Progress in Nuclear Energy 83 (2015) 294–304

Contents lists available at ScienceDirect

Progress in Nuclear Energy

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

A passive decay heat removal system for the lead cooled fast reactor demonstrator "Alfred"

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ARTICLE INFO

Article history:
Received 9 July 2014
Received in revised form
27 March 2015
Accepted 11 April 2015
Available online 16 May 2015

Keywords:
Decay heat removal system
Safety
Bayonet heat exchangers

ABSTRACT

The generation IV lead cooled fast reactors are of particular interest for the Italian research. At present, one significant European project in progress is LEADER (Lead cooled European Advanced DEmonstrator Reactor) which includes, among its goals, the construction of a lead-cooled fast reactor demonstrator, ALFRED (Advanced Lead Fast Reactor European Demonstrator). The demonstrator provides technical solutions that simplify the construction phase and assure full safety in operation; according to the latest guidelines, ALFRED final configuration will be characterized by a secondary loop providing bayonet-tube steam generators. In a previous paper, the Authors proposed the EBBSG (External Boiling Bayonet Steam Generator) system, in which the reaction heat is extracted from the lead by means of coolant under vapor phase. In the present paper, the Authors propose a decay heat removal (DHR) system to match the EBBSG scheme. The DHR system is fully passive, exploiting natural circulation phenomena. The performance of the system is investigated through a Matlab–Simulink model. The results are satisfactory since, according to simulations, the proposed DHR system is able to keep the primary coolant temperature within a safety range for a sufficient time, avoiding the lead freezing or over-heating.

1. Introduction

After the conclusion of the ELSY (European Lead-cooled System) (Alemberti et al., 2009, 2011) program, the research on the generation IV lead cooled fast reactors is going to be continued with the LEADER (Lead Cooled European Advanced DEmonstrator Reactor) program, planned to refine the design of the large-scale lead fast reactor according to the ELSY results obtained.

Among its goals, the LEADER program includes the conceptual design of the ALFRED (Advanced Lead Fast Reactor European Demonstrator) small-scale demonstrator. ALFRED is conceived as a pure lead pool type reactor, of 300 MW thermal power, based on the present day technology to permit construction and marketing by 2025.

To achieve the aims of safety and reliability, the ALFRED demonstrator has been conceived from the beginning to meet the principle of passive safety. Devices based on external energy sources are avoided, being more likely to fail. The feature of passive safety is required for both the primary and the secondary loop.

One of the most recent design proposals for the ALFRED secondary loop consists in the utilization of bayonet-tube steam generators equipped with an efficient rupture detection system (De Fur, 1975; Belloni et al., 2011); the latter consists of two steel layers within the outer pipes of the bayonets, separated by a gap where pressurized helium (contained in a dedicated plenum) can permeate; the gap is filled with microspheres of conductive material, such as aluminum or industrial diamonds, in order to compensate for the gas low conductivity (Raffray et al., 1989; Slavin et al., 2000). In case of failure, only one of the two metal layers composing the external pipe is expected to break, exposing the helium layer to make contact with either lead (in case of external layer rupture) or steam (in case of internal layer rupture) and causing a helium pressure variation, easily detectable by sensors positioned in the gas plenum. This allows the damaged steam generator to be identified and isolated (Damiani et al., 2013).

The possibility of a continuous fault monitoring during operation allows the steam generators to be included as components of a decay heat removal (DHR) system. One example of a passive DHR device including the steam generators in the emergency reactor

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http://dx.doi.org/10.1016/j.pnucene.2015.04.005
0149-1970/

core cooling loop is described in Leoncini et al. (2009) and Burgazzi (2002).

In the present paper, the Authors apply a fully passive DHR device to the External Boiling Bayonet Steam Generator (hereinafter EBBSG) system, already described in Damiani et al. (2014), intended as an alternative to the classical steam generators. The proposed passive safety system, named Steam Natural Circulation–Decay Heat Removal (hereinafter SNC–DHR), fully relies on natural circulation, and is designed to assure the removal of the decay power produced in emergency situations, avoiding lead overheating (temperature overcoming 550 °C (Weisenburger et al., 2011)) or freezing (temperature below 327 °C) for a sufficient time without the intervention of operators.

The operation of the SNC–DHR system was investigated through a dynamic simulation model implemented in the Matlab–Simulink environment, in order to understand the variation in time of the parameters related to the physical phenomena involved. The results presented are satisfactory.

2. The EBBSG system

The EBBSG (External Boiling Bayonet Steam Generator) system, utilized in the ALFRED reactor secondary loop, joins together the two solutions of the known Loeffler indirect boiling system and of the bayonet-tube heat exchangers. The EBBSG system scheme is depicted in Fig. 1.

As described in Damiani et al. (2014), a large part (over 74%) of the steam superheated in the bayonet heat exchangers enters in contact with the feed-water in the steam drum (this last presenting a sub-cooling of 5 °C) coming from the pre-heaters. The mixing, in the correct proportions, between feed-water and superheated steam produces a saturated steam flow-rate equal to the sum of the two original flow-rates; such steam is delivered through a steam blower to the bayonet heat exchangers, where superheating occurs by heat exchange with the lead. Through a correct sizing of the bayonets, the superheated steam rising in the annulus can raise the temperature of the descending steam in the central pipe up to a sufficient temperature above lead solidification.

The main advantages of the EBBSG system are: the lower secondary fluid pressure with respect to the classical system in which the phase change occurs into the steam generator; the vapor-only

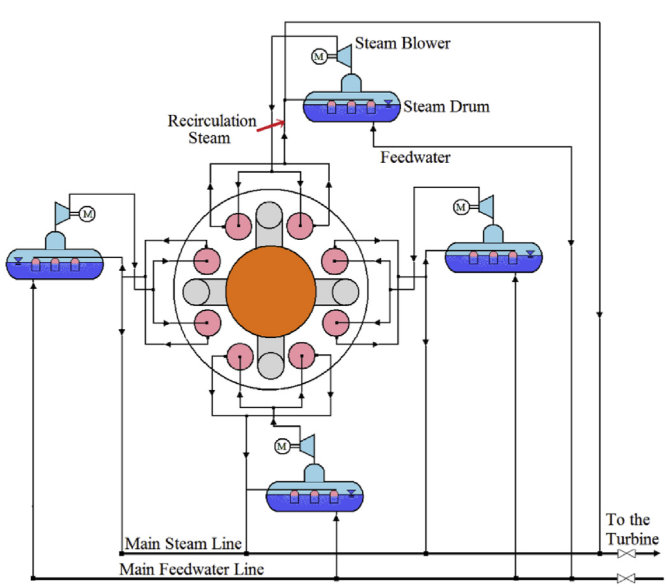

Fig. 1. Lead-cooled reactor secondary loops, composed by four EBBSG systems.

flow in the heat exchanger inside of the reactor vessel, assuring a higher safety in case of pipe rupture, since the explosive phenomenon of the liquid water flashing is avoided; the absence of phase change in the heat exchanger, allowing the use of a noise detection system instead of the helium gap to individuate the potential leakages in case of a heat exchanger pipe cracking.

The main disadvantages are: the necessity of a steam blower and the larger size of the lead-steam heat exchangers, influencing negatively the vessel diameter.

Among the reactor geometries agreed in the course of the international projects for lead cooled reactors, the Authors assumed the configuration visible in Fig. 1, providing a central core and four groups comprising one central lead pump feeding two circular bayonet heat exchangers; the aforementioned groups are linked to four Loeffler steam drums, thus providing four separated EBBSG systems.

The secondary loop designed for the ALFRED lead reactor, more widely described in Damiani et al. (2014), is characterized by an evaporation pressure of 80 bar in the steam drums and a live steam temperature of 450 °C; as in the traditional nuclear plants a live steam re-heating is effected downstream of the high pressure expansion, at a pressure of 9 bar. The plant main features and performance are indicated in Table 1.

3. Natural circulation DHR system: operation principle

In case of a severe plant failure, the emergency control system provides the actuation of the reactor shutdown (SCRAM) and the turbine trip. From this instant on, the reactor core produces the thermal power owing to decay reactions, which decreases in time with exponential law.

If the plant condenser and the steam blowers are still available, the decay heat is removed through the non-safety grade water-steam system. In case of unavailability of the water-steam loop, for example if the failure affects more than one blower or the plant main condenser, the emergency DHR system described in the present paragraph is initiated.

The call of the SNC–DHR (Steam Natural Circulation–Decay Heat Removal system) starts with the isolation of the Loeffler loops, closing the interception valves on the feed-water line and on the main steam line. According to the EBBSG scheme (Fig. 1), a natural circulation may be established in the loop comprising the drum, the bayonet heat exchanger and the recirculation steam line, thanks to the density difference between a “cold leg” (saturated steam contained in the pipe connecting the drum to the bayonets inlet) and a “hot leg” (superheated steam contained in the pipe connecting the bayonets outlet to the drum), provided that a sufficient head *H* exists between drum and heat exchanger centers of gravity. This steam loop will transfer heat from the lead to the steam drum, from which a second loop is required to discharge the thermal power in the atmosphere. For this purpose, a solution providing an Isolation Condenser immersed in a cold water pool was here preferred to the Air Condenser proposed in Damiani and Pini Prato (2012). In the following, a more detailed description of the SNC–DHR system is provided.

3.1. Operation of the SNC–DHR in normal reactor conditions

Natural circulation will be established as hot leg and cold leg temperature (i.e. density) difference is sufficient to generate the force needed for steam motion. In order to maintain said temperature difference, during normal reactor operation a small superheated steam flow-rate $\dot{m}_0$ is delivered to the Isolation Condenser through the three-way valve V_1, as visible in Fig. 2a. Being such flow-rate very small, it is immediately condensed into water as it