbonaceous material” revealed that local coolant degradation was probably due to flow stagnation at certain parts of the fuel element, leading to local hot spots and coolant polymerization. While there was no indication of cladding failure anywhere in the core, the AEC made the decision not to restart the reactor in 1966.

Before the shutdown of Piqua, other activities surrounding organic reactor development in the U.S. had already commenced. By 1959 Atomics International had conducted a detailed design study for a shipboard organic moderated reactor to provide propulsion and power [4]. Westinghouse proposed an organic moderated fluidized bed reactor consisting of fuel spheres suspended in coolant with reactivity control via coolant flow [5]. While others had abandoned the prospect of a direct cycle organic reactor due to fouling and other concerns, the Marquardt Corporation was actively pursuing a direct cycle diphenyl reactor design [6]. The AEC was also extending the program started with OMRE, building the Experimental Organic Cooled Reactor (EOCR), with construction completed in 1962.

However, the AEC made an important decision with the EOCR in 1963, marking the beginning of the decline of the U.S. organic nuclear reactor program. In light of the successes of the U.S. Naval LWR program and at Shippingport, along with the perception that uranium resources were severely limited, the AEC chose not to fuel the EOCR and cancelled the program. The AEC instead chose to focus on one open fuel cycle concept (LWRs) for near-term deployment while simultaneously investing in fast breeder reactor research with the intent that it would support LWRs in the long-term as uranium resources dwindled.

Despite the cancellation of the EOCR project in 1963, internationally the organic concept was gaining traction. The Soviets independently pursued the organic concept for small modular power generation, with the commissioning of the Arbus Nuclear Power Station in 1963 in modern-day Melekess,

Russia. Canada, with the support of the U.S. AEC, was also undertaking an ambitious program to study a heavy water moderated, organic cooled reactor. Experience with OMRE led both the U.S. and Canada to recognize the advantages of using a separate moderator with the organic coolant to reduce coolant degradation. *Comitato Nazionale per l'Energia Nucleare* of Italy had its own organic reactor program, leading to the construction of the *Reattore Organico Sperimentale Potenza O* critical experiment which began operation in 1963 [7]. *Reattore Organico Sperimentale Potenza O* utilized a plate-type geometry of UO_2 /stainless steel cermet fuel which was cooled and moderated by an organic liquid. Denmark had an organic cooled exponential power facility, EXPO [8], to support the D_2O moderated, organic cooled reactor concept. Euratom was also aggressively pursuing organically cooled reactors, with the planned heavy-water moderated, organic cooled ORGEL power demonstration reactor. The ESSOR test reactor [9] was originally built by Euratom with the intent of supporting the ORGEL design. ESSOR operated from 1967 to 1983 and consisted of a D_2O moderator and multiple independent coolant loops, at least one of which was originally intended to support organic coolant research (unclear if it ever actually used an organic coolant).

The Soviet and Canadian programs serve as prime examples for the potential of the organic nuclear concept for simple and economical electricity generation. The Soviet reactor Arbus, organically cooled and moderated, operated successfully for 25 years. Initially operating at 5 MW(th) with 750 kw(e) net electric output, Arbus was the epitome of a very small modular nuclear power plant. The prefabricated plant consisted of 19 “units,” each weighing less than 20 tons to accommodate transport by train, barge, or even truck. The entire plant, including biological shielding and the coolant reclamation system, was only about 360 tons. Arbus demonstrated one of the inherent advantages of organic cooled plants—the reduction in biological shielding required due to better shielding by the coolant, reduced coolant activation, and reduction in carryover of activated corrosion products. Arbus could also be operated with as few as three people. In 1979 Arbus was retrofitted to supply process heat (Arbus AST-1), with the output increased to 12 MW(th). The Soviets, also recognizing the advantage of having a separate moderator, began to explore the compatibility of graphite with organic coolants under irradiation using the Arbus reactor [10]. Studies indicated no adverse interaction between the organic coolant and graphite, but Arbus was shut down in 1988, precluding further investigation of graphite as a potential moderator.

The Atomic Energy of Canada Limited (AECL) heavy water moderated, organically cooled project, Whiteshell Reactor 1 (WR-1), clearly demonstrated the advantage of having a separate moderator to reduce radiation damage to the coolant. Achieving criticality in 1965, WR-1 operated as a materials test reactor for 20 years. At its shutdown in 1985, WR-1 had operated with a noteworthy 85% capacity factor. In addition to the simplicity of operation attested to by its operators [11], the experience gained with WR-1 demonstrated that maintenance to the primary coolant system could be performed on-line with minimal exposure to personnel [12].

Despite the successes of Arbus and WR-1, organic reactor designs had largely fallen out of U.S. interest by the 1980s. In the 1980s nuclear energy research and development (R&D) focused

Table 1 – Summary of completed organic nuclear reactor projects.

	OMRE	EOCR	PNPF	Arbus	WR-1
Yr operational	1957–1963	Const. 1962 (see note)	1963–1966	1963–1979 (NPS) 1979–1988 (AST-1)	1965–1985
Location	Natl. Reactor Testing Station, Idaho AI/AEC	Natl. Reactor Testing Station, Idaho AI/AEC	Piqua, Ohio	Melekeess, Russia	Whiteshell Nuclear Research Establishment, Canada
Designer/operator	AI/AEC	AI/AEC	AI/City of Piqua	USSR	Canadian General Electric/AECL
Purpose	Expt. reactor	Expt. reactor	Power reactor	SMR prototype for electricity gen. (NPS); process heat (AST-1)	Materials test reactor
Power	15 MW(th)	40 MW(th)	11.4 MW(e) [45.5 MW(th)] Santowax OMP	750 kW(e) [5 MW(th)](NPS); 12 MW(th)/(AST-1)	60 MW(th)
Coolant	Santowax OM (Core I); Santowax R (Core II)	Terphenyl	Santowax OMP	GSG; HTpH; DTM	HB-40 (OS84)
Moderator	Santowax OM (Core I); Santowax R (Core II)	Terphenyl	Santowax OMP	GSG; HTpH; DTM	D ₂ O
Fuel geometry	Plate	Plate	Annular Tube	Plates (NPS); hexagonal tubes (AST-1)	Tube
Fuel type	UO ₂ /SS cermet (Core I-III); U-3.8 Mo-0.2 Al (Core IV)	UO ₂ /SS cermet, SS cladding	U-3.5Mo-0.2Al/Si alloy, Al-finned cladding	UAl alloy; UO ₂ /Al cermet	UC, Zr-2.5 Nb cladding
Coolant temp. (T _{in} /T _{out})	260–371°C/271–377°C	260°C/274°C	271°C/302°C	230°C/243°C	280–400°C/ 320–425°C
Operating pressure	200 psig	157 psi	120 psia	88 psig	165 psig
Notes	- Organic Moderated Reactor Experiment - At least three cores and a fourth prototype over operating history to test different fuels and conditions	- Expt. Organic Cooled Reactor - Reactor completed but fuel never loaded	- Piqua Nuclear Power Facility - Fuel 1.9% enriched in U-235	- Arctic Modular Plant - 3 persons/shift to operate	- Whiteshell Reactor 1 - Boasted 85% capacity factor over operating life
References	[15–17]	[18–20]	[21, 22]	[23, 24]	[11, 25]
	AEC, Atomic Energy Commission; AI, Atomics International; DTM, ditolylmethane; EOGR, Experimental Organic Cooled Reactor; Expt, experiment; GSG, gasoil; Natl, national; OMRE, Organic Moderated Reactor Experiment; SMR, small modular reactor; USSR, Union of Soviet Socialist Republics, WR-1, Whiteshell Reactor 1.				

Table 2 – Unirradiated properties of candidate organic coolants for the Organic Simplified Nuclear Reactor. Adapted from [28, 29] safety data sheets, and manufacturing specification sheets.

	Santowax OM	Santowax OMP	HB-40	Dowtherm A ^a	Syltherm 800	PFPE-1
Fluid type	15–25% o-terphenyl; 60–80% m-terphenyl; 4% p-terphenyl	< 0.1% biphenyl; 10–13% o-terphenyl; 55–62% m-terphenyl; 27–34% p-terphenyl; < 1% H.B.S	–0.2 to 1.9% biphenyl; –18% o-terphenyl; –82% hydro-terphenyl;	73.0% diphenyl oxide; 27.0% biphenyl	Polydimethyl-siloxane	Perfluoro-polyether
Chemical formula	C ₁₈ H ₁₄	C ₁₈ H ₁₄	C ₁₂ H ₁₀ ; C ₁₈ H ₁₄ ; C ₁₈ H ₂₂	C ₁₂ H ₁₀ ; C ₁₂ H ₁₀	C ₈ H ₂₄ O ₂ Si ₃	CF ₃ CF ₂ CF ₂ O-[CF(CF ₃)CF ₂ O-] _n CF ₂ CF ₃
Freezing or pour point (°C)	~85 (liquidus)	~175 (liquidus)	–24 (pour point)	12 (freeze)	–60 (freeze)	–66 (pour point)
Atm. boiling point (°C)	~315	~350	342	257	~205	Up to 270 (depends on M.W.)
Max. recommended film temperature (°C)	N/A	N/A	N/A	427	427	400 (> 450 with inert atmosphere)
Density (kg/m ³)	813 (371°C)	823 (371°C)	737 (371°C)	1,056 (20°C) 680 (400°C)	936 (20°C) 547 (400°C)	1,860–1,910 (20°C)
Thermal conductivity (W/m-K)	0.11 (371°C)	0.11 (371°C)	0.11 (371°C)	0.138 (25°C) 0.078 (400°C)	0.135 (20°C) 0.064 (400°C)	0.0831–0.0934 (38°C)
Specific heat capacity (J/kg-K)	2,529 (371°C)	2,508 (371°C)	2,387 (371°C)	1,587 (25°C) 2,702 (400°C)	1,608 (20°C) 2,257 (400°C)	962–1,004 (38°C)
Dynamic viscosity (mPa-sec)	0.23 (371°C)	0.27 (371°C)	0.26 (371°C)	3.71 (25°C) 0.13 (400°C)	9.1 (20°C) 0.25 (400°C)	6.14 (99°C)
Flash point (closed cup, °C)	172	190	170	113	> 160	Does not flash
Autoignition temperature (°C)	578	> 538	374	599	385	Does not ignite
Toxicity	Moderate toxicity to humans. Highly toxic to aquatic life.	Moderate toxicity to humans. Highly toxic to aquatic life.	Moderate toxicity to humans. Highly toxic to aquatic life.	Slight toxicity to humans. Highly toxic to aquatic life.	Essentially nontoxic to humans and aquatic life.	Nontoxic.

^a Dowtherm is a registered trademark of the Dow Chemical Company. Syltherm is a registered trademark of the Dow Corning Company. Santowax is a registered trademark of Monsanto Chemical Co. Atm., atmospheric; Max., maximum; PFPE, perfluoropolyether.

on breeding and fuel reprocessing as fears of depletion of uranium reserves were present. However, today uranium availability is no longer of high priority, and rather improving economics and “walk away” safety features of nuclear energy are the focus of much R&D. While organic coolants have been proposed for postulated fusion reactor designs [13, 14], the organic nuclear concept has rarely been discussed in the nuclear field over the past 35 years. Table 1 summarizes organic nuclear projects that were completed, both in the U.S. and internationally.

3. Overview of organic fluid properties

Organic coolant selection is a crucial part in the design of an organic nuclear reactor. Terphenyl mixtures, formerly sold under the commercial name Santowax by the Monsanto Chemical Company, were viewed as attractive due to high atmospheric boiling points and good thermal and radiation stability. Many of the Santowax mixtures are a solid, wax-like substance at room temperature. In one respect this could be an advantage, as in the event of a leak or spill the coolant would solidify upon cooling, preventing its spread. However, freezing of the coolant in the reactor at shut down was generally undesirable and required heaters to maintain the coolant in a liquid state. For this reason, AECL pursued the use of HB-40 (later sold under the name OS-84), a biphenyl/terphenyl mixture which remained a liquid at room temperature.

Coolant degradation is a significant issue, and was studied in depth by several programs in the late 1950s through the 1960s. An in-pile loop was operated at the Massachusetts Institute of Technology Research Reactor to evaluate the combined thermal and radiolytic degradation of Santowax OM and Santowax WR [26]. AECL investigated degradation of a variety of coolants with their X-7 in-pile loop in the NRX reactor and the U-3 loop in the National Research Universal reactor [27]. In general, thermal and radiolytic degradation changes coolant properties, increasing viscosity and producing both volatile products and “higher boilers.”

Siloxane or perfluoropolyether (PFPE)-based fluids may offer potential alternatives to terphenyl-based coolants, with good radiation and thermal stability. PFPE oils are currently used as a radiation stable base for greases and other lubricants used in the nuclear industry. In addition to not being flammable, even in the presence of liquid oxygen, PFPE does not degrade into solid or sludge-like materials. However, these fluids have relatively poor neutron economy compared with terphenyl-based coolants and the presence of oxygen will diminish the advantage of OCRs to operate with low induced radioactivity in all primary systems. Table 2 summarizes some properties of siloxane-based and PFPE fluids compared to past organic coolants. For this study, Santowax OMP (C₁₈H₁₄) was used as the working fluid.

4. Reactor design

This section outlines the design of a small modular Organic Simplified Nuclear Reactor (OSNR) for offshore deployment in

the 2030–2040 time frame to be compared with a PWR in a similar setting [30]. The key elements of the OSNR design that are presented here are applicable to a larger, more traditional reactor size. The offshore seabed deployment brings additional constraints on the size of the reactor hull and frequency of moving the hull on-shore for refueling. However, in an underwater setting, it is much easier to keep the hull (e.g., reactor containment) inert and eliminate the possibility of an organic coolant fire under beyond design basis (severe) accident conditions. The hull is an expensive component, the size of which is limited by cost constraints and ability for full submersion. Unfortunately, the last operated OCR, WR-1, featured a low power density (15 kW/L) that resulted in large vessel requirements. A fraction of the organic fluid also needs to be constantly replaced while the reactor is under operation since it undergoes decomposition by interacting with fast neutrons and gammas. Therefore, sufficient space needs to be accommodated for in the hull to make up the degraded coolant for offshore deployment. It is noted that improving both the power density and coolant degradation rate is a conundrum. In WR-1, the use of heavy water yielded too low a power density and increased the cost, although it provided an effective radiation shield for the organic coolant to protect it from undergoing excess degradation and thus reducing its makeup rate requirements. The presence of heavy water could also lead to unsafe (positive) coolant temperature or void reactivity coefficients [31]. Therefore, a competitive OCR design must overcome these limitations. Additionally, in this study, the OSNR was designed with a refueling frequency of every 5 years.

4.1. Reactor physics

Reactor physics analyses were carried out using the Monte Carlo N-Particle code (MCNP) and CASMO deterministic transport codes [32]. Both codes are able to perform neutron and gamma transport calculations for thermal spectrum reactors. Since CASMO's computational time is orders of magnitude shorter than MCNP, MCNP was only used as a verification code, since CASMO's performance for non-LWR type materials is not well-established. Luckily, CASMO4e has the ability to model advanced gas reactors that have nontraditional geometry and use graphite as a moderator, which is used as part of the OSNR assembly design.

As listed in Table 2, terphenyls are composed of carbon and hydrogen, with density similar to water at PWR conditions. Since the ratio of hydrogen to carbon is also similar to the ratio of hydrogen to oxygen in water, the neutronic impact of replacing water with an organic fluid such as Santowax OMP is expected to not be significant. The Piqua (with aluminum fins homogenized for the model in the coolant) [22] and WR-1 [11] fuel elements are shown in Figs. 1A and 1B. The energy deposition in the coolant from slowing down of fast neutrons and gamma irradiation as the fraction of total fission energy in the Piqua design is 10.5 times more than for the WR-1 design. The 1,000 MW(e) conceptual heavy water moderator organically cool reactor (HWOCR) [31] had fuel designed similar to WR-1 but with an extra ring of fuel on the outside. The fuel-to-fuel pitch was also increased to operate with negative moderator density and temperature coefficients. One of the goals of the reactor physics calculations is to design an OSNR

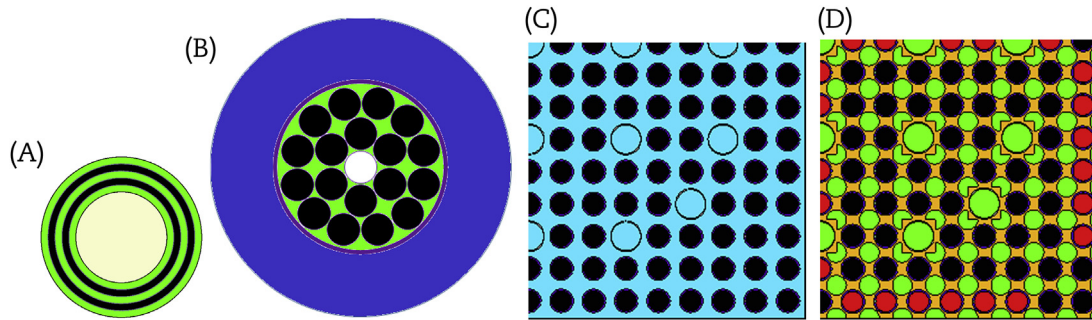


Fig. 1 – Diagrams (from left to right). (A) Piqua (B) Whiteshell Reactor 1. (C) A quarter symmetric pressurized water reactor. (D) Organic Simplified Nuclear Reactor uranium carbide assembly. ^a Black, fuel; Green, Santowax OMP; Blue, water; Dark Blue, heavy water; Red, zirc-hydride; Purple, zirc-4 cladding; Yellow, graphite (1.75 g/cm³ density).

assembly that resembles a PWR but exhibits a similar energy deposition fraction as the conceptual commercial HWO CR design that was developed based on the operating experience gained in WR-1.

Figs. 1C and 1D display a quarter PWR assembly and an equivalent OSNR assembly. The approach leading to the final OSNR UC assembly design and its reactor physics performance is detailed in the following steps and shown in Fig. 2, respectively:

1. Standard PWR configuration: 4.5% enriched ²³⁵U Westinghouse RFA 17 × 17 assembly (PWR) [33].
2. OSNR 1: PWR but all water replaced with Santowx OMP.
3. OSNR 2: OSNR 1 but 40% of the coolant volume replaced with graphite, where the coolant will flow through 7.6-mm diameter channels.
4. OSNR 3: OSNR 2 but 66 fuel rods replaced with ZrH_{1.6} rods and radius of fuel increased by 0.2 mm (e.g., decreasing fuel cladding thickness by 0.2 mm).

5. OSNR UC or uranium nitride (UN): OSNR 3 but fuel changed from UO₂ (10.3 g/cm³ density) to either UN or UC with 13.5 g/cm³ density.

The geometry and fuel change in steps 4 and 5, respectively, were in response to the reduction of total fuel volume and decrease in neutron economy from the introduction of ZrH_{1.6}. This allows the “OSNR 4” to operate at the same power density as a PWR with the same ²³⁵U enrichment level. The reduction in cladding thickness as part of step 4 is allowable since the cladding experiences smaller stresses and far less corrosion with the OSNR compared with a PWR. The stress is reduced since the plenum volume can easily be increased to accommodate fission gases, since the reactor pressure vessel operates at 20 times less operating pressure. The stress induced from potential pellet-clad interaction is also reduced since there is no cladding creep at the OSNR operating pressure. The cladding corrosion is virtually eliminated since there

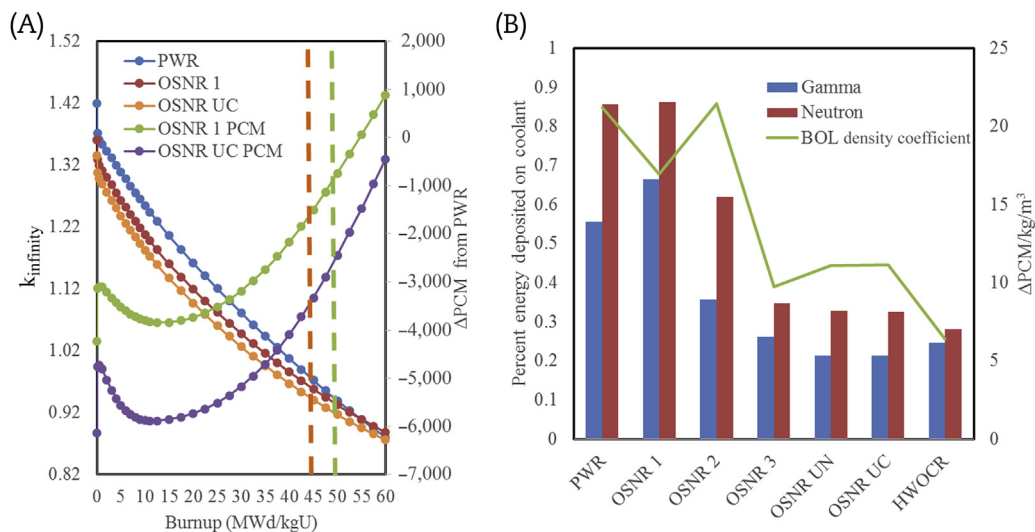


Fig. 2 – The k_{∞} and reactivity difference relative to the pressurized water reactor (PWR) versus burnup curves (A) and percent energy deposition on the coolant and beginning of life (BOL) density coefficient (B) for selected designs. HWO CR, heavy water moderator organically cool reactor; OSNR, Organic Simplified Nuclear Reactor; PCM, per cent mille; UC, uranium carbide; UN, uranium nitride.

is no oxygen in the OSNR design and the fuel cladding is not in contact with the coolant as shown in Fig. 1D.

The motivation for using $ZrH_{1.6}$ instead of additional graphite was to increase the core power density at the cost of slightly poorer neutron economy from the added zirconium in the design. The use of ZrH_x in nuclear reactors is perhaps best known in TRIGA research reactors [34]. ZrH_x has also been considered for a control material for fast reactors as well as a moderator/shielding material for thermal reactors [35]. More recently, its performance for a supercritical water reactor was analyzed [36]. However, compared with graphite, ZrH_x has temperature limitations due to lower hydrogen diffusion as well as structural integrity. At hydrogen to Zr atomic concentrations above approximately 1.4, undesirable hydride phases can be formed at high temperatures greater than 400°C. A concentration of 1.6 is picked (e.g., $ZrH_{1.6}$) similar to Buongiorno et al [36] study. Since the organic coolant outlet temperature is no more than 350°C, it is expected that the hydrogen concentration will remain relatively the same for a 5-year core residence time.

Fig. 2A shows k_{∞} versus burnup curves for selected designs as well as the reactivity decrement relative to the PWR assembly. As shown in Fig. 2A, the Santowax OMP coolant actually displays higher reactivity at 60 MWd/kgU when comparing the PWR with the OSNR 1 design because of the reduction of absorption by hydrogen. In general, the reactivity swing with the organic coolant is smaller than the PWR, which implies a flatter core radial assembly power distribution. The k_{∞} decreased by 11,000 PCM when moving from the OSNR 1 to OSNR 2 design due to the loss of hydrogen (moderation power) in the system. Thus, the introduction of $ZrH_{1.6}$ was necessary if a similar assembly size as a standard PWR is desired. The fuel loading per assembly cross-sectional area in the OSNR UC design is approximately 10% greater than a PWR so both designs would require the same enrichment at any given power density, since the OSNR UC k_{∞} at 45 MWd/kg U burnup is similar to the PWR k_{∞} at 50 MWd/kg U, as shown in Fig. 2A. Of course, the additional 10% of fuel loading in the OSNR design results in a higher fuel cycle cost relative to the PWR at a given power density. The control rod worth was also calculated by assuming standard Ag-In-Cd PWR rods are fully inserted in the guide tubes (except for the central instrument tube) as shown in Figs. 1C and 1D. The control rod worth at the beginning of life was found to be approximately 18% higher for OSNR 3, while the worth at 50 MWd/kgU was similar to the PWR assembly (within approx. 3%).

Fig. 2B displays the percent energy deposited on the coolant for each design including the HWOCR conceptual design. As shown, when switching to an organic coolant, the gamma dose on the coolant increases by approximately 20%. However, the introduction of graphite and eventually $ZrH_{1.6}$ reduces the energy deposition from both gamma and fast neutrons substantially, similar to levels in the HWOCR design. The reliance on solid moderators is the key advantage of the OSNR design compared to HWOCR, which was designed with expensive heavy water systems. As shown in Fig. 2, the density coefficient reduces by about half for the OSNR UC design compared to the PWR; however, it is still

negative and sufficiently below zero. In addition, the peak pin power within the assemblies without use of any burnable absorbers for all designs ranged from 1.266 for the OSNR UC to 1.043 for the OSNR 1, which is manageable. If the $ZrH_{1.6}$ rods were distributed in the assembly uniformly as oppose to being lined up on the edges, the intra-assembly pin peaking factor of OSNR UC would reduce to 1.18. However, at the same time the neutron damage rate to the coolant would increase by 5%. Also, cooling will be further complicated with many fuel and non-fuel regions adjacent to each other.

Use of either UC or UN, with similar fuel densities, results in similar behavior. The C in UC slightly reduces the neutron damage rate on the coolant compared with UN. The other disadvantage of UN compared with UC is that the nitrogen needs to be 100% enriched in ^{15}N ; otherwise, a significant enrichment increase is required with natural nitrogen, due to neutron absorption by ^{14}N . For the sake of this analysis, UC is considered as the reference design, similar to some elements in the WR-1 reactor.

4.2. Thermal hydraulic analysis

In addition to the higher fuel loading, the consideration of the UC fuel form was based on its substantially higher thermal conductivity compared to UO_2 , about a factor of 5 at 1,000°C. The higher fuel thermal conductivity allows replacing 40% of the coolant volume by graphite to reduce coolant damage. For a given power density and fuel type, the outlined OSNR 3 assembly design results in higher fuel temperatures compared with a PWR due to both decreased coolant volume and the relatively poorer convective heat transport properties of Santowax OMP. However, the fuel temperature is lower when comparing the OSNR UC design with the PWR with UO_2 . It is noted that other innovative OSNR designs with graphite and $ZrH_{1.6}$ have been considered by the authors that result in the same peak fuel temperature with UO_2 fuel as well [37].

The steady state thermal hydraulic analysis of the OSNR UC design is simplified compared with a PWR as the coolant channels are made of round tubes with single phase coolant flow (no subcooled boiling). The commonly used Dittus-Boelter wall heat transfer and Blasius friction factor correlations that have shown good agreement with available Santowax OMP data [31] were used in this study. For the departure from nucleate boiling ratio (DNBR), the following equation was derived for Santowax OMP DNB data to calculate the critical heat flux (CHF):

$$q''_{\text{critical}} = 129,000 + 11 \Delta T_{\text{SC}} G^{0.8} \quad (1)$$

where q''_{critical} is the CHF in Btu/hr-ft², ΔT_{SC} is the subcooling temperature in °F, and G is the mass flux in lb/sec-ft². The minimum DNBR (MDNBR) limit of 2.0 has been used in the past to avoid CHF [31]. It is noted that for the sake of simplicity, constant fluid properties were used in this analysis but future analyses should take into account both temperature and degradation product (“higher boiler”) dependent fluid properties for more accurate prediction of the thermal hydraulic performance of OSNR.

Table 3 lists OSNR's reactor parameters compared to an offshore SMR PWR [30,38]. The main limiting design constraint was maintaining the peak wall temperature below the saturation temperature to avoid subcooled nucleate boiling. The system pressure drop was also limited to 200 kPa to avoid moving too far from atmospheric pressure. Even though, from a reactor physics point of view, the OSNR assembly has the potential to operate at the same power density as the SMR PWR (approx. 70 kW/L), its active core power density was limited to 40 kW/L. The core outlet pressure was designed to be approximately 0.55 MPa where the saturation temperature of Santowax OMP is 482°C [31]. The maximum pressure in the primary system occurs at the core inlet (approx. 0.75 MPa), which is 20 times less than in a PWR. Assuming a conservative 1.3 intra-assembly pin peaking factor and 1.45 intracore assembly peaking factor with 95% nominal rated mass flux, the maximum bulk fluid temperature in the core is calculated to be 358°C. Therefore, sufficient margin in the event of an accident is expected. A peak wall temperature of 417°C was calculated, assuming a chopped cosine power shape with 1.25 peaking factor. The peak wall temperature is also less than the saturation temperature, which eliminates the presence of subcooled nucleate boiling. The MDNBR of 2.36 was calculated using the CHF correlation in Eq. (1). The lower power density of the OSNR allows the fuel to be enriched less than the current ^{235}U enrichment limit of 5% while enabling a 5-year refueling frequency. The PWR SMR design needs to decrease its power density or power output to meet the 5% enrichment limit, as shown in Table 3.

Table 3 – Operating parameters for the Organic Simplified Nuclear Reactor (OSNR) design.

Parameters	PWR SMR	OSNR
Power [MW(th)]	500	500
Core power density (kW/L)	70	40
Hull power density (kW/m ³)	115	192
Thermodynamic efficiency	~33%	~33%
Core outlet pressure (MPa)	15.5	0.55
Reactor pressure vessel thickness (cm)	60	10
Core outlet temperature (ΔT ; °C)	320 (35)	320 (35)
Working fluid chemical formula	H ₂ O	C ₁₈ H ₁₄
Core flow rate (kg/s)	2,600	5,700
Core pressure drop ΔP (kPa)	60	155
Mass flux (kg/m ² -sec)	2,200	6,300
No. of assemblies	52	91
Core equivalent diameter (m)	1.72	2.3
Fuel height (m)	3	3
Assembly array size	W 17 × 17 RFA	W 17 × 17 RFA
No. of fuel rods (ZrH _{1.6} rods)	264 (0)	198 (66)
Fuel/clad materials	UO ₂ /Zr	UC/Zr
Core fuel loading (tons)	21.53	40.74
Average LHGR (kW/m)	12.14	9.25
Peak cladding temperature (°C)	350	390
Minimum DNB ratio	2.43	2.36
Energy deposited in coolant (%)	1.41	0.54
Core average enrichment (%)	5.4	4.5
Cycle length (yr)	5	5

DNB, departure from nucleate boiling; LHGR, Linear Heat Generation Rate, PWR, pressurized water reactor; RFA, robust fuel assembly; SMR, small modular reactor; UC, uranium carbide.

Since the placement of the coolant channel relative to fuel will result in uneven azimuthal temperature at the wall, turbulent computational fluid dynamic simulations were performed using the STARCCM+10.06.009 software [39]. To estimate the fuel centerline temperature, the thermal conductivity of UC as function of temperature was implemented [40]. The thermal conductivity of graphite was assumed to be 10 W/m-K considering both temperature and irradiation induced conductivity degradation [41]. Even though the current fuel-cladding gap in PWRs is on the order of approximately 60 μm , in this analysis, a 100- μm gap was conservatively assumed for the OSNR design. The peak azimuthal cladding temperature agreed well with the Dittus-Boelter correlation as shown in Fig. 3. The peak fuel centerline temperature in the core was calculated to be approximately 1,020°C assuming the conservative gap size (Fig. 3).

The average coolant heat transfer coefficient in the OSNR is a mediocre approximately 8,800 W/m²-K compared with 60,000 W/m²-K for a PWR. However, designing a system with a low heat transfer coefficient has an advantage during accident scenarios, where loss of flow will not greatly affect system performance. Given the density change in the coolant across the core at steady state operating conditions, a natural circulation flow rate of approximately 10% of the rated coolant flow rate is possible. Thus, the OSNR design has great potential to be designed with full passive safety to achieve indefinite removal of decay heat upon a safety control rod axe man.

One of the OSNR thermal design goals was to ensure the ZrH_{1.6} temperature remained below 400°C. Based on reactor physics calculations, it was found that 0.7% of the total fission power is deposited in the ZrH_{1.6} in the form of mostly gamma energy and adequate cooling is already available in the current design to keep its centerline temperature below 400°C. Lastly, concerns regarding plugging of the 7.6-mm Outer Diameter coolant channels due to build-up of corrosion products that are typically present in PWRs is alleviated, since the “oxygen free” environment of OSNR drastically reduces corrosion rate in the primary loop. Additionally, even upon accidental blockage of one of the coolant channels, thermal analysis implies the heat transfer via conduction in the graphite is sufficient to keep the fuel and cladding below

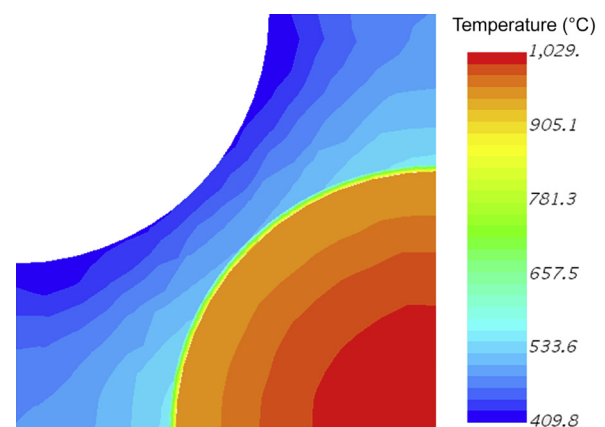


Fig. 3 – Fuel temperature distribution of the peak Organic Simplified Nuclear Reactor uranium carbide channel (1/4 symmetric).

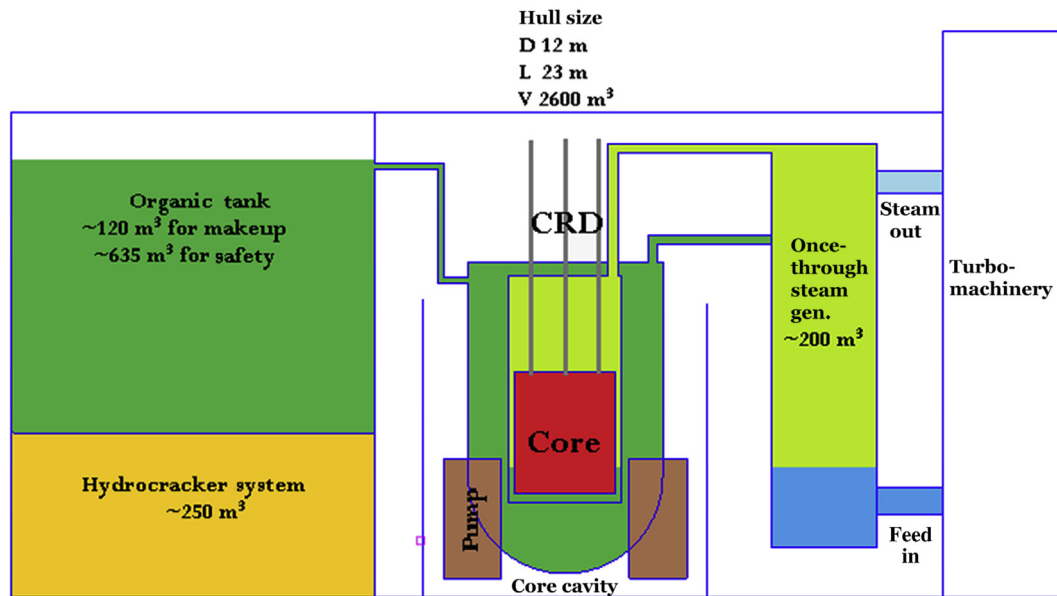


Fig. 4 – Outline of the Organic Simplified Nuclear Reactor offshore design in a cylindrical hull (note: the hull rest on the seabed). CRD, control rod drive; D, diameter; Gen., generator; L, length; V, volume.

melting. Future analysis on the percentage of tolerable blocked channels will be of interest.

4.3. Coolant makeup rate

The coolant replacement rate (from both thermal and radiation degradation) calculated for the conceptual HWCOR 2,850 MW(th) design [31] was 680 kg/h. Therefore, for a base design reactor size of 500 MW(th), the coolant degradation is estimated at approximately 1,000 m³ per year. That is the reason why the Canadian design used a hydrocracker system to recycle the damaged fluids; although, the use of the hydrocracker system only affects the makeup rate of the organic coolant and does not affect the degradation rate of the coolant in the core. Thus, the Canadian design also used a separate moderate to control the composition of the organic coolant in the core. The 1960s hydrocracker system was able to achieve a conversion efficiently of 87% with maximum efficiency of 90% [31, 42]. However, hydrocracker technology has advanced tremendously in the oil and gas refining industries and currently a maximum conversion efficiency of 98% can be achieved [43]. Assuming 98% efficiency by the 2030–2040 time frame, the required organic makeup rate is estimated to be approximately 20 m³ per year for the OSNR. The hydrocracker system for the HWCOR conceptual plant was estimated to require many tanks with a total volume of approximately 250 m³. Since the pumps and piping volumes were ignored in the plant estimation, the same volume of approximately 250 m³ is used as a rough estimate for the size of the hydrocracker system for our smaller design. The hydrocracker system with 250 m³ of space is able to save approximately 978 m³ per year of space that would otherwise be required to make up for the loss of organic fluids due to thermal and irradiation degradation.

4.4. Plant layout

The new OSNR concept outlined in the previous section has a higher power density than the Canadian design, as well as no space requirements for the heavy water systems. Therefore, the volume required for this system with the volumes required for the hydrocracker and makeup systems for a period of 5 years was used to create a new plant layout design. Fig. 4 shows such a layout by using a traditional shell and tube heat exchanger. The shell and tube heat exchanger size was estimated using the ASPEN heat exchanger design tool [44] that includes Santowax fluid properties, since the tool is predominately used in the chemical oil/gas industry. The organic fluid was assumed to flow in the tubes, while the secondary side fluid that drives a steam Rankine power cycle with similar operating conditions as a PWR would flow on the shell side. This configuration will put the steam generator tubes in compression and eliminate the possibility of stress induced tube failures. The possible ingress of steam to the organic side and its chemical interaction with Santowax and over pressurization of the primary side were considered in the EOGR safety analysis report and the design response to such an accident was deemed satisfactory [45].

The volume required to accommodate the organic tank and hydrocracker system is also shown in Fig. 4. The volume of organic coolant needed for safety injection from the suppression pool is assumed to be similar to that of a PWR. While the boiling point of the organic is much higher (approx. 350°C) than water at atmospheric pressures, its thermal capacity is about half that of water. The upper plenum shown in Fig. 4 is larger than a typical LWR since operation at atmospheric pressure will require a longer plenum length in order to accommodate space for the fission gases. The turbo-machinery for the OCR design will

have the same options as the PWR design with the same thermodynamic efficiencies.

5. Discussion

5.1. Economic and safety considerations

It is noted that the design outlined thus far is still in the preliminary stages, and therefore a qualitative approach is taken in this section. Perhaps the most important area of cost savings for the new OSNR concept over the SMR PWR design [30] is the less-expensive hull (40% reduction in volume), vessel, and primary system piping, as smaller thicknesses are required with no stainless steel liner. The OSNR steam generator itself is larger than that required for a PWR due to the poorer heat transfer properties of the organic coolants. However, the tubes do not need to be rated at 16-MPa pressure and can be made with less expensive steel alloys, since tensile stress has been eliminated in the tubes. Therefore, the total cost for the steam generators should be roughly the same or cheaper. The other area of potential cost savings arises from the low induced radioactivity with the organic coolant due to low corrosion rates. Therefore, during refueling components such as the steam generator can go through extensive maintenance without worries that activated corrosion products will induce dose on refueling personal or equipment.

The OSNR fuel layout and enrichment requirement is similar to a PWR in order to utilize existing manufacturing and nuclear waste disposal capability. The additional cost of graphite and $ZrH_{1.6}$ is not expected to be significant [36] compared with the 10% additional cost of uranium to accommodate the extra neutron absorption due to presence of $ZrH_{1.6}$. The proposed fuel, UC, also needs to go through additional R&D for this application. Another area of cost increase is the hydrocracker system, although a PWR does require some coolant chemistry control, especially if boron is used in the coolant. The cost of the organic coolant itself is expected to be negligible (approx. \$300/m³), so the additional cost of the hydrocracker system needs to be estimated in a future study and compared with the large gain in capital cost reduction and maintenance.

The OSNR system pressure is only approximately 0.6 MPa, virtually eliminating the pressure gradient driving coolant out of the primary system during loss of coolant accidents. It is noted that this is true for an underwater concept, where the magnitude of vibrations due to earthquakes and external events is drastically reduced. The hull and the internal containment walls are not required to withstand peak pressures experienced by loss of coolant accidents for PWRs as well. The reactivity coefficient is less negative but still sufficient. The reactivity control system does not need to differ significantly from that of the PWR SMR. The high boiling point of fluid at atmospheric pressure is another advantage of OSNR. There is little concern regarding organic coolant flammability while the hull is submerged in water where an inert environment can be reliably maintained. In the case of a breach of the hull by water, the water density is higher than Santowax and thus Santowax will float and the water will be able to directly cool the fuel. There are no criticality accident

issues as both water and Santowax exhibit similar neutronic characteristics. Since the system is designed in an under-moderated region (Fig. 1B), loss of hydrogen from ZrH upon its diffusion at high temperatures will not result in any added reactivity concerns. In terms of severe accident consideration, the mass of zirconium and hydrogen in the system is comparable to current BWRs. It has been shown that annealing graphite at a temperature range around 200–300°C can release most of its stored energy upon irradiation (Wigner Energy) [46]. Thus, proper heat treatment can avoid issues arising from graphite stored energy for the OSNR design that operates at approximately 300°C.

5.2. Applicability for land-based OSNRs

For a land based reactor, the components of the OSNR must withstand events such as earthquakes according to the required regulations. Thus the cost savings on materials may not be as much as the seabed reactor design. The $ZrH_{1.6}$ rods may not be necessary for a land-based design since space is not limited, which will improve the fuel cycle cost of the OSNR. While the PWR SMRs typically use control rods as the primary method of reactivity control, conventional PWRs use of soluble boron could be challenging for an OSNR to operate with comparable peaking factors. However, a chemically stable mixture of boron and organic fluid may be feasible [37] and is left as one area of future investigation.

Perhaps the biggest concern for a land based OSNR is the ability to guarantee an inert environment to eliminate the possibility of fires in beyond design basis (severe) accident conditions. Since the organic fluid carries hydrogen, much like water, the chemical potential energy stored in an OSNR design is similar to a PWR. If the regulator questions the ability to keep the reactor primary side inert and ignores experience shown by previous operating OCRs, then a large containment to withstand the coolant fire might be needed, which reduces the economic incentive of OSNR compared with already established PWR technology. Though, with increased use of risk informed methodology in licensing and acceptance of inherit safety concepts, a land based OSNR might be able avoid such stringent regulatory requirements.

6. Conclusion

A new organic concept capable of operating at 40 kW/L while maintaining a negative density reactivity coefficient was outlined for deployment by a 2030–2040 time frame. The assembly design utilizes a combination of graphite and $ZrH_{1.6}$ in order to achieve optimum features while minimizing radiation induced damage to the organic coolant. The OSNR concept with UC fuel was designed for offshore deployment where the design hull is the most expensive component. The design with a shell and tube steam generator results in a 40% smaller hull size than the base PWR design. In addition, this concept offers significant reduction in the cost of primary system components.

The analysis presented in this work is at the “proof-of-concept” level, and more detailed analysis is needed,

especially regarding safety licensing level analysis and the design behavior under severe accident conditions. This is left as future work. This study has highlighted the potential of an OSNR to take advantage of decades of innovation in the optimization of organic fluids, hydrocarbon reprocessing, and development of radiation resistant materials. In conclusion, the OSNR concept has the potential to play a key role in the promotion of nuclear energy in the future with significant potential gains in economic performance, especially for those developing nations that desire nuclear energy but do not have infrastructure to support specialized nuclear manufacturing.

Conflicts of interest

The authors have nothing to disclose.

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