Progress in Nuclear Energy 99 (2017) 127–139

Contents lists available at ScienceDirect

Progress in Nuclear Energy

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

Thermal hydraulic analysis of a passively controlled DHR system

M. Caramello [a, b, *], M. Gregorini [b], C. Bertani [a], M. De Salve [a], A. Alemberti [b], B. Panella [a]

[a] *Department of Energy, Politecnico di Torino, Corso Duca degli Abruzzi, 24, 10129 Torino, Italy*
[b] *Ansaldo Nucleare S.p.A., Corso F. M. Perrone 25, 16161 Genova, Italy*

ARTICLE INFO

Article history:
Received 7 January 2017
Received in revised form
10 May 2017
Accepted 16 May 2017

Keywords:
Passive safety system control
ALFRED
Fast reactor
Relap5
Thermalhydraulics
Liquid metals

ABSTRACT

The safe operation of nuclear reactors cooled by liquid metal is an important issue to be addressed for the development of nuclear technology and presents specific aspects related to the properties of the coolant. While the main parameters influencing safety for water-cooled reactors are reasonably well known, DHR systems for reactors cooled by liquid metal present additional challenges related to coolant freezing, since solidification temperature is higher than the temperature of the final heat sink. If the primary coolant solidifies obstructions of the primary flow path can occur, inhibiting natural circulation and core cooling. This paper presents an innovative passive safety system for decay heat removal which passively delays the coolant freezing. The system adopts noncondensable gases to passively control the power removed from the primary system and to delay freezing in the long term while keeping primary system temperatures below an acceptable limit. The system is simulated by means of the Relap5-3D computer code for a loss of offsite power of the innovative lead-cooled reactor ALFRED. A sensitivity analysis has been carried out in order to study the effect of noncondensable gas pressure on the performance of the passive decay heat removal system, and in particular on the primary coolant temperatures.

1. Introduction

In the framework of the development of Generation IV nuclear power plants safety is recognized as one of the main goals of these new projects and is considered one of the main aspects to increase public acceptance of the nuclear energy. These innovative plants promise to meet the guidelines proposed by the Generation IV international forum (USDOE, 2002), so to excel in safety minimizing the probability and magnitude of core damage and eliminating the need for off-site emergency response.

To achieve the previous goals, innovative safety systems for decay heat removal need to be developed. These systems must be able to remove the decay heat generated in the core in case of any accidental event. Considering the experience gained from commercial reactors and Generation III + reactors (IAEA TECDOC-1624, 2009), as well as from several experimental campaigns (Paladino and Dreier 2012; Reyes, 2006) and reliability studies (IAEA TECDOC-1752, 2014), an important feature to improve the safety is to adopt passive systems and components. It is well known that a passive system does not need external inputs for the operation (such as electricity) and relies on simple physical principles like gravity. Anyway, it is important to stress that, in accordance with IAEA standards, a passive system can still use active components in a limited manner, mainly to start the passive operation. In particular, actuation is allowed by means of an external energy, provided that it comes from an independent stored source, and active components are allowed (i.e. valves), provided that their operation is single-action and relies on stored energy. Under no circumstances, manual activation is permitted (IAEA, 2016).

Reliability studies can be helpful to understand the behavior of passive safety systems. In the reference IAEA TECDOC-1752 (2014), which has been reported above, there is, in particular, the citation of an interesting study of the passive system reliability of isolation condensers (Burgazzi, 2002). Mackay et al. (2008) included a time-dependent reliability analysis in the thermal-hydraulic safety study of a passive cooling system for a nuclear reactor cooled by helium. Uncertainties associated with core roughness, valves leak, heat transfer coefficients and inertia of rotating machines were propagated through a model of the plant developed by means of RELAP5-3D code. The mechanistic model by itself has allowed the observation of unique features of core bypass when decay heat removal systems are simulated independently, whereas the combination of input values of the parameters affected by uncertainty, which can

* Corresponding author. Department of Energy, Politecnico di Torino, Corso Duca degli Abruzzi, 24, 10129 Torino, Italy.
E-mail address: marco.caramello@polito.it (M. Caramello).

http://dx.doi.org/10.1016/j.pnucene.2017.05.015
0149-1970/

lead to clad damage or hot leg failure, has been determined by means of the reliability analysis.

The development of passive safety systems and their integration in innovative reactors has been object of several studies in literature.

Bandini et al. (2008) developed several analyses of the decay heat removal (DHR) system of EFIT, a pool-type reactor cooled by pure molten lead. Its DHR consists of four natural circulation loops containing an organic diathermic fluid (oil): each loop removes heat from the primary system by a bundle of bayonet tubes immersed in the primary coolant and releases it to the final heat sink by a finned air heat exchanger. The DHR was modeled by SIMMER-III system code and a modified Relap5/MOD3 version in order to evaluate its performance. Relap5/MOD3 has been modified by adding thermal and transport properties of liquid lead and suitable correlations to calculate the heat transfer coefficient for the liquid metal. Numerical simulations of protected[1] loss of heat sink (PLOHS) with both codes assuming the operation of 3 out of 4 loops demonstrated the capability of the system to correctly remove the decay heat and to limit the primary system temperatures.

Krepper and Beyer, 2010 studied both numerically and experimentally natural circulation systems using safety heat exchangers immersed in large pools (final heat sink). The results highlighted the occurrence of thermal stratification, which strongly affects the heat transfer to the pool. According to their study, thermal stratification is important during the first phase of the operation. When the water in the pool reaches saturation temperature stratification is broken thanks to the enhanced pool mixing due to boiling.

Parthasarathy et al. (2012) studied a safety DHR with reference to the Indian reactor PFBR. The system consists of a shell and tube heat exchanger housed in the primary system, connected to an air heat exchanger transferring heat to the environment. The safety system is actuated by opening air dampers on the chimney of the final heat sink. They developed a CFD model of the primary system and coupled it with a one-dimensional model describing the safety system. The study investigates the impact of the reactor design on the operation of the safety system. The figures of merit are the coolant temperature and the hot spot temperature; as a result, two elements can reduce temperatures as the safety system operates: the secondary systems for normal operation and the interwrapper flow between the fuel assemblies. If these terms are not considered in the modelling coolant and clad temperatures would be higher.

De Santis et al. (2013) proposed a passive component for the decay heat removal from the primary system of a pool-type liquid metal reactor. The component is a shell and bayonet heat exchanger. The outermost tubes of the bayonet are finned and vacuum is interposed between the fins, so that radiative heat transfer is the most important mechanism to remove power. Sensitivity studies performed by means of a commercial CFD code show that the most important parameter for heat removal is the coolant temperature, and that radiative heat transfer inhibits the heat removal when the primary system is at lower temperature.

Wang et al., 2013a developed a sub-channel analysis code named SACOS-PB based on conservation equations and semi-empirical closure equations to calculate the heat transfer coefficients and pressure drops due to friction, with the goal to analyze the steady state operation of ALBFR fuel assembly. The results show that the maximum clad and coolant temperatures are below design limits. The code has been compared against a novel analytical method to determine the optimum pitch-to-diameter ratio showing good results. Tian et al. (2013) developed a coupled neutronic and thermal-hydraulic code to study the behavior of PBWFR reactor under unprotected transient overpower, unprotected loss of flow and unprotected loss of heat sink. The results show that the reactor is adequately protected against loss of flow and loss of heat sink, thanks to the good thermal and neutronic properties of the coolant, whereas a lower safety limit is obtained against overpower event because of the limiting clad temperature.

Some examples of research activities are also on-going on passive systems devoted to light water reactors. Wang et al. (2013b) investigated the effectiveness of the passive Core Makeup Tank of CPR1000 design against Steam Generator Tube Rupture by means of the system code RELAP5/MOD3.4. The results show that the system, in conjunction with a passive residual heat removal, is able to keep primary system temperatures below saturated conditions. On a second paper, Wang et al. (2014) developed and investigated an alternative design of passive residual heat removal system for the Chinese pressurized reactor CPR1000. A heat exchanger is connected to the shell side of the steam generator, set in a stand-by condition during normal operating conditions. Actuation valves and water inventory for the safety system are located outside the containment building. Once actuated, the water in the storage tank can be used both to fill the tank of the heat exchanger or to provide water to the steam generator. A model of the primary system and the safety system has been developed by means of RELAP5/MOD3.4 code and both Station black out and Feedwater line break accident have been simulated. Results show that the system is able to effectively remove the decay heat from the primary system.

Decay heat removal systems for water cooled reactors must limit core temperatures according to the safety limits of the materials used. This is obviously true also for the case of liquid metal cooled reactors with an additional requirement: the DHR for liquid metal reactors must be designed taking into account coolant freezing. Coolant freezing may occur when the power removed from the primary system is higher than decay heat for a time sufficient to decrease the coolant temperature down to the solidification temperature. Solidified lead may constitute an obstruction for the natural circulation and therefore may hinder the core cooling. Moreover, lead freezing could induce additional mechanical stresses on structures. Therefore it is very important to prevent lead freezing, or at least delay its occurrence as much as possible, so that the decay heat reaches values so low that it could be removed by heat losses from the primary system without any integrity risk for the core. So to ensure both high power removal at the beginning of the transient and delay as much as possible of the liquid metal solidification, the heat transfer between the primary system and the safety system must be controlled. Obviously by definition the passive DHR system control cannot be achieved using active control systems, so that the only solution is to identify a physical phenomenon able to passively limit the heat exchange between the primary and the DHR system.

To the authors' knowledge, studies about passive systems for the removal of the decay heat able to prevent or at least delay lead freezing during the evolution of the accident are still lacking in the literature. The present work fills this gap of knowledge by suggesting a passive method to control the power removed by the DHR system.

A promising technique for a DHR system based on evaporation and condensation phenomena is to use noncondensable gases to passively limit the heat transfer of the safety system. It is well known that steam condensation can be strongly reduced by the presence of noncondensable gases, as reported for example by Silver (1947) and Colburn and Hougen (1934). Condensation inside vertical pipes in presence of noncondensable gases has been more recently studied for different pipe geometry in both forced and natural circulation (Akaki et al., 1995; Maheshwari et al., 2004; Oh

[1] A transient is protected when the correct operation of the control rods following the initiating event is assumed.