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An Innovative Reactivity Control Strategy for Small Modular Reactors

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ABSTRACT

Currently, the main reactivity control methods for small modular reactors (SMR) use control rods as the primary control system, with chemical SHIM or burnable absorbers as secondary systems to control the reactivity excess. However, this kind of control system presents some risks, such as control rod undesired drop or positive moderator coefficient due to the high concentration of boric acid in the moderator. This paper evaluates the possibility of using a displaceable heavy neutron reflector with a neutron absorber (boron) as a secondary reactivity control method. The reference NuScale core geometry has been simulated using the DRAGON5 and DONJON5 deterministic codes, computing the neutron flux and power distribution at each reflector withdrawal step. Two different strategies have been considered: 1) withdrawing the entire movable reflector block towards the upper part of the vessel and 2) separating the reflector block into two equal parts, removing each in different directions from the core equator region. Results indicate that the most suitable reflector withdrawal mechanism is the latter: this solution is promising to replace secondary reactivity control methods in small reactor cores.

1 INTRODUCTION

The global electricity demand is projected to grow by an average of 3.7% from 2021 to 2030 [1], leading to increased concerns about climate change and the need for clean energy sources. Nuclear power has emerged as a promising option for reducing carbon emissions due to its low CO2 output and high-capacity factor. However, the construction of large nuclear power plants (NPPs) is often economically and technically unattractive, as they require significant investments and face challenges in integrating with smaller grids. To address these issues, Small Modular Reactors (SMRs) have gained attention: these reactors aim to provide a solution by offering smaller and more flexible units. There are currently over 80 SMR designs worldwide in various stages of development [2].

Just like large reactors, ensuring the safe operation of SMRs requires controlling the rate of fission events. Typically, two reactivity control measures are employed: control rods and neutron-absorbing materials like boric acid or burnable absorbers. However, these methods carry inherent risks, for instance, there's a potential for minor coolant losses to trigger critical conditions, even when control rods are fully inserted. A notable instance of this risk materialised through the boric acid leak, causing the development of a 2050 cubic centimetres corrosion pit on the Davis-Besse nuclear power reactor head in 2002 [3].

Given that Small Modular Reactors (SMRs) are founded on upgraded safety features, it's imperative to curtail the likelihood of coolant leakage or vessel impairment. This is especially

crucial considering that SMRs are often situated in remote locations and operate with reduced staff, thereby elongating inspection intervals. Furthermore, maximising neutron economy is of paramount importance. Although SMRs may exhibit marginally elevated Levelized Cost of Electricity (LCOE), a reactivity control technique that can optimise the neutron economy emerges as a priority. Considering this, the present article explores an alternative reactivity control approach for SMRs. This approach holds the potential for adaptation in commercial Nuclear Power Plants (NPPs). The proposed method involves withdrawing a movable heavy neutron reflector containing a neutron absorber material (boron). Previously, the concept of a movable reflector was proposed in [4], without the absorber material, but it was not expanded upon, and in this sense, this work presents, to the authors' knowledge, the first in-depth investigation of this control method, which potentially can eliminate the need for chemical SHIM or burnable absorbers. Two withdrawal alternatives are presented and compared to determine the most effective reactivity control mechanism. Overall, this article explores innovative reactivity control methods for SMRs and their potential applicability to NPPs, utilising advanced computational tools and a standardised core design.

The document is structured as follows: a brief review of SMR technology is provided (Section 1.1); then, in Section 2 the methodology is described. Results are presented in Section 3, leading to Section 4 which summarises the key conclusions of the present work and provides some suggestions for future research.

1.1 Small Modular Reactors

Small Modular Reactors are defined by [2] as advanced reactors concepts that can produce electricity up to 300 MWe per unit; indeed, SMRs are envisaged with modular technology, pursuing economies of series production and short construction times [5]. Among the SMR designs under development, several technologies can be identified: the reference design used in this paper belongs to the water-cooled, specifically to the Pressurised Water Reactor (PWR), type, which is the most common technology among commercial NPP with over 70% operating reactors out of all operating reactors in the world [6]. In general, the main characteristics of SMR are modularity, improved safety, lower capital investment and flexibility.

With over 70 years of Nuclear Power Plant (NPP) operational experience with established and well-accepted reactivity control methods, the advent of diverse Small Modular Reactor (SMR) designs necessitates innovative reactivity solutions adaptable to these variations. SMRs prioritise enhanced safety, requiring careful reactivity adjustments to avoid compromising this aspect, which can be addressed through the incorporation of movable/absorbing reflectors that can potentially replace chemical SHIM management. Neutron economy optimization also takes precedence, aiming to minimise operational costs and enhance competitiveness against conventional NPPs and renewable energy sources. In this evolving landscape, adaptable and secure reactivity management remains pivotal for SMR viability.

2 METHODOLOGY

For the reactor database construction, that is, the collection of all the information needed to solve the neutron transport equation with the chosen codes, the work developed by [7] was taken as reference and the specific parameters from the reference SMR design were changed regarding geometry and compositions. For the analysis, the DRAGON and DONJON Version 5 open-source deterministic codes were used.

2.1 Reactor Lattice Codes

Reactor lattice codes (RLC) are used to calculate the neutron flux and the infinite medium multiplication factor (κ_∞). As input, these codes require a library of nuclear information and a description of the reactor lattice geometry (including the expected operating temperature ranges).

The codes then solve the neutron transport equation within a specific region of the reactor lattice by using proper numerical schemes to solve a set of equations discretised in the spatial and energy variables. The neutron flux obtained can then be used to calculate the macroscopic cross-sections homogenised over the selected sub-regions within a broad neutrons energy group and to calculate reaction rates of in-fuel depletion. The macroscopic cross-sections are then used as an input to solve the neutron transport equation or the diffusion equation [8] with DONJON. Brief schemes of the DRAGON and the DONJON workflow are shown, respectively, in Figure 1 and 2.

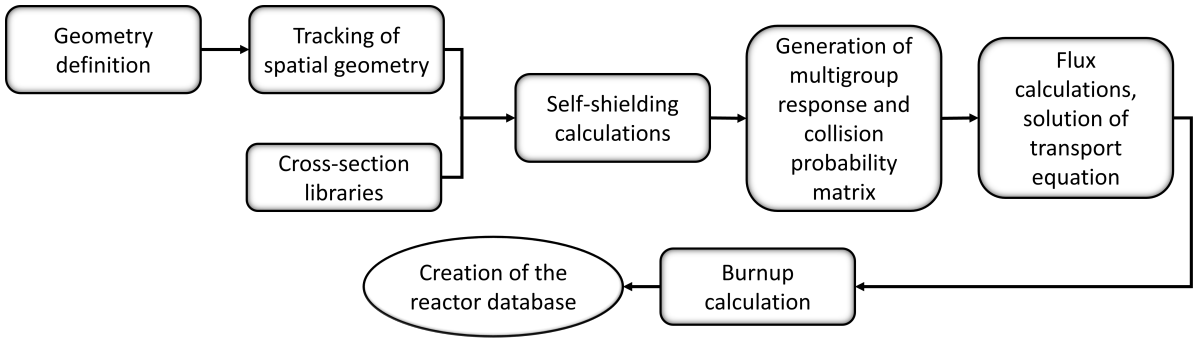


Figure 1: DRAGON lattice code scheme.

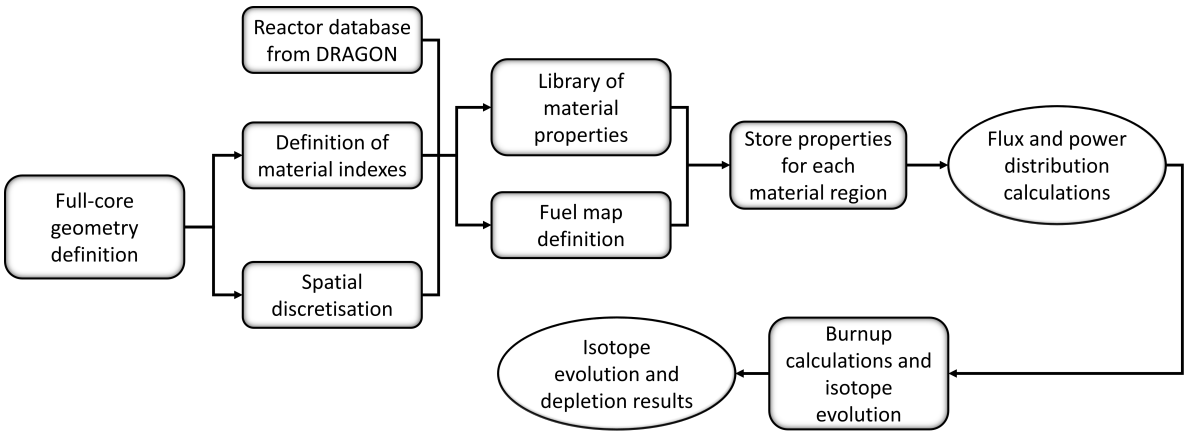


Figure 2: DONJON simplified scheme.

2.1.1 DRAGON Lattice Code

DRAGON is a computational lattice code that enables simulation of the neutronic behaviour in a unit cell or fuel assembly. It utilises various solving techniques for the neutron transport equation and operates through a deterministic approach. The code consists of multiple calculation modules that are invoked as per user requirements [9]. DRAGON employs verified neutron cross-section libraries developed by global research institutions, with the option to convert libraries into compatible formats using the NJOY-2016 tool. Its applications include solving the neutron transport equation, generating reactor databases for full core simulations, and conducting burn-up fuel analysis. The code follows a sequential process involving geometry definition, tracking module analysis, self-shielding calculations, and flux solution computation. Additionally, it facilitates burnup calculations and offers a reactor database for tracking parameter variations during full-core simulations.

2.1.2 DONJON Diffusion Code

DONJON is a computational code used to simulate full-core geometries based on neutron diffusion theory, with a specific focus on reactors like the NuScale design. The code requires complementary software packages such as DRAGON, UTILIB, GANLIB, and TRIVAC to perform simulations. DONJON consists of modules designed for various user requirements, and it operates in a 3D geometry. The code enables full-core simulations under stationary conditions, providing data on power, flux distribution, and reactor core geometry. The input data is obtained from the reactor database generated by the DRAGON lattice code, allowing for the computation of macroscopic cross-section libraries. The simulation scheme involves defining the 3D full-core geometry, assigning materials indexes, connecting the geometry to the reactor, and discretizing the geometry using TRIVAC. Burnup calculations can be performed as instant or time average calculations [10].

2.2 Fuel Pin Geometry and Core Model

The considered fuel pin geometry includes the fuel pellet, cladding, gap, and moderator. To calculate the neutron flux, the fuel pellet is discretised in four regions in the radial direction, as reported in Table 1a (the percentages indicate the volume fraction occupied by the pellet region) [11]. The reference fuel assembly has a 17x17 square configuration with 264 fuel rods, 24 guide tubes and 1 instrument tube [12]. Six different initial values of U-235 have been simulated (in weight percentage): 2.5%, 2.7%, 3%, 3.7%, 4% and 4.5%. Two different fuel initial enrichment are considered in the core: the external region, closer to the movable reflector with the absorbing material, has higher enrichment compared to the central one, as seen in Table Table 1b. On the other hand, in Table 2, the reactor core geometry characteristics are presented.

Table 1: Simulated fuel characteristics and core enrichment layouts.

(a) Fuel characteristics.

Description	Dimension (cm)
Fuel pellet radius	0.406
Region 1 (50%)	0.2871
Region 2 (30%)	0.3631
Region 3 (15%)	0.3957
Region 4 (5%)	0.406
Gap width	0.0082
Cladding thickness	0.0609
Overall fuel radius	0.4751
Fuel rod pitch	1.259

(b) Simulated core layouts.

Internal	External
2.5%	3%
2.5%	4%
2.5%	4.5%
3%	3%
3%	3.7%

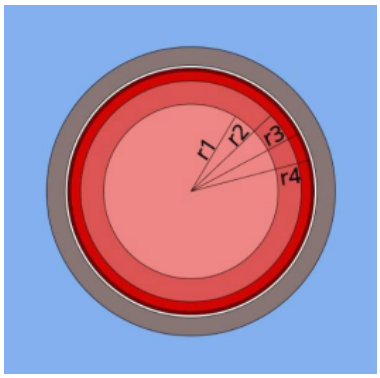
Uranium dioxide (UO_2) pellets with an operation temperature range from 270 to 1730 °C were considered, simulating different U-235 compositions. For the cladding, Zircaloy-4 was employed with a temperature range of 270 to 430 °C; for the moderator, water with a temperature range of 270 to 430 °C was used. It must be noted that neither the moderator nor the cladding includes initial boron or burnable absorbers. Indeed, the main objective of this work is to verify the possibility of controlling reactivity by using boron in the heavy neutron reflector only.

The entire core geometry was discretized uniformly in 13 regions in the X and Y axes, while 10 regions are considered for the Z-axis. For the reflector material, stainless steel AISI 316 was proposed due to its corrosion resistance and mechanical resistance; regarding boron, the proposed steel has been used in the presence of 4% in boron enrichment in two different thickness values, 10 and 25 cm [13]. Figure 3 reports the adopted model.

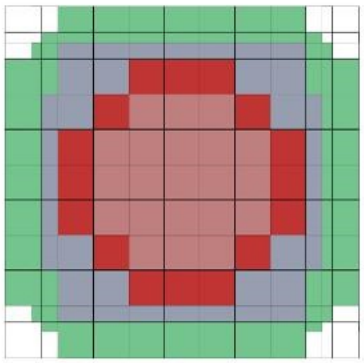
Two different reflector displacement methods were studied: the first consists of axially displacing the reflector as a single piece; the second consists of axially displacing the reflector from

Table 2: Simulated core characteristics

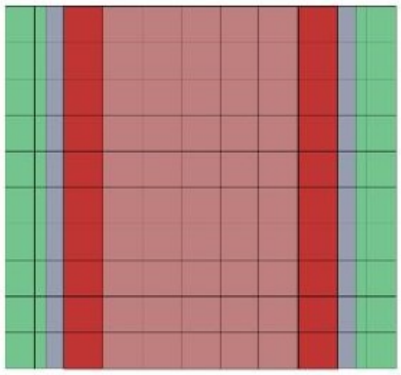
Parameter	Value	Units
Reactor core power	160	MW_{th}
Core diameter	150.5	cm
Core active height	200	cm
Fuel assemblies	37	
Fuel assembly pitch	21.5	cm
Pins per assembly	17×17	
Fuel pellet density	10.97	g/cc
Cladding material	Zircaloy-4	
Moderator / Coolant	Light water	
Mean coolant temperature	600	K
Moving reflector thickness	10 - 25	cm
Fuel material	UO_2 with varying ^{235}U	



(a) Radial discretisation of the fuel rod



(b) Radial discretisation of the core (each square block in the red regions corresponds to a fuel assembly).



(c) Axial discretisation of the core.

Figure 3: Adopted geometry (fuel and core), with the following legend: light red $\rightarrow$ internal core region; dark red $\rightarrow$ external core region; grey $\rightarrow$ movable reflector; green $\rightarrow$ fixed reflector.

its equator in two equal parts. The reflector displacement was discretized in equally sized steps for both cases (single and two-parts): each Z-axis step corresponds to a portion equivalent to 1/10th of the core. Table 3 summarises the removal steps for both cases.

Table 3: Reflector removal steps for the two cases.

Core status	Single-block	Two-block
Completely surrounded	None	None
75% surrounded	1-3	4-6
50% surrounded	1-5	3-7
25% surrounded	1-8	2-8

2.3 Nuclear Data Library

To ensure the correct calculation of neutron flux, a proper nuclear library must be selected. This work uses the JEFF version 3.1 SHEM-281 energy mesh, with 281 energy groups. The SHEM was developed by [14] to overcome precision issues regarding self-shielding errors in neutron

thermal resonant absorption. To address the long computation time associated with solving the transport equation using 281 energy groups, a condensed representation using 26 energy groups was proposed by [7] and implemented in the lattice code flux calculation. This reduction in energy groups was proven to significantly reduce the computation time while maintaining comparable results. Once the reactor database is established, the entire core geometry can be simulated. The next section will provide details on the computational tool and simulation methodology employed.

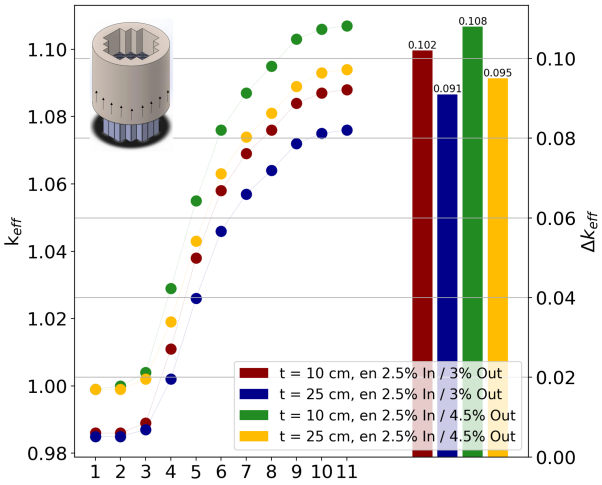
3 RESULTS AND DISCUSSION

In this section, the results of the investigation of the feasibility of a movable neutron reflector containing boron as a neutron absorber material will be presented. If this approach is satisfactory, the necessity of chemical SHIM in the moderator or burnable absorbers is no longer required, thus increasing the safety during operation, improving neutron economy, and avoiding positive moderator coefficient due to the high concentration of boric acid in the moderator. The reflector (surrounding the core) will be axially displaced by a mechanism that will be defined in later studies. The reactor's geometry and initial conditions are: i) steady-state operation condition; ii) fresh fuel; iii) no chemical SHIM in the moderator; iv) no burnable absorbers in the cladding; v) control rods fully extracted.

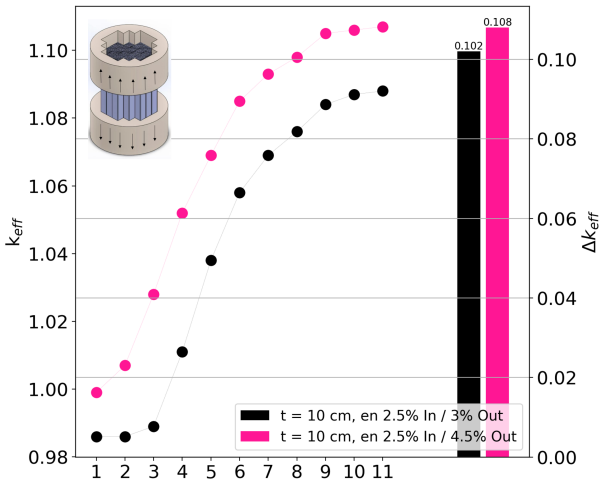
When the core is fully surrounded by the movable reflector, the reactor must be in sub-critical conditions due to the presence of a neutron absorber such as boron in it, according to the simulated enrichment configuration; in some cases, the reactor will reach criticality right after the first withdrawal step. Different values of boron composition were simulated, obtaining different effective multiplication factor values (κ_{eff}). In particular, with 55'000 ppm of Boron (composed by Boron-10 in 20% and Boron-11 in 80% in weight), the reactor is in a sub-critical state with κ_{eff} = 0.9993 when its core is fully surrounded by the reflector, and further increases in the Boron concentration do not significantly alter this value: therefore this value of Boron concentration has been considered in the following.

Figure 4a shows how κ_{eff} varies for the single-block reflector with varying reflector thickness and core enrichment layout, for each withdrawal step (with step 1 corresponding to a fully surrounded core and step 11 to a bare core). The configuration 10 cm of reflector thickness with core layout 2.5% internal and 4.5% is the one that guarantees the higher variation in κ_{eff} (equal to 0.108). The two-block reflector case (Figure 4b) shows a similar behaviour. In general, the variation is greater for thinner reflectors and higher enrichment in the external region: the former can be explained given the higher amount of Boron for thicker reflectors that, even for the bare core configuration, still influences the reactivity; the latter can be explained since the external region is the one that is mostly affected by the presence (or absence) of the reflector. The overall variation in κ_{eff} for all simulated cases is summarised in Figure 5a.

Figure 5b shows a comparison between the κ_{eff} values for the two different moving configurations for the case with reflector thickness equal to 10 cm, internal region enrichment equal to 2.5% and external region enrichment equal to 4.5%. The two-part reflector removal shows a larger change in the multiplication factor during the first steps, mainly due to the uncovering of the central region of the core where the neutron flux is higher. Thus, this strategy offers a better performance in terms of reactivity control. In addition, since in this case the reflector is divided into two parts, the blocks that must be displaced are lighter than the single reflector block, potentially allowing a simpler movement mechanism for each half. A possible drawback could be the increase in size of the vessel since one-half of the reflector must be displaced towards the bottom part of the vessel which thus must be large enough to fully accommodate it. Overall, the configuration 10 cm thickness, internal enrichment 2.5%, external enrichment 4.5% and two-block movement mechanism gives a total reactivity worth of 16.63$.

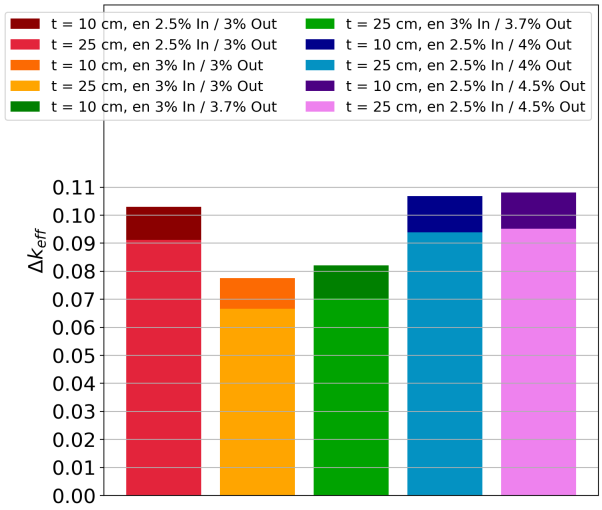


(a) Single-block reflector case.

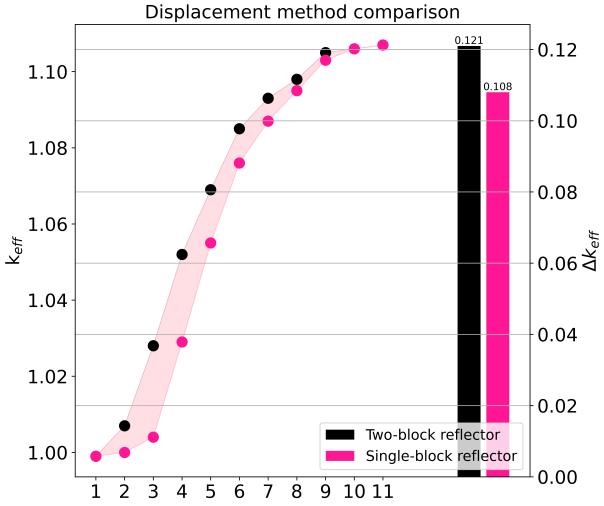


(b) Two-block reflector case.

Figure 4: Variation in κ_{eff} for different thickness and core enrichment layouts (single-block and two-block reflector cases).



(a) κ_{eff} variation for all simulated cases for the two-block reflector.



(b) Comparison of κ_{eff} for the two displacement methods for the optimal case (thickness 10 cm, internal enrichment 2.5%, external enrichment 4.5%.

Figure 5: Variation in κ_{eff} for different thickness, core enrichment layouts (single-block and two-block reflector cases) and movement mechanism.

4 CONCLUSIONS

This study explored an alternative reactivity control method for small modular reactors by moving a heavy neutron reflector around the core. Using deterministic computational codes (DRAGON and DONJON), the NuScale reactor design was considered as a reference and simulated, considering fuel characteristics, core geometry, reflector, and moderator materials. The research found that this alternative control strategy is feasible for small reactor cores as a mechanism to control the effective multiplication factor, with the potential to reach criticality during the first intermediate withdrawal step . Splitting the reflector into two parts and extracting them in opposite directions proved to be the most effective withdrawal method compared to moving a single reflector block. While control rods remain the primary reactivity control system, this approach can reduce the risks associated with current secondary systems, such as boron-related accidents, by

incorporating the neutron absorber material into the reflector. Varying the reflector material thickness and boron concentration demonstrated the impact on the reactivity of these parameters. The research also provides insights for optimising fuel enrichment and reflector material properties for this control strategy.

Future investigations should validate the proposed strategy by considering dynamic changes during reactor operation using stochastic computational tools. Although based on the NuScale design, this control strategy could be extended to other SMRs with similar characteristics or conventional nuclear power plants with geometry modifications.

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