APPLICABILITY OF SMALL FAST REACTOR "4S" FOR OIL SANDS RECOVERY

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Abstract

"4S" (Super-Safe, Small and Simple) is a small-sized sodium cooled reactor with a reflector-controlled long life core. The concept for a steam production plant consisting of the 4S with a thermal rating of 135 MWt for a typical SAGD (Steam Assisted Gravity Drainage) plant was established. The 4S, provided for oil sands recovery, will significantly reduce greenhouse gas emissions and has applicability to an oil sands plant. The burden for development and licensing will be reduced in tie-ups with the development and licensing program for the 4S with a thermal rating of 30MWt which is now in the process of pre-application review with the U.S. Nuclear Regulatory Commission.

1. Introduction

The 4S, Super-Safe, Small and Simple is a small-sized sodium cooled fast reactor. Toshiba has been developing the concept of 4S since 1988 in corporation with CRIEPI (Central Research Institute of Electric Power Industry) [1]-[52]. The 4S has the following features; infrequent refueling, plant shutdown and decay heat removal without active safety-related systems, and low maintenance requirements for in-vessel structures. Based on these features, application of the 4S to the electricity supply for remote areas without a developed grid, seawater desalination facilities and mining facilities has been investigated. It is also expected that the 4S can serve as a non-proliferation reactor for the Global Nuclear Energy Partnership (GNEP).

In the development of the 4S, two types of the power output, which are 30MWt and 135MWt, have been created. System design of the 4S with a thermal rating of 30 MWt (hereinafter called "4S-30MWt") has been completed [53]. Toshiba applied to U.S. Nuclear Regulatory Commission (NRC) for the pre-application review of the 4S-30MWt with the cooperation of CRIEPI and Argonne National Laboratory (ANL). The pre-application review commenced in Oct. 2007. Four public meetings were held in phase 1 of the pre-application review at the proposal of Toshiba. Meeting agendas included "Overview" in the 1st meeting, "System design and long life fuel" in the 2nd meeting, "Safety design and safety analysis" in the 3rd meeting and "Review of PIRT (Phenomena Identification Ranking Table)" in the 4th meeting. In this series of meetings, a vigorous discussion was held among the many attendees from NRC and the system and safety design of the 4S were recognized by NRC.

In this study, the 4S with a thermal rating of 135MWt is applied to continuous steam production for recovery of bitumen from oil sands, and a steam production plant concept was established assuming Steam Assisted Gravity Drainage (SAGD) as the bitumen recovery method. In this paper, a steam production plant applying to the 4S with a thermal rating of 135MWt is hereinafter called "4S-

135MWt" although the 4S with a thermal rating of 135 MWt can also be designed to supply electricity for the requirements of the SAGD plant and the house loads of the 4S-135MWt itself and to supply heat for hydrogen production for upgrading of the bitumen.

2. Design principle

The 4S-135 MWt provides only steam with the preferable temperature for an SAGD plant and it doesn't generate any electricity in order to supply steam stably with higher plant availability. Electricity requirements for the SAGD plant and the electrical house loads of the 4S-135MWt are assumed to be supplied by a conventional facility and ignored in this study.

Although SAGD plants vary in their steam conditions, general steam temperature is around 300 degree C [60]. Since it is saturated, the steam pressure is primarily determined by steam temperature. Condition of the steam delivered from the 4S-135MWt to the SAGD plant was set to be 310 degree C and 10 MPa in consideration of a certain temperature loss between the 4S-135MWt and the SAGD plant.

The core life time of the 4S-30MWt is 30 years in order to eliminate refueling during a plant life time. Meanwhile, target of the refueling interval of the 4S-135MWt reactor was set to be 10 years because a typical operating duration is about 10 years in a specific mine lot of the SAGD plant.

3. System design overview

The 4S has passive safety features achieved by passive heat removal capability, and negative temperature reactivity feedback in the core. Maintenance requirements are minimized by utilizing an electromagnetic (EM) pump with no moving parts. Long life core is achieved by adopting metallic fuels and reflector control mechanisms. Overview of the 4S-135MWt system is described below.

3.1 Overall plant

System configuration of the 4S-135MWt is shown in Figure 1. Heat transport systems of the 4S consist of the primary heat transport system (PHTS), the intermediate heat transport system (IHTS) and the water/steam system.

The 4S is a pool-type reactor. The primary coolant flows inside the reactor vessel. The reactor vessel includes the intermediate heat exchanger (IHX), two EM pumps, internal structures, a core and shielding. The containment system consists of a top dome and a guard vessel, which encloses the entire PHTS. A schematic cross-section view of the reactor building is shown in Figure 2. The reactor system and the IHTS are located in the reactor building. The reactor building itself is supported by seismic isolators, which provide horizontal seismic isolation. This seismic isolation system provides flexibility for siting.

Plant design parameters of the 4S-135MWt are listed in Table 1.

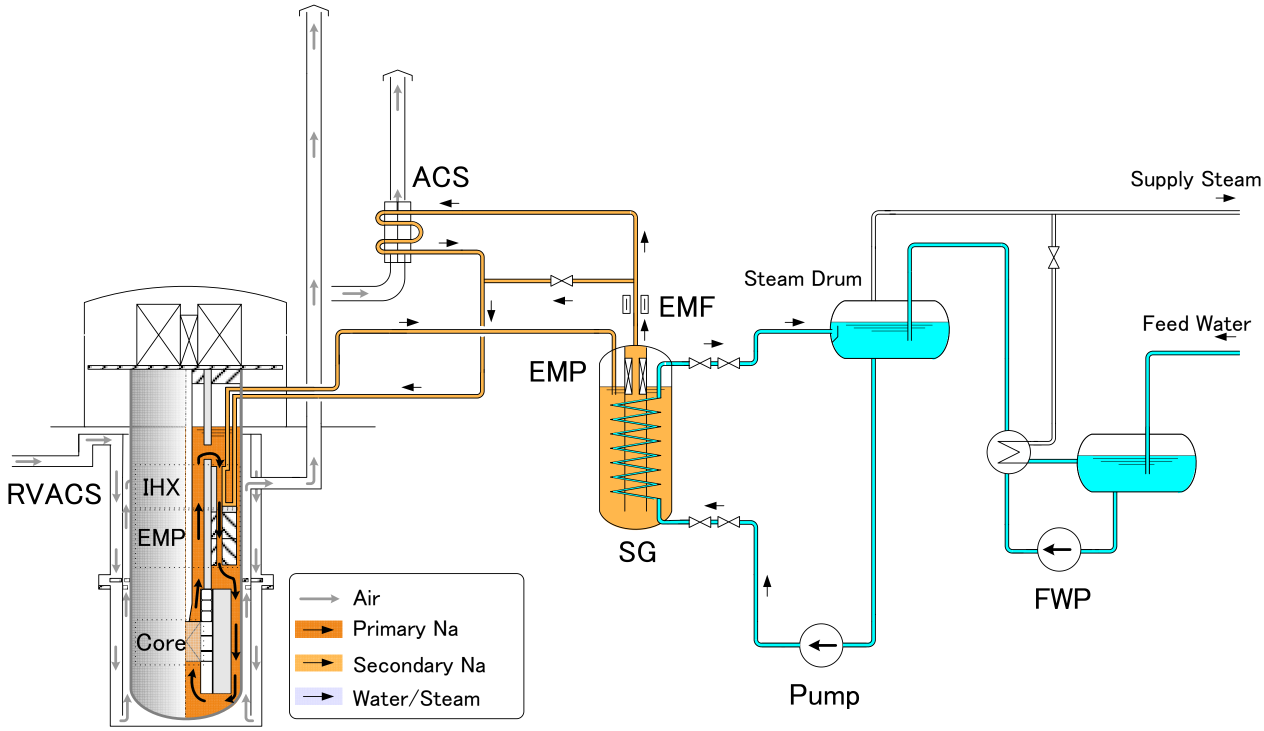

Figure 1 System configuration of the 4S-135MWt [59]

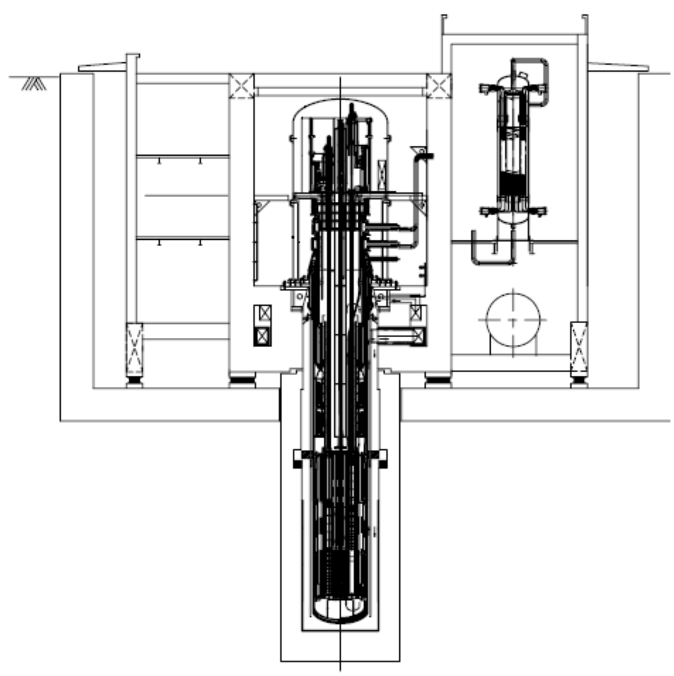

Figure 2 Section view of reactor building [53]

Table 1 Plant design parameters

Type	Sodium cooled fast neutron reactor (pool type)
Electric Output	—
Thermal Output	135 MWt
Number of Loops	1
Plant / Fuel Life Time	30 / 10 years
Fuel / Clad Material	U-10%Zr / HT-9
Primary Sodium Inlet / Outlet Temperature	355 / 510 degree C
Steam Condition (between the 4S-135MWt and SAGD plant)	310 degree C, 10.0 MPa
Supply Steam Flow Rate (between the 4S-135MWt and SAGD plant)	238 t/h
Decay Heat Removal System	RVACS + IRACS
Reactivity Control System	Reflector Controlled
Primary EM Pump	Single stator type Linear annular induction type
Intermediate Heat Exchanger (IHX)	Vertical shell-and-tube type Straight tube
Steam Generator	Double wall tube with wire mesh helical coil type
Reactor Vessel Dimension	Inner diameter : 3.6 m Total height : 25m
Reactor Building Dimension	31 m Long, 25 m Wide, 22 m High

3.2 Reactor and core

The reactor assembly of the 4S is shown in Figure 3. The configuration of the reactor assembly and the core in the 4S-135MWt is the same as in the 4S-30MWt. The reactor assembly mainly consists of a core, primary EM pumps, an IHX, reflectors and a shutdown rod.

The core consists of 18 fuel assemblies and one central assembly including a shutdown rod and fixed absorbers. The fuel material is U-10% Zr alloy, and the cladding and duct of the fuel assembly is made from HT-9. The reactivity and power of the reactor are controlled by cylindrical reflectors surrounding the core. The reflector has a sufficient worth to enable shutdown without using any additional means. In addition, the shutdown rod has a sufficient worth itself to bring the core to subcriticality under cold conditions.

The target for the refueling interval was set to be 10 years as previously mentioned.

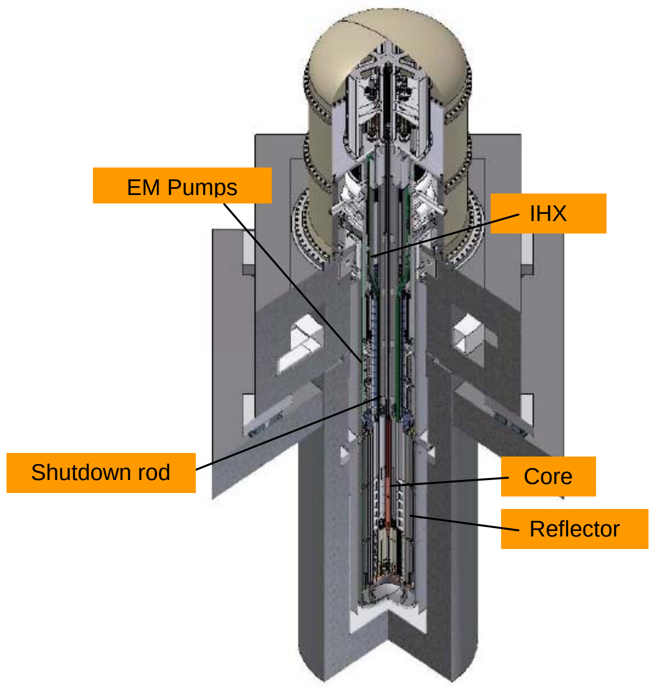

Figure 3 Reactor assembly of the 4S [55]

3.3 Heat transport system

3.3.1 Primary heat transport system

The configuration of the PHTS in the 4S-135MWt is the same as in the 4S-30MWt. The primary coolant flows inside the reactor vessel. The coolant from the core flows up through the central part of the reactor outlet plenum and flows into the IHX. The coolant descends in the IHX and then in the primary EM pumps in the annular region of the peripheral part of the reactor outlet plenum, and flows into the core through the shielding zone and the lower plenum.

3.3.2 Intermediate heat transport system

The IHTS mainly consists of a steam generator (SG), a main circulating EM pump, an electromagnetic flowmeter (EMF) and an air cooler of the intermediate reactor auxiliary cooling system (IRACS). The IRACS is installed in parallel with a sodium valve in the cold leg of the IHTS in the 4S-135MWt whereas it is in series in the cold leg of the IHTS in the 4S-30MWt, because of the increment of intermediate coolant flow rate. The sodium valve is usually opened and most of the intermediate coolant flows through the sodium valve during normal operation.

The steam generator consists of helically coiled double wall heat transfer tubes with wire mesh. The double wall tube with wire mesh enables continuous monitoring of single side leakage of the heat transfer tube and the probability of sodium/water reaction caused by heat transfer tube failure from both sides can be reduced significantly.

In the 4S-135MWt, an EM pump enclosed within the steam generator was adopted in order to reduce the overall footprint of the IHTS. The main circulating EM pump is installed inside the internal cylinder which composes the riser piping from the heat transfer tube bundle of the steam generator.

3.3.3 Water/Steam system

The system configuration of the water/steam system in the 4S-135MWt differs from that in the 4S-30MWt. The recirculating-type steam generator system was adopted in the water/steam system of the 4S-135MWt. This type of system provides a stable supply of saturated steam at 310 degree C from the steam drum.

3.4 Decay heat removal system

System configuration of the decay heat removal system (DHRS) in the 4S-135MWt is the same as in the 4S-30MWt. DHRS in the 4S consists of reactor vessel auxiliary cooling system (RVACS) and the IRACS. The RVACS removes decay heat with natural convection from air outside the reactor guard vessel. The IRACS removes decay heat by using an air cooler in the IHTS.

4. Performance and advantage

4.1 Bitumen production capability

Steam requirements for SAGD depend on the steam to oil ratio (SOR). SOR is typically between 2 and 4 [60]. The 4S-135MWt supplies 238 t/h of steam. Bitumen production capability was calculated on the basis of this steam supply capacity. Calculation results are shown in Table 2 and Figure 4.

Bitumen production capacity of existing or currently-projected oil sands recovery plants is generally from several tens of thousands to hundreds of thousands bpd (barrel per day) [61]. Many plants start at a smaller production rate than final design capability, and increase the production rates in stages. Adopting a modular construction model, one or more reactor modules are constructed in the first stage and then the other reactor modules are incrementally constructed in accordance with the expansion of the bitumen production rate of the SAGD plant. Common auxiliaries, such as refueling and spent fuel storage facilities, can be shared among the reactor modules.

Table 2 Bitumen production capability of the 4S-135MWt

Steam Production	238 t/h 36,000 bpd (57,234 m^3/day)
Bitumen Production Capability (SOR=2)	18,000 bpd (28,617 m^3/day)
Bitumen Production Capability (SOR=3)	12,000 bpd (19,078 m^3/day)
Bitumen Production Capability (SOR=4)	9,000 bpd (14,309 m^3/day)

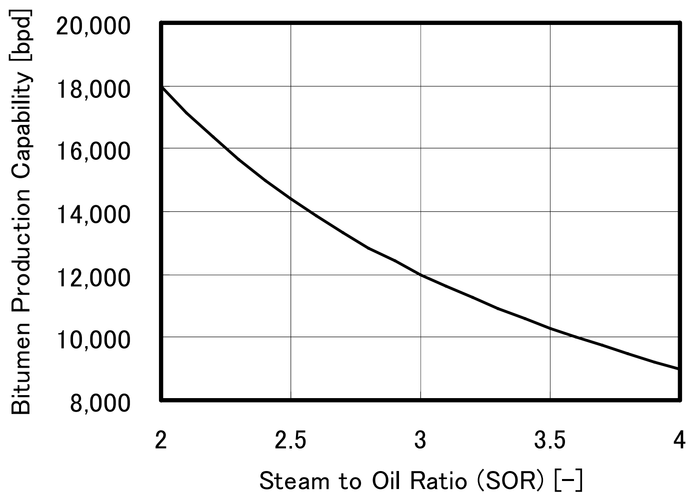

Figure 4 Bitumen production capability of the 4S-135MWt

4.2 Plant availability

The 4S minimizes maintenance requirements by adopting EM pumps. Moreover, an outage of the 4S-135 MWt is very short because it is designed only for steam production and it does not have a turbine generator. The outage for refueling and other maintenance of the 4S-135MWt is expected to be no more than one month. A full power period of operation is equal to the refueling interval and it is approximately 120 months. Predicted lifetime availability of the 4S-135MWt is calculated by 120 / (120+1) = 99%.

4.3 Reduction of greenhouse gas emissions

Existing SAGD plants use about 1.0 - 1.5 Mcf (thousand cubic feet) (28.3 - 42.5 m^3) of natural gas for each barrel of bitumen production [60]. By applying the 4S-135MWt to steam production for SAGD, greenhouse gas (GHG) emissions are reduced by about 400,000 ton of CO2 / year / reactor.

This study focuses only on steam production, but the 4S with a thermal rating of 135 MWt can also be designed for the electricity supply and/or the heat supply for hydrogen production. The 4S with a thermal rating of 135MWt produces hydrogen efficiently because the core outlet temperature is higher than a CANDU or LWR. A significant amount of hydrogen is required to upgrade the bitumen. GHG emissions can be reduced further by applying the 4S with a thermal rating of 135 MWt to hydrogen production or replacing the 4S-135MWt of the steam supply type with the hydrogen production type after depletion of the initial oil sands fields.

4.4 Modular construction

Several modules of the 4S-135MWt are constructed in stages in accordance with the design capacity and expansion program for bitumen production in a specific SAGD plant. The common facilities, such as refueling and spent fuel storage facilities are not necessary to be completed in the initial stage and can be constructed in accordance with additional construction of the 4S-135MWt modules. These construction procedures reduce the initial capital cost and the risk associated with expansion of bitumen production. By adopting a modular design, the 4S-135MWt is standardized and the construction cost per module can be reduced.

Modular construction allows that some modules are designed for the steam supply and the rest of the modules are designed for the electricity supply for the SAGD plant and the house load of the modules themselves. In that case, the capital and O&M costs are slightly larger than in the case of modules only for steam supply because of the turbine / generator portion for the electricity supply.

In the case of applying a nuclear plant to Canadian oil sands extraction, there are some factors affecting the construction cost, such as the specific site conditions and climate. That is, the remoteness of the site may increase delivery cost of components and some construction activities would be limited to shorter time frames within each year due to the severe weather conditions. However, the heaviest component (reactor vessel) of the 4S-135MWt is less than 100 tons and all the components can be delivered by truck. The construction schedule is planned to be less than 24 months.

5. Conclusion

The concept of a steam production plant consisting of the 4S-135MWt for a typical SAGD (Steam Assisted Gravity Drainage) plant was established. The 4S, provided for oil sands recovery, will significantly reduce greenhouse gas emissions and has applicability to the oil sands plant. The burden for development and licensing will be reduced in tie-ups with the development and licensing program for the 4S-30MWt which is now in the process of pre-application review by U.S. NRC.

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