Progress in Nuclear Energy 83 (2015) 433–442

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: www.elsevier.com/locate/pnucene

Advanced passive design of small modular reactor cooled by heavy liquid metal natural circulation

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ARTICLE INFO

Article history:
Received 30 September 2013
Received in revised form
17 August 2014
Accepted 4 January 2015
Available online 6 April 2015

Keywords:
Small modular reactor
Fast reactor
Long burning cycle
Lead–bismuth eutectic
Natural circulation
Passive safety

ABSTRACT

We applied a passive cooling feature to both normal and abnormal operations of a small modular reactor (SMR) without external power sources and reactor coolant pumps. The SMR, named as URANUS, with a thermal power rating of 100 MW is well suited as a distributed power source because it has a refueling interval of 20 years without assembly reconfiguration. This reactor is a pool type fast reactor with an array of heterogeneous hexagonal core using UO_2 fuels. Material corrosion is limited by using corrosion-resistant materials and keeping acceptable low outlet temperature in combination with an oxygen control technique. The reactivity swing during the core lifetime is less than $1 without burnable poison rods to minimize excess reactivity. Three-dimensional seismic isolators are deployed underneath the entire reactor building allowing an earthquake of 0.5 g zero period acceleration for the safe shutdown earthquake. The adoption of the complete passive safety systems enhances the safety performance of the reactor, but simultaneously limits volume power density and discharge burn-up. Thus, the future study on this reactor will focus on the power maximization of the reactor while maintaining land transportable sizes and coolant natural circulation.

1. Introduction

The growth of emerging economies in Asia including China and the Middle East was a main driving force for the rapid expansion of nuclear power up to the outbreak of the Fukushima accident in 2011 (Choi et al., 2009). The Fukushima accident suggested that the current active safety systems in nuclear power plants may not be reliably performed during beyond design basis accidents. A highly complex system like a nuclear power plant is now required to meet enhanced social demands for proliferation resistant, environmental friendly, and accident tolerant technology. We attempted to apply a passive cooling feature to both normal and abnormal operations of a small modular reactor (SMR) without external power sources in order to resolve the deficiency of passive safety capability in large-scale reactors (Cho et al., 2011; Choi et al., 2011a, 2011b).

An SMR has been recognized as an innovative product for niche markets where large-scale nuclear reactors are unstable for technical, economic, and safety limitations (Abderrahim et al., 2001; Adamovich et al., 2007; Chang et al., 2005; Choi et al., 2011a; Fetterman et al., 2011; Hwang et al., 2000; Kim et al., 2001; Peterson et al., 2008; Reyes and Lorenzini, 2010; Smith et al., 2008; Toshinsky et al., 2002; Ueda et al., 2005; Wade et al., 2002). The niche markets include a sparsely populated off-grid region, an off-grid industrial complex, a seawater desalination process, and a district heating system (Choi et al., 2011a; Kuznetsov, 2008). To ensure nonproliferation and nuclear security, many SMR concepts require no on-site refueling strategy and adopt cradle-to-grave fuel services. Because these approaches increase the frequency and difficulty of fuel transportation from a reactor site to a vendor plant, several SMRs aim at realizing a long-burning fuel cycle.

This paper conceptualizes a lead–bismuth eutectic (LBE) cooled SMR, named as Ubiquitous, Rugged, Accident-forgiving, Non-proliferating, and Ultra-lasting Sustainer (URANUS) with a thermal power rating of 100 MW. The refueling interval is 20 years without assembly reconfiguration. This reactor is a pool type fast reactor with an array of heterogeneous hexagonal core (Choi et al., 2011b). The coolant is chemically inert, and has good neutron characteristics and a high boiling point. To avoid the unexpected common failures of active safety systems, the primary cooling system is

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http://dx.doi.org/10.1016/j.pnucene.2015.01.002

operated without reactor coolant pumps. Material corrosion is limited by using corrosion-resistant materials in combination with an oxygen control technique (Ballinger and Lim, 2004; Fazio et al., 2001; Hwang et al., 2000; Li, 2008; Müller et al., 2000; Sekimoto and Su'ud, 1995; Takahashi et al., 2008). The entire reactor containment and its heat transport systems are seismically isolated from the ground through 3D based isolators.

This paper highlights a detailed overview of the URANUS systems to share it with plant designers, business planners, and policy makers. After presenting design goals and constraints in Section 2, Section 3 describes the design of reactor core and its steady-state and kinetic characteristics. Section 4 offers the description of primary and secondary heat transport systems and the results of thermal-hydraulic analysis. Section 5 includes the design description of vessels, fuel rods, and seismic isolators.

2. Design goals and constraints

This section first identifies the advantages and challenges of LBE-cooled fast reactor systems, and then presents design goals and constraints.

2.1. Overview of heavy liquid metal coolant reactor technology

Compared to water, metal coolants have a higher thermal conductivity and a lower specific heat capacity. Also, the kinematic viscosity of metal coolants is considerably smaller than that of air or water. Among the metal coolants, lead and lead-alloys can significantly reduce the risk of coolant boiling because of their high boiling points (for example, 1,749 °C for lead, 1,670 °C for LBE). They are also compatible with water, steam, air, and CO_2 excluding the possibility of fire or explosions. In addition, LBE has a low melting point (123.5 °C) that limits concern about flow channel blockages by coolant freezing. The high inertia characteristics of LBE coolant result in a strong driving force for fully passive cooling systems without reactor coolant pumps. With these advantages, lead alloy-cooled fast reactor (LFR) systems were selected in the Generation IV International Forum (GIF).

A drawback connected with LBE is the accumulation of the alpha-emitter ^{210}Po ($T_{1/2}$ = 138 days) produced from the neutron capture of ^{209}Bi. Many methods to remove ^{210}Po from PbPo compounds have been developed such as distillation, hydride stripping, alkaline extraction, rare-earth filtration, and electro-deposition. In addition, the heavy liquid metal coolant (HLMC), ten times heavier than sodium and water coolants, requires better seismic isolation systems. Until now, the corrosion issues of LBE have been extensively explored. FeCrAl and FeCrSi alloys were developed to increase corrosion resistance in high temperature and strong radiation environments. The studies to improve their mechanical characteristics are in progress by using a FeCrAl or FeCrSi alloy as coating or overlay welding. Also, FeCrAl or FeCrSi based oxide dispersion strengthened (ODS) steels may solve corrosion and mechanical problems (Hosemann et al., 2008; Kimura et al., 2011; Takaya et al., 2012).

Table 1
Design parameters of URANUS.

Design parameters	Values or characteristics
Thermal power	100 (MWt)
Refueling interval	20 (years)
Plant design lifetime	60 (years)
Primary coolant	Lead–bismuth eutectic
Primary heat transport system	Compact pool type
Core configuration	Open hexagonal array
Primary normal cooling mode	Fully natural circulation
Normal decay heat removal	Coolant natural circulation in the primary system combined with water/steam forced circulation in the secondary system
Abnormal decay heat removal	Reactor vessel auxiliary cooling by air
Fuel	UO_2
Cladding	HT-9 or T-91 overlaid with Al containing ferritic steels
Steam generators	8 modules of straight shell-tube type
Secondary water/steam cycle	Rankine cycle with superheated steam
Seismic design	3D based isolators

2.2. Design goals and constraints

Table 1 shows the key design parameters of this reactor. These design parameters were calculated based on 4 design goals for ensuring technical, operational, and economic performance:

1) The reactor is required to produce 100 MWt;
2) The length of one cycle is 20 effective full power years without fuel refueling or assembly reconfiguration;
3) Geometrical configurations permit full heat removal by only coolant natural circulation by reducing pressure loss;
4) The diameters of reactor vessel and active core are respectively smaller than 4.5 m and 2 m for ensuring land-transportable sizes.

Previously, we developed a conceptual SMR design with similar design goals (Choi et al., 2011a). The first design goal, 100 MWt, can be adjusted to reach the goal of electric power rate when the system analysis is completed with a detailed secondary system design. Major changes were made for key design specifications. The changes include the following:

1) From metal fuels to oxide fuels;
2) From recycled U-TRU-Zr fuels to enriched uranium fuels;
3) From a square assembly to a hexagonal assembly.

Design constraints were selected for safe and secure operation with sufficient margins without thermal, radiation, material, and structural failures (Choi et al., 2011a; Nam et al., 2007). The thermal design constraints are:

1) Fuel centerline temperature at the hottest rod must not exceed the melting temperature of UO_2 fuel, 2,865 °C, with sufficient safety margin during all operating conditions including design basis accidents;
2) Peak cladding temperature must not exceed the melting point of HT-9 or T-91 cladding overlaid with Al containing ferritic steels, 1,500 °C, with sufficient safety margin;
3) Inherent negative reactivity feedback has to be secured with sufficient safety margins under all operating conditions to prevent fuels from melting down (Choi et al., 2011a);
4) Reactivity swing has to be less than $1 without burnable poison rods to minimize positive reactivity insertions in the case of control assembly withdrawal without scram (Choi et al., 2011a);
5) Decay heat can be removed passively by the reactor vessel auxiliary cooling system (RVACS) which uses air cooling in accident conditions (Choi et al., 2011a).

The radiation design constraints are:

1) Peak discharge fuel burn-up is required to be as large as possible, but is limited not to exceed an experimentally verified value, 100,000 MWd/MTU (Astegiano et al., 2004);
2) Fast neutron fluence is limited not to exceed an experimentally verified value to avoid material embrittlement caused by radiation damage and to ensure fuel cladding integrity (Nam et al.,