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# New steam generation system for lead-cooled fast reactors, based on steam re-circulation through ejector

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## HIGHLIGHTS

- Innovative steam generation system for lead-cooled fast reactors secondary loop.
- Water evaporation outside of vessel heated by recirculation steam in a surface exchanger.
- Steam recirculation occurs through steam jet ejector feeding bayonet heat exchangers.
- Improvement of safety, availability and efficiency with respect to Loeffler system (EBBSG).

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## ABSTRACT

The EBBSG (External Boiling Bayonet Steam Generator) system, proposed in previous publications, offers an alternative to the classical once-through high pressure steam generators. This system exploits the combination between the Loeffler external boiling scheme and the bayonet-tube steam generator and is expected to provide advantages in terms of safety while keeping good values of cycle performance and vessel size. The main disadvantages result in the increased size of the heat exchangers with respect to once-through steam boilers and in the need of steam blowers, as envisaged under the Loeffler scheme.

In the present paper, a new and more efficient system is proposed, in which the steam circulation is assured by steam-jet ejectors instead of blowers. The innovative solution, named SJ-EBBSG (Steam-Jet External Boiling Bayonet Steam Generator), is expected to provide several advantages with respect to the original scheme. In particular, the advantages envisage an increased global efficiency (+0.49% with respect to EBBSG) due to the lower power consumption of the auxiliaries and smaller size of the bayonet heat exchangers (−6.1% diameter, −7.3% length), other than increased safety and plant availability.

Throughout the article, the two steam generation solutions are compared and the advantages demonstrated by calculations.



## 1. Introduction

Within the Generation IV nuclear reactors projects [1–5], the interest in lead-cooled fast reactors design is increasing also in Italy [6–8]; presently, important Italian societies as Ansaldo Nucleare and ENEA are engaged in the development of the conceptual design of ALFRED (Advanced Lead-cooled Fast Reactor Demonstrator) demonstration facility.

The most recent research in the field of lead fast reactors secondary loops is presently focused on dynamic modeling for control and stability purpose [9–11], investigation on heat exchangers for decay heat removal purpose [12] and experimental investigations of natural circulation [13]. At present, new designs for the lead-cooled fast reactors secondary cycles are quite few in literature.

An original design proposal for the ALFRED steam generators envisages the use of once-through bayonet-tube components [8,14,15] in which feed-water is transformed into superheated steam at 180 bar. The choice of bayonet-tube steam generators is motivated by the possibility of introducing an efficient pipe rupture detection system consisting in the outer pipe of the bayonets equipped with two steel layers 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 [16,17]. In case of failure, only one of the two metal layers composing the external pipe is expected to break, exposing the helium layer to the contact with either lead (in case of external layer rupture) or steam (in case of internal layer

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**Nomenclature**

| | |
|---|---|
| $c_p$ | specific heat capacity (kJ kg$^{-1}$ K$^{-1}$) |
| $h$ | enthalpy of liquid water (kJ kg$^{-1}$) |
| $H$ | enthalpy of vapor water (kJ kg$^{-1}$) |
| $k$ | isentropic expansion coefficient (–) |
| $\dot{m}$ | mass flow rate (kg s$^{-1}$) |
| $M$ | local Mach number (–) |
| $M^*$ | critical Mach number (–) |
| $p$ | pressure (bar) |
| $u$ | ejector entrainment ratio (–) |
| $\eta$ | efficiency (–) |

*Subscripts*

| | |
|---|---|
| $a$ | driven fluid |
| $B$ | blower |
| $C$ | convergent duct |
| $D$ | diffuser |
| $L$ | de Laval nozzle |
| $m$ | driving fluid |
| $p$ | pre-heated-feed-water |
| $R$ | recirculation |
| $T$ | related to the secondary cycle |

rupture); the consequent pressure variation is easily detectable by sensors positioned in the helium plenum, allowing to individuate and isolate the damaged steam generator.

The solution of bayonet-tube steam generators inspired the idea of the EBBSG (External Boiling Bayonet Steam Generator) system, widely described in [18,19]; this solution allows a gaseous-phase only flow through the heat exchangers in contact with lead, coupling the idea of bayonet tubes with the Loeffler external boiling scheme. The advantages in terms of reactor safety are evident: indeed, 80 bar steam is expected to cause less structural damages than water at 180 bar or more, as this last tends to flash and determine an explosive volume increase inside the pool. In addition, the absence of a phase transition in the bayonets permits to avoid installing a double wall helium layer rupture detection system, replaced by a much simpler and more economical noise detection system [18,19] (pressure wave, ultrasounds, etc.). Other advantages involve the large thermal reservoir constituted by the Loeffler steam drum, capable to mitigate problems connected to accidental feed-water temperature variations, and the structural benefits deriving from the lower pressure insisting on the bayonets support plate of the heat exchanger. The previous paper [18] demonstrated the EBBSG system suitability compared to three other secondary loops, namely a helium, a supercritical carbon dioxide and a supercritical water solution.

The main weakness of the EBBSG system is the presence of the blower required for steam circulation in the Loeffler loop. In the present paper, the authors propose a solution for assuring steam circulation with no need of installing steam blowers, by exploiting the properties of steam-jet ejectors.

The solution was named Steam-Jet External Boiling Bayonet Steam Generator (hereinafter, SJ-EBBSG). The innovation stands in the fact that this solution represents a new type of reactor secondary loop, changing completely the EBBSG steam re-circulation scheme as will be explained in the following.

In the course of the present paper, the SJ-EBBSG scheme is presented and described in detail and the comparison with the EBBSG system is provided in terms of performance, through the design of a reference secondary cycle, and in terms of size of the heat exchangers. As will be demonstrated by calculations, among the other improvements, the new cycle is expected, in theory, to increase the plant performance because it eliminates the energy-consuming blowers: indeed, according to the calculations carried out, global efficiency slightly increases with respect to the EBBSG.

## 2. The SJ-EBBSG system

In this paragraph is described the operating principle of the SJ-EBBSG system, which is compared with the EBBSG system from which it derives, in order to highlight its strengths with respect to the original scheme.

### 2.1. Description of the system

The EBBSG system description is here repeated for clarity, being the starting point for the SJ-EBBSG scheme development. The EBBSG scheme is represented in Fig. 1.

Evaporation occurs outside of the bayonet lead-steam heat exchanger, which has the only function of superheating the saturated steam to the required temperature. To achieve the external evaporation, the known Loeffler boiler scheme is employed, according to which a superheated steam flow (thermodynamic state 2), $\dot{m}_R$, is mixed in a drum with the feed-water pre-heated in the regenerators (flow rate $\dot{m}_T$ at the thermodynamic conditions $p$). The mixing of the two streams in a large volume determines saturation conditions; therefore, a saturated steam flow-rate at state 0, equal to the sum of the two entering flow-rates, leaves the drum. To ensure the steam circulation in the loop, a steam blower is required to contrast the pressure drops.

The saturated steam at state 1 descends through the bayonets inner pipes, is heated up by the heat exchange with fluid rising in the annulus and arrives at the bottom of the bayonets with a temperature of 330 °C, while avoiding lead solidification. The heat exchange between lead and steam occurs in the bayonets annulus. A correct sizing of the bayonet heat exchanger allows to achieve the desired super-heating of the steam flow, up to state 2. The occurrence of these phenomena was demonstrated in [18].

The main weakness of the simple EBBSG scheme is the necessity of a steam blower, required to overcome the pressure losses (assumed as 3 bar in total) in the recirculation loop. The blower is a critical component in terms of reliability and penalizes the plant global efficiency, owing to the remarkable power spent to compress a gaseous state fluid.

To eliminate the steam blower, a different scheme was introduced, in which the fluid motion in the loop is ensured by a steam-jet ejector as represented in Fig. 2.

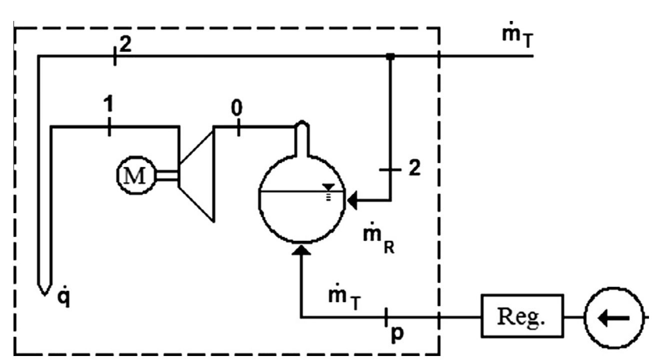


**Fig. 1.** Scheme of the steam-recirculation EBBSG system.