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Transient analysis of SIRIO using RELAP5/MOD3.3 system code

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Abstract. The main outcome of the present paper is the feasibility analysis of SIRIO (Sistema di rimozione della Potenza di decadimento per Reattori InnOvativi) facility with conditions based on those of its reference facility. The aim of SIRIO project is to study an innovative Decay Heat Removal System (DHRS) for liquid metal reactor and advanced Light Water Reactor (LWR). Such system must ensure passive control of the power removed from the primary system in abnormal condition, and must ensure reactor cooling in both short and long term. This study present numerical simulations developed with RELAP5/MOD3.3, of two operational procedures: the first one is a steady-state and the second one is a transient phase with decay heat generation. The thermal-hydraulic model, developed with RELAP5/MOD3.3, simulates the whole facility including lines, valves, water and gas tanks, and the Molten Salts (MS) gap. Since there is not experimental data, the present paper is a pre-test study based on SIRO facility design.

Key words: *natural circulation, in-pool heat exchange, isolation condenser, passive safety systems, passive self-regulation, heat exchanger, lead cooled fast reactor*

1. Introduction

The SIRIO project is partially funded by the Italian Ministry of Economic Development and is developed by a consortium of research institution (ENEA) and industrial companies (Ansaldo Nucleare, SIET, SRS). The aim of the project is to study an innovative Decay Heat Removal System (DHRS) for liquid metal reactors and advanced LWRs, able to ensure passive control of the power removed from the primary system, both in short and long term.

When a rector is shutdown, the core still produces the decay heat. This decay heat must be removed by the cooling system to prevent the overheating of the core and the reactor pressure and temperature increasing. From the Fukushima Daiichi Accident, the interest in safety system at different levels of passivity has grown rapidly [1]. This happens because during abnormal conditions, a reactor provided with Passive Safety Systems (PSSs) can reach safety conditions without the need of external energy supply or human intervention, according to the degree of passivity, for a pre evaluated and known period.

As shown in Ref. [2], the PSSs can be accumulators, evaporative or condensation heat exchangers, and gravity driven safety injection systems. Thanks to the presence of PSSs the maintenance and the operation of active components can be eliminated, increasing the safety systems reliability.

There are different types of PSSs, for both the core and the reactor containment. Different technologies have been studied, some of these are the effectiveness of the Core Makeup Tank in Ref. [3] through which borated water flows to the core. The Passive Residual Heat Removal System is used to remove the decay heat through a natural circulation loop and a single phase liquid, in Ref. [4] and Ref. [5] has been studied for the Molten Salts Reactors. The same type of DHRS has been studied for liquid metal reactor in Ref. [6] and for light water reactor in Ref [7]. In the Passive Isolation Condenser studied in Ref. [8] and Ref. [9], the steam goes towards the isolation condenser and the condensate return to the core by gravity. Another type of Passive Isolation Condenser, shown in Ref.[10], foresees the passive regulation of the power removed. Another example of PSS is the Sump Natural Circulation shown in Ref. 10[11], here the reactor cavity is filled with water which can be the reservoir in case of damage of the primary system. The reactor cavity can collect the coolant in case of loss of water from the primary system.

About the reactor containment PSSs, the Pressure Suppression Pool studied in Ref. [12], is a system able to condense the steam vented from the containment, avoiding the over pressurization of the system.

The DHRS actuates to remove decay heat produced in the core. The safety system must be able of self-regulating the power removed from the primary circuit, to avoid primary coolant freezing in case of liquid metal coolants, and the excessive thermal stresses of the primary system in case of LWR.

To ensure the passive self-regulation of the power removed, Ansaldo Nucleare patented a DHRS which allows the control of heat transfer rate through the injection of Non-Condensable (NC) gas into the circuit, passively regulated by the pressure difference of NC gas with steam [13].

The SIRIO facility is a non-nuclear test facility, scaled from the DHRS of the Advanced Lead Cooled Fast Reactor European Demonstrator (ALFRED) [14]. The aim of the experiment is to assess feasibility of passive self-regulation of heat removal with the proposed solution.

In Figure 1 it can be seen the ALFRED DHRS. The bayonet tube heat exchanger (i.e., Steam Generator) is the one always used during the normal operation. The Steam Generator (SG) has the Hot Leg (HL) and the Cold Leg (CL) intercepted by the DHRS in case of abnormal condition through the steam isolation valve and the condensate isolation valve, shown upstream and downstream of the Isolation Condenser (IC) in Figure 1. The IC is composed of vertical tubes connected with the NC gas line to NC gas tank.

When the DHRS is isolated from the circuit, the NC gas fill also the IC tube side, at a pressure of about 110 bar. When DHRS is activated, the SG HL and CL are intercepted, and when the steam flows into the IC tube side the NC gases are confined and then pressurized into the NC gas tank. The steam into the IC is condensed by the heat exchange with a water pool in environmental conditions. When the IC tube side pressure is reduced to the NC gas pressure, the NC gas flows into the IC tube side. The purpose of using NC gas is to degrade the Heat Transfer Coefficient (HTC) of the steam in condensation phase with the water pool. In this way passive self-regulation of the power removed by DHRS is done.

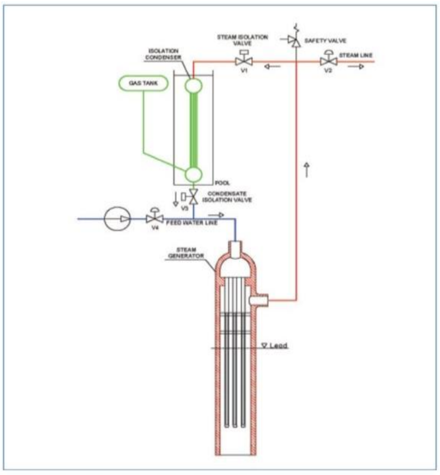

Figure 1: ALFRED DHRS schematic diagram [2]

The Department of Astronautical Electrical and Energy Engineering (DIAEE) of "Sapienza" University of Rome, has developed a thermal-hydraulic model of the SIRIO facility, which includes all the described components. To study the operational procedures a modified version of the system thermal-hydraulics (STH) code RELAP5/MOD3.3 [15] was used. The fundamental equation of RELAP5/MOD3.3 are based on a two-fluid, nonequilibrium, nonhomogeneous model for transient behavior with six-equations (the mass continuity, energy conservation and the momentum conservation for both the phases), as explained in Ref. [15].The modified version has different implementation, which consist in: lithium-lead (LiPb) and HITEC© working fluids with their thermophysical properties, new heat transfer correlations for liquid metals and MS, helical tubes heat transfer correlations and two-phase flow maps, module for MHD modelling capabilities and new heat transfer correlation for the evaluation of HTC in nucleate pool boiling and film condensation. The modified code has already been validated for different models such as helical tubes heat transfer correlations shown in Ref. [16], module for MHD modelling capabilities shown in Ref. [17] and correlations for the evaluation of HTC in nucleate pool boiling and film condensation, through submerged heat exchangers in water pools [18] and is able to simulate this type of system.

In this framework the aim of this study is to verify the feasibility of experiments based on the conditions of the reference facility ALFRED. Since there is no experimental data to be compared with numerical simulations, this study is a pre-test phase based on the design of the SIRIO facility.

2. Facility overview and scaling procedure

The SIRIO facility is a non-nuclear test facility, scaled form the ALFRED DHRS shown in Figure 1. The scaling approach is "power-to-volume": power density is kept constant, elevation and operational pressure are the same of the reference facility. The scaling factor has been defined with the NC gas tank as a reference component, and the volume scaling factor is 1:47 [14].

The primary circuit is composed by the SG, steam line, feedwater line, IC tube side and bypass HX tube side. The secondary circuit is composed by the bypass HX pool side and the IC pool side. The primary circuit is fully driven by natural circulation.

As it can be seen in Figure 2, the main difference between SIRIO configuration and the reference system shown in Figure 1, is the bypass Heat eXchanger (HX) line which provides for steady state conditions before transient testing.

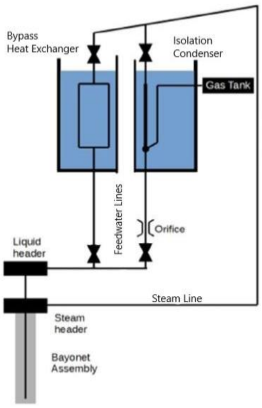

Figure 2: SIRIO schematic diagram [2]

The SG is composed of 11 tubes, each one composed of 6 components as shown in Figure 3. The component 1 in Figure 3 is the feedwater header which takes the fluid from the feedwater line; the component 2 in Figure 3 is the inner tube which role is the feedwater downcomer; the component 3 in Figure 3 is the steam trap which role is to limit regeneration phenomena for the initial downcomer region, in normal operation conditions; the component 4 in Figure 3 is the steam riser, is the most external tube through which the steam goes up towards the steam header; the component 5 in Figure 3is the steam header which collect the steam of the SG; the last component the is the Molten Salt (MS) gap (component 6 in Figure 3). The MS gap is a coaxial tube, used to simulate the power supplied by natural circulation in a same way of the reference facility ALFRED. Thermal power is supplied to the SG through electrically heated MS gap. The feedwater goes through the SG inner tube, and then goes up through the outer tube towards the steam header becoming steam. The steam, exiting the SG header, rises through the steam line towards the bypass HX or the IC.

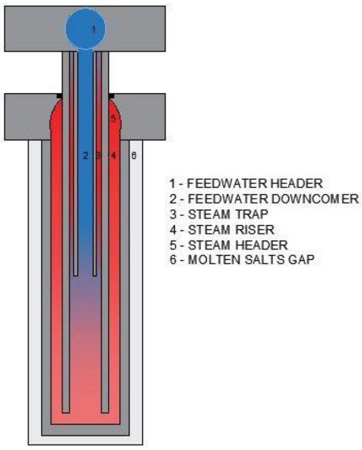

Figure 3: SIRIO - bayonet tube notional view

The SIRIO IC consists of a single tube immersed in the water pool. From the scaling procedure it was chosen to simulate the piping keeping the internal diameter (ID) and the outer diameter (OD) equal to those of ALFRED DHRS, with a pipe length of 0.68 m (compared to 2m of ALFRED DHRS [19]), thus having a deformation of the scaling factor of 0.39%.

This choice has an impact on natural circulation. However, considering the height of the facility (about 15 m), the distortion has been considered acceptable [14].

As it can be seen in Figure 1, for ALFRED DHRS configuration the IC has a top header and a bottom header. From scaling procedure, to simulate the volume occupied by these two headers, a pipe with ID of 2½'', downstream of IC is used.

The bypass line is not present in the reference system, but its presence is necessary because its role is to bring the facility to steady-state conditions, allowing the natural circulation of the fluid. In the reference configuration the fluid circulates thanks to the conditions resulting from the normal operations of the plant. As it can be seen in Figure 2, the bypass line is an independent line parallel to the IC and is completely isolated when the IC comes into operation. When bypass HX comes into operation, the IC is completely isolated from the rest of the circuit. The bypass HX or IC activation or isolation takes place through a one upstream valve and one downstream valve for each bypass HX and IC. The bypass HX has the function of being the heat sink during the steady state. This HX is made up of two parallel pipes immersed in a water pool of 2 m high. The steam from the steam line, goes downward inside these tubes and is condensed.

Components for both feedwater and steam line, were chosen respecting the scaling procedure and the economic/scientific characteristics (i.e., avoiding the flow pattern variations, keeping the pressure drops comparable to those of ALFRED, minimization of heat losses). Into the feedwater line coming from the IC, there is an orifice of 5 mm, which role is to prevent the NC from flowing outside the IC tube side.

The gas tank is connected downstream of the IC tube side, via the NC gas line.

3. Models

The SIRIO nodalization is divided in 3 hydrodynamic regions: the primary circuit, the IC pool and the bypass HX pool. The model is composed of hydrodynamic components, Heat Structures (HS), and control systems. The model is developed with the sliced approach for the whole facility, and the length ratio of the adjacent nodes is kept into the range of 1 ÷ 1.25.

Steam line and feedwater line are simulated with 5 and 8 pipe components, respectively. Actual bends, section variations, tees, and orifice are included in the modeling. The bypass HX has been simulated with two parallel pipe components for tube side and two parallel pipe components for pool side, to allow the simulation of fluid mixing. The isolation condenser was simulated with the single tube on the tube side and also in this case two pipe components for pool side to simulate the mixing of the fluid.

The NC gas line has been simulated considering all the curves present in the circuit.

The hydrodynamic characteristics of the SG are modeled collapsing all the 11 tubes into a single bayonet element. The SG flow area is the total flow area, while the hydraulic diameter is evaluated according to the geometry of the single subchannel.

Active and passive HS are included in the modeling. The active HS are those that provide for the heat exchange between the components, while the passive HS are those used to thermally insulate the components. Active HS involve heat exchange in the SG, bypass HX and IC. As shown in Figure 4, for the SG three different HS have been simulated, for each of these the heat exchange area used is the total heat exchange area. The first one (named as HS 13 in Figure 4) has the purpose of simulating the power supplied to the SG through a multilayer HS, thanks to which it is possible to simulate the heat exchange by conduction through the MS; the second HS (HS 14 in Figure 4) simulates the heat exchange between the steam riser and steam trap (component 3 in Figure 4) and the second region of the water downcomer; the third HS (HS 15 in Figure 4) simulates the heat exchange between the steam trap and the water downcomer. For the bypass HX there is a HS for each pipe component, which simulates the heat exchange between the tube side and the pool side. For the IC, there is a HS that simulates the heat exchange between the tube side and the pool side.

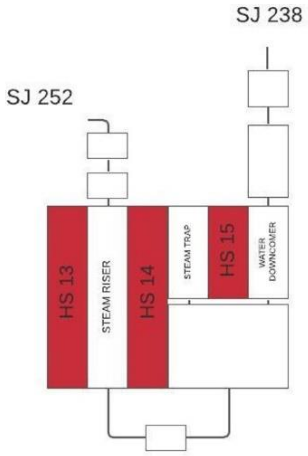

Figure 4: SIRIO SG thermal-hydraulic model

There are passive HS for all the insulated pipes. The pipe components are insulated with Rockwool, and are simulated the environmental temperature of 303 K, and environmental HTC of 15 W/m^{2}K.

4. Test: steady-state phase

The test phase is divided into two parts: a steady state phase and a transient phase with decay heat generation.

For the steady state phase, a constant power is provided to the SG, equal to 55 kW. To reach a steady state phase, an equilibrium between power removed by bypass HX and power supplied to SG is necessary, at rated pressure. To reach this balance condition shown in Figure 5, the bypass HX pool side has been initialized as empty as shown in Figure 6. Through a time dependent junction the level was quickly increased to 0.76 m (38% of the total height). After the initial phase, the flow rate has been adjusted to maintain a constant level of the bypass HX pool side, at around 0.63 m (31.5% of the total height).

Into the primary circuit there aren't control system. Bypass HX upstream and downstream valve are kept fully open. IC upstream and downstream valve are closed for the whole test, keeping this line isolated.

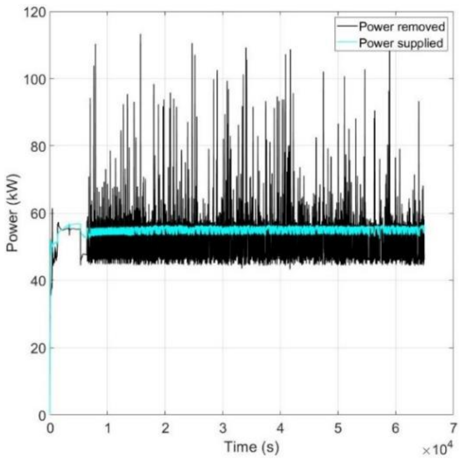

Figure 5: power removed and supplied during steady-state phase

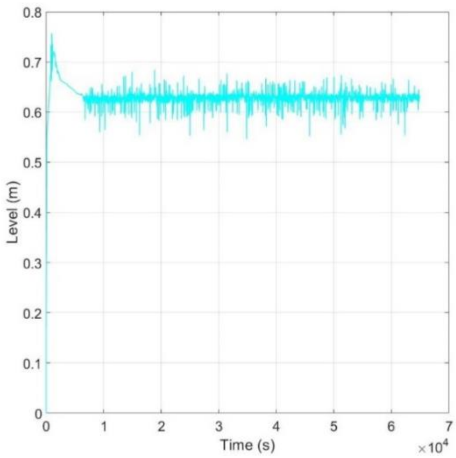

Figure 6: Bypass HX pool side - Water level

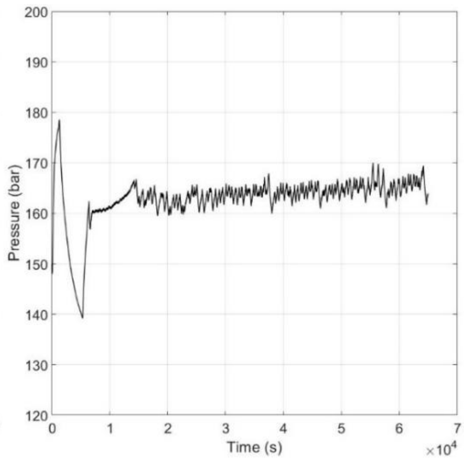

Figure 7: Primary side pressure trend

Looking at the power trend in Figure 5 and the bypass HX pool side water level in Figure 6, it is possible to notice that an equilibrium condition has been reached between power removed and supplied, and how the water pool level stability of the bypass HX has been achieved, albeit with oscillations. However, the pressure trend (Figure 7) in the primary circuit of the facility is characterized by strong oscillations, and its trend is less stable when compared to Figure 6 one.

The nature of these oscillations observed in Figure 6, Figure 7 and Figure 8 may be due to: the detail of the model, either of a computational nature or of a thermal-hydraulic nature. The first cause can be excluded, since the magnitude of level variations are all within the same control volume. If the oscillation had not remained confined within the same control volume as the IC component, this cause could not be excluded. The other two possibilities have to be investigated. The computational nature of the oscillation cannot be excluded. The last possibility is thermal-hydraulic instability characteristic of parallel pipes. The latter is possible due to the fact that both the IC pool side and the bypass HX have been modeled with parallel pipes connected through multiple junctions. Nevertheless, the results can be considered satisfactory for the purpose of the present activity.

5. Test: transient phase - decay heat generation

The second part of the test is a transient phase with decay heat generation. For the test: the steam line is isolated from the heat sink, so pressure in the primary circuit increases reaching the DHRS setpoint pressure of 190 bar. When DHRS is activated, the power supplied follows a decay heat generation trend[1], simulated as shown in Table 1, from 55 kW of the steady-state phase down to 4.84 kW in around 24 h. The time zero represents the bypass HX isolation instant, starting from 34800 s of the steady state test.

Table 1: Decay heat trend

Time (s)	Power (kW)
0	55.00
2000	55.00
2060	31.43
2600	20.64
5600	12.38
12800	8.89
38000	6.03
88400	4.84

[1] Full power is provided for 2000 seconds from begin of test to account metal structures heat capacity and reduce its impact on global power balance.

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When the steam line is isolated, there is a sharp increase in pressure up to 190 bar, shown in Figure 8. This represents the opening set point for the upstream valve of the IC. With a delay of 60 s from the opening of the upstream valve, also the downstream valve of the IC opens, as shown in Table 2.

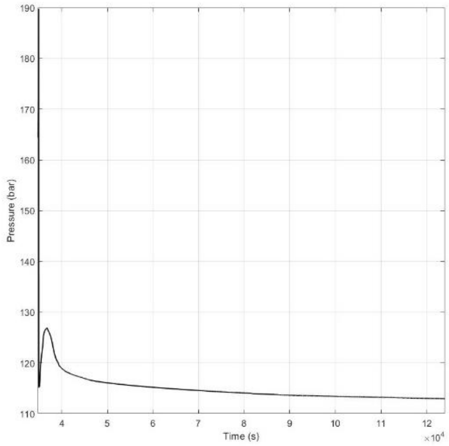


Figure 8: Pressure trend after IC activation

When IC upstream valve is opened, the NC gas are confined and pressurized int the NC line and NC gas tank. In this way steam condenses in absence of NC gas and as it can be seen in Figure 8, there is a sharp drop of pressure right after the DHRS activation.

After 115s from the IC downstream valve opening, the differential pressure of steam into IC tube side and NC gas vanishes, and the NC gas flows into the primary circuit. When NCs flows into the circuit, they also enter in the SG feedwater downcomer for about 13800 s, and in the SG steam riser for about 3300 s, during which there are maximum NC quality of 0.87 e 0.008514 respectively. After 14468 s from IC downstream valve opening, the NC gas are confined into the IC tube side. In fact, IC tube NC quality is around 0.9, as shown in Figure 9.

Table 2: Valves operation

Valve	Open/Close condition	Opening/Closing Time
Bypass HX – upstream/downstream	Time	0 s
IC – upstream	Pressure – 190 bar	152 s
IC - downstream	Time – 60 s after IC upstream	212 s

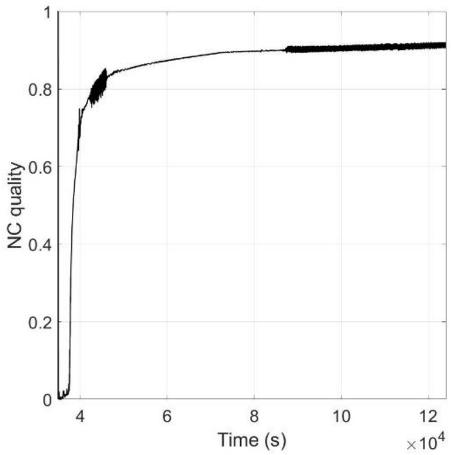
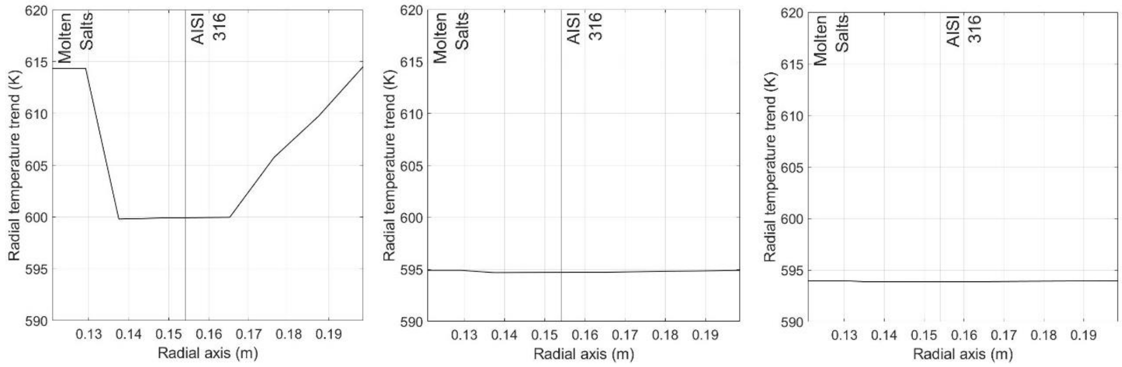


Figure 9: NC gas quality in IC tube side

As the objective is to verify the anti-freezing feature of the system in liquid metal-cooled reactors, and thermal stresses mitigation in case of liquid water reactors, Figure 10 shows temperature profiles, from MS side to SG steam riser wall temperature respectively: 1 h after DHRS activation (Figure 10a), 12 h after DHRS activation (Figure 10b) and 24 h after DHRS activation (Figure 10c).



(a) *(b)* *(c)*

Figure 10: Temperature profiles from MS to SG after 1h (a), 12 h (b) and 24 h (c) of DHRS activation

Even during the transient phase – decay heat generation test, the results are satisfactory. The purpose of confining the NC gas thanks to the orifice is achieved, thus confining the NCs. The purpose of HTC degradation during heat removal is achieved. From the facility point of view, the temperature reached by the MS is not an issue because the MS used (Dynalene MS-2) has a melting point of 403 K.

6. Conclusions

Both test phases were carried out in respecting all the required boundary conditions, and as much as possible the constructive characteristics of the test facility. In the steady-state case, despite the oscillations present on the studied parameters in the primary circuit, a satisfactory result was obtained with the achievement of a quasi-steady-state.

In the study of the second test phase, the behavior of the passive self-regulation system of the power removed was seen. In this case the behavior of all active and passive components has been simulated.

The NC gas confinement with an orifice is achieved, and so the passive self-regulation of the power removed.

Due to these results, future sensitivity analyses (nodalization, boundary conditions and MS components simulation) are required and comparisons with experimental results, to better estimate differences of numerical simulations results with experimental data, are required.

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