SEALER:
A small lead-cooled reactor for power production in the Canadian Arctic

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Abstract. SEALER (Swedish Advanced Lead Reactor) is a 3-10 MWe lead-cooled fast reactor operating on 19.9.% enriched UO_2 fuel. It is designed for commercial production of electricity in communities and mining operations in the Canadian Arctic. The reactor is capable of passive decay heat removal by radiation through the primary vessel and will make use of novel, highly corrosion resistant aluminum alloyed steels developed by LeadCold engineers. Passive shut-down is accomplished by gravity assisted insertion of tungsten-rhenium boride absorber elements.

In this paper, we present the general technical concept of SEALER, together with the plan for licensing SEALER in Canada, including the pre-licensing design review process with CNSC, the R&D program necessary to qualify the design and associated materials, and the siting of a demo-plant in southern Canada. We also outline the business plan for producing and selling up to 100 SEALER units on the Canadian market.

Key Words: Small LFR, passive decay heat removal, aluminum alloyed steels, market oriented design.

1. Introduction

In remote areas without connection to the national power grid, electricity is often produced using diesel generators. Such diesel power plants today account for 3% of global CO_2 emissions. In Arctic regions, diesel supplies are expensive to transport and store, leading to very high costs for electricity and heat. Example given, the average cost of electricity for the consumer in Nunavut, Canada, is 0.67 CAD/kWh, more than five times higher than that charged in southern Canada. Small nuclear power plants hold the potential to replace diesel in such regions, at a competitive cost.

By eliminating on-site fuel-cycle operations through the use of a long-life core, one may reduce costs and mitigate proliferation concerns related to operation of a nuclear reactor in a remote location. To this end, fast reactors are better suited than thermal reactors, thanks to their superior breeding performance. Both sodium and lead-cooled reactors have been considered for this application

A distinct advantage of lead-cooled reactors in this context is that both passive safety and severe accident mitigation can be achieved in a much more compact configuration, simplifying transport to the site.

SEALER (Swedish Advanced Lead Reactor) is designed by LeadCold Reactors to meet the demands for commercial power production in Arctic regions of Canada. In Nunavut and the North-West Territories, about ten off-grid communities are of the size that power supply from a stand-alone SEALER unit can be made commercially viable. Moreover, as power constitutes 30-50% of the cost for producing a commodity in the Arctic mining industry, a set of SEALER units can be applied at each mining site, allowing to reduce expenses and to make lower grade ores profitable.

2. General technical concept

SEALER is designed for being constructed and operated in the Canadian Arctic, in locations where there is no access by road. Heavy supplies have to be shipped by sea-lift during the short open-sea season in July and August. However, all communities and mining sites are accessible by air, and components with a weight of less than 25 tons may be transported to the site any-time of the year using transport air-craft.

Hence, the diameter of the SEALER primary vessel (2.7 m) was designed to fit into an Hercules C-130 freighter. The height of the vessel (6.0 m) was adjusted to allow for natural convection to remove decay heat without a significant increase in coolant temperatures. Moreover, the height is short enough to ensure a benign performance during seismic events. The general configuration of the primary system is displayed in Figure 1. Forced convection of lead is provided by eight pumps located in the space between the core barrel and the main vessel. Heat removal during nominal operation is accomplished by eight steam generators located below the pump. The foreseen steam generator tube material is a highly corrosion tolerant Fe-10Cr-4Al-0.2Zr alloy, which was developed by LeadCold engineers in collaboration with Swedish steel industry [1].

FIG. 1. SEALER primary system

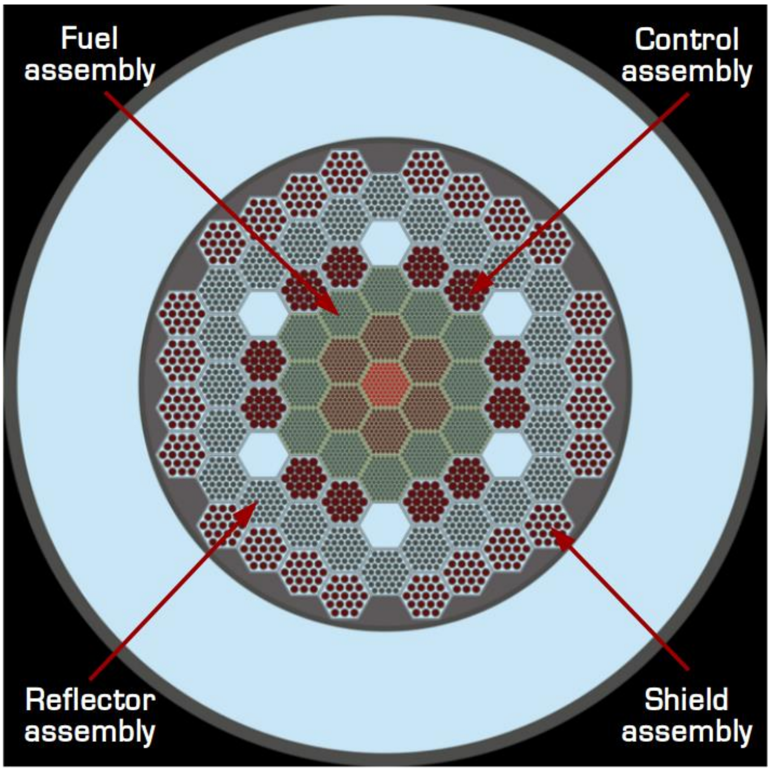

FIG. 2. SEALER core map

As illustrated in Figure 2, the core features 19 hexagonal fuel assemblies, each with 91 fuel rods containing 19.9% enriched UO_2 pellets. The number of fuel assemblies was determined by the requirement that each of the control assemblies located at the periphery of the core should have a reactivity worth of less than 0.5 dollars, while their combined worth should be large enough to ensure a safe shut-down state. This may be achieved by a combination of 12 control assemblies and 6 shut-down assemblies. The geometry of the fuel rods, the fuel assemblies and the core was obtained using the multi-variable fast reactor core optimization code ADOPT [2], applying boundary conditions for temperature and pressure gradients over the core, lead velocity and peak stress in fuel cladding tubes and ducts.

The 12 control assemblies provide a reactivity reserve of 5400 pcm. The calculated reactivity loss for the SEALER core is 1400 pcm per percent burn-up. Consequently, the average burn-up of the core is limited to about 33 GWd/ton. Since the position of the control rods is at the periphery of the core, the radial peaking factor of about 1.5 is higher in SEALER than in more conventional fast reactor designs. However, the corresponding peak burn-up of 58 GWd/ton is modest in the context of UO_2 fuel in fast reactors.

Fuel cladding tubes are made of 12R72 (Sandvik's 15-15Ti grade). Corrosion protection is ensured by surface alloying the tubes with Fe-10Cr-6Al, using the GESA method developed by KIT [3].

Whereas the absorbing material of the control rod assemblies is natural boron carbide, the absorber material intended for use in shut-down rods is $(W,Re)^{10}B_2$, a compound having a density significantly higher than lead. The use of this novel material permits passive insertion of the shut-down elements by means of gravity, without introduction of tungsten ballast.

Reflector assemblies contain rods with yttria stabilized zirconia pellets, and shielding of the core barrel is provided by 96% enriched boron carbide absorbers.

More detailed specifications of materials and geometry of the core and primary system can be found in other papers contributed by LeadCold to this conference [4].

Values for the main thermal hydraulic parameters of the system when operating at 8 MW thermal power are listed in Table 1.

TABLE I: MAIN THERMAL HYDRAULIC PARAMETERS OF PRIMARY SYSTEM

Parameter	**Value**
Thermal power	8.0 MW
Average linear power	4.2 kW/m
Total Pb mass flow	1300 kg/s
Pump mass flow	160 kg/s
Core inlet temperature	390°C
Core outlet temperature	432°C
Core pressure drop	1.1 bar
Max Pb velocity in core	1.6 m/s
Max clad temperature	450°C

During normal operation, eight steam generators with a capacity of 1 MW thermal each provide heat removal to the secondary system. Operating with a conventional Rankin cycle, the secondary system provides an electrical conversion efficiency of 36% and the residence time of the fuel is 27 full power years. Thus, SEALER functions as a nuclear battery, without the need for any refueling, when deployed in an Arctic community with a peak demand of 3 MWe.

As described in more detail in [4], decay heat removal is accomplished in a completely passive fashion, through a combination of natural convection of the lead coolant and radiation through the vessel.

3. Licensing of SEALER in Canada

The Canadian Nuclear Safety Commission (CNSC) has developed a regulatory framework which allows for licensing of small reactors using a so called "graded" approach [5]. According to CNSC, the graded approach "is a method in which the stringency of the design measures and analyses applied is commensurate with the level of risk posed by the reactor facility."

In addition, CNSC offers to make a pre-licensing review of the vendor's reactor design, for the purpose of familiarizing the vendor with Canadian regulations, to evaluate the licensability of the concept in Canada and for improving regulatory certainty [6]. A positive outcome of the design review does not constitute a license to construct or operate the reactor.

LeadCold entered Phase 1 of the CNSC's vendor's design review in January 2017. Documentation for 21 focus areas, including corrosion mitigation and coolant conditioning will be submitted by LeadCold for CNSC to evaluate how LeadCold complies with and understands Canadian regulations. The review process is expected to last 15 months.

LeadCold aims at entering Phase 2 of CNSC's vendor's design review in 2018.

Teaming up with a licensed nuclear operator, LeadCold plans to submit a request for licensing of a demonstration SEALER unit on an existing nuclear site in southern Canada in 2019. The mimimum time required by CNSC to review such a license application is 24 months.

4. R&D program

CNSC requires vendors to carry out an R&D program, the results of which shall be taken into account in the power plant design [7]. The R&D program is presented to CSNC as a focus area in the vendor's design review.

The R&D program of LeadCold includes the following activities:

1. Long term (5 year) corrosion tests of novel aluminum alloyed steels under well controlled, stagnant conditions.
2. Irradiation tests of aluminum alloyed steels, surface alloyed 12R72 tubes and novel absorber materials in a materials test reactor. The irradiation campaign is foreseen to start in 2018.
3. Long term endurance tests of pumps and pump impeller materials. The SEALER pump will be made by an established lead pump manufacturer from the UK. The test facility is to be constructed at KTH and the endurance test of the impeller will commence in 2018. The loop where the pump is installed will also be used to study erosion and fretting issues.
4. The in-house computer code BELLA for transient analysis of SEALER [4,8] will be revised in compliance with CSA (Canadian Standards Association) standards for design of nuclear power plants. BELLA is to be benchmarked with respect to available experimental data and other state-of-the art codes.
5. The construction and operation of an electrically heated one-to-one scale mock-up of SEALER in Canada. In this mock-up, the design, computer codes, operational procedures and the safety performance of SEALER under transient can be validated. Moreover, materials performance can be evaluated under realistic and complex conditions. Once a demo-reactor is operational, the mock-up facility may be used for education and training of operators and maintenance personnel.

5. Siting of a demonstration plant

Landowners, stakeholders and LeadCold's potential customers in the Arctic regions of Canada have expressed an interest in assessing SEALER for power production. All of them see the operation of a demonstration plant as mandatory for such an evaluation to become meaningful. Together with Canadian Nuclear Laboratories (CNL), LeadCold is assessing the Chalk River site in Ontario as a potential location for this demonstration unit. The site currently hosts the NRU materials test reactor, which is slated for closure in 2018. The demo unit is foreseen to produce power to the Chalk River site and would be used to qualify next generation fuels and materials for SEALER. In addition, the business model includes irradiation testing for commercial customers. It is foreseen that an environmental assessment for this site will start within the near future.

6. Business plan for the Canadian market

Since the timing for starting a mining operation and its associated power unit is not well defined, LeadCold focuses its initial marketing efforts on reaching out to off-grid communities in the Canadian Arctic, with a power consumption in the range of 2-10 MW. The company has identified nine such communities in Nunavut and one in the North-West Territories, to which the 3 MWe version of SEALER will be offered.

A preliminary assessment of heat production in the aforementioned communities indicates no immediate commercial incentive, considering the cost for establishing infrastructure for district heating.

Considering customers in the mining industry, the typical requirement is for 20±5 MW electricity. LeadCold intends to offer a solution of 2x10 MWe units to this industry. The estimated market in Canada, including Yukon and northern Ontario is for a total of two new mines, or about four SEALER units per year. Over a period of a few decades, of the order of 100 reactors may be deployed for commercial off-grid power production in Canada.

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