Potential Safety Features and Safety Analysis Aspects for High Performance Light Water Reactor (HPLWR)

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Research Activities are ongoing worldwide to develop advanced nuclear power plants with high thermal efficiency for the purpose to improve their economical competitiveness. Within the 5th Framework Programme of the European Commission, a project has been launched with the main objective to assess the technical and economical feasibility of a high efficiency LWR operating at supercritical pressure conditions. Several European research institutions, industrial partners and the University of Tokyo participated and worked in this common research project.

Within the aims of the development of the HPLWR is to use both passive and active safety systems for performing safety related functions in the event of transients or accidents. Consequently substantial effort has been invested in order to define the safety features of the plant in a European environment, as well as to incorporate passive safety features into the design. Throughout this process, the European Utility Requirements (EUR) and requirements known from Generation IV initiative were considered as a guideline in general terms in order to include further advanced ideas. The HPLWR general features were compared to both requirements, indicating a potential to meet these.

Since, the supercritical HPLWR represents a challenge for best-estimate safety codes like RELAP5, CATHARE and TRAB due to the fact that these codes were developed for two-phase or single-phase coolant at pressures far below critical point, work on the preliminary assessment of the appropriateness of these codes have been performed for selected relevant phenomena, and application of the codes to the selected transients on the basis of defined “reference design”. An overview on their successful upgrade to supercritical pressures and application to some plant safety analysis are provided in the paper. Further elaborations in relation to future needs are also discussed.

KEYWORDS: Safety features, Safety requirements, Passive systems, Safety analysis and heat transfer, Super critical LWR, Advanced reactors.

I. Introduction

The concept of the supercritical-pressure light water cooled reactor has been studied by the University of Tokyo over the past decade. Though this development effort has been primarily theoretical and conceptual, specific features have been pointed out which indicate potential merit of this concept. After some review work, this concept has been chosen as a starting point for the current project with the aim to reach a conclusion whether or not it is possible to build a once-through supercritical-pressure Light Water Reactor, which is economically and physically a viable solution to sustain the nuclear option. Because of the expected high efficiency, high temperature and high pressure this concept was named High Performance Light Water Reactor (HPLWR).

The plant concept, which is considered here, is described in some detail in reference and is equipped with a reactor of the 1000 MWe class operating at supercritical steam conditions. The system pressure is about 25 MPa. One of the characteristics of supercritical water is that it does not exhibit a change of phase. The heat is effectively removed near the pseudo-critical temperature. For 25 MPa this temperature is about 385°C. Steam water separation is not necessary since supercritical water behaves like a single-phase medium. The turbines are directly driven by the outlet coolant.

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In this paper, potential safety features and a general application of safety aspects of European utility requirements \(^5,6\) and Generation IV requirements \(^7\) to the present conceptual design of the HPLWR are provided. In addition, the effort spent within the HPLWR project to evaluate and upgrade three computer codes that could be used in the safety evaluation of the HPLWR is summarized. This analytical effort proved to be a rather difficult and complex task, in which three well established computer codes, i.e. RELAP5, CATHARE, and TRAB were involved. It turned out that crossing the critical point of water during a transient (e.g. LOCA, etc.) is not at all a trivial matter. This requires a substantial effort in model development, code modification and code verification. In addition, the thermodynamic properties used within these codes had to be extended to supercritical conditions. Few results that demonstrate the code capabilities as well as preliminary calculations (with un-verified codes under supercritical water conditions) and show the behavior of the HPLWR under some transient conditions are presented. In this paper, system calculations will be emphasized; phenomenon related investigations (e.g. critical flow, reflooding in tight lattice bundle \(^8\), etc.) would not be included.

II. Passive and Active Accident Control Systems \(^9,10\)

It is the aim of the development of the HPLWR to use both passive and active safety systems for performing safety-related functions in the event of transients or accidents. The most frequent events requiring system function for prevention of intolerable fuel rod temperatures comprise anomalies in plant operation, or so-called transients. As a result of the specific properties of supercritical water, the water inventory within a HPLWR RPV is about 1/10th of that of a BWR or a PWR. This means that in case of incidents and accidents, the heat storage capacity of the existing water inventory in the primary circuit is low. Concerning the control of incidents and accidents this fact has to be considered appropriately. In general this means that as fast as possible, flow, which is able to cool the core has to be maintained. Later on the core has to be flooded with water from all sources, including water reservoirs external to the primary circuit.

From the comparison of analyses for a hot line break and a loss of feed-water flow accident \(^1,2\), it is recognized that a reduction of temperature occurs in the first case, while in the second case under assumption of a fast HP water injection into the RPV a considerable larger temperature increase occurs. As a consequence of these results, it is expected that the core cooling is more effective in case of loss of flow accidents, if the ADS is activated and followed by a low pressure water injection from the suppression pool, compared to an HP injection. Although this has to be substantiated by further analyses, this procedure seems to be the appropriate mode to control these kinds of accidents.

Therefore in case of incidents with loss of feed-water flow injection. Whether accumulators can be used in addition or even instead of the pumps has to be analyzed further. This mode should result in the lowest temperature loads of the fuel rods and in reliable systems for accident control. It should be pointed out that the same design philosophy has also been adopted in the design of Advanced Light Water Reactors (ALWR).

In case of most of the transients as well as in the event of accidents, the following safety functions must be assured:

- Reactor scram
- Containment isolation
- RPV pressure relief and depressurization
- Heat removal from the RPV
- Reactor water makeup and control of core coolant inventory
- Heat removal from the containment

The passive and active systems planned for these tasks are described below. In Table 1, an overview is given about the systems installed to control the individual accident scenarios.

### Table 1- Safety Systems

<table>
<thead>
<tr>
<th>Safety functions</th>
<th>Systems provided</th>
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<tr>
<td>Reactivity control</td>
<td>Two independent scram systems</td>
</tr>
<tr>
<td>Containment isolation</td>
<td>2 main steam isolation valves per train</td>
</tr>
<tr>
<td>Reactor pressure control and reactor depressurization</td>
<td>6 safety relief valves; 4 emergency condensers</td>
</tr>
<tr>
<td>Core flooding</td>
<td>4 RHR and LPCI systems; flooding lines; possibly accumulators</td>
</tr>
<tr>
<td>RHR from RPV</td>
<td>4 RHR and LPCI systems; 4 emergency condensers</td>
</tr>
<tr>
<td>RHR from containment</td>
<td>4 RHR and LPCI systems; 4 containment condensers</td>
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</tbody>
</table>

Figs. 1 and 2 present in a schematic form the once through super critical concept \(^2\) and the proposed safety systems for HPLWR \(^4\).

1. Safety Relief Valve System

The tasks of the safety relief valve system are as follows:

- Protection of the reactor coolant pressure boundary against pressure in excess of allowable limits (pressure relief)
- Automatic depressurization of the RPV in the event of loss of feed-water flow accidents and cold line LOCA
Fig. 1  Schematics of the University of Tokyo once-through supercritical reactor concept

Fig. 2  Schematics of the HPLWR primary circuit, safety systems and containment concept
• Prevention of high pressure core melt path
• Short term removal of excess steam in the event of turbine trip and load shedding

The safety relief valve system is located inside the containment and consists of the safety relief valves and relief lines with steam quenchers, which are installed in the core flooding pool.

2. Emergency Condenser
The emergency condensers function as passive devices for residual heat removal from the RPV to the core flooding pool potentially both at high pressure and low pressure. The system consists of four separate subsystems. Each subsystem consists of a steam line leading from an RPV nozzle to a condensate return line, back to the RPV. The emergency condensers are connected to the RPV with an isolating valve each, which are activated from a pressure criterion. The condensate returns to the RPV by gravity flow.

3. Low Pressure Coolant Injection and Residual Heat Removal Systems
The system performs the following tasks:
• Low pressure injection of coolant into the RPV and heat removal
• Reactor cooling during operational shutdown and in the shutdown condition
• Water transfer operations prior and subsequent to refueling
• Operational heat removal from the core flooding pool and pressure suppression pool water
• Heat removal from the containment in the event of loss of main heat sink by cooling the pressure suppression pool and core flooding pool.

The system is actuated via safety I&C criteria and system-associated electrical loads are connected to the emergency power supply system.

4. Containment and Passive Safety Features
The containment concept is based on that of recent-generation BWR plants. It is a cylindrical containment made from steel reinforced concrete equipped with an inner liner and a pressure suppression system (Fig. 2). The containment is divided into a drywell, which includes 4 flooding pools and a pressure suppression system, as required by the pressure suppression system. It is considered that the containment design pressure is determined by a maximum LOCA, which is expected to result in a design pressure of about 0.2-0.3 MPa. It should be noticed that since the containment is similar to an advanced design BWR, which in turn conforms to the EUR, it is highly expected that the proposed HPLWR containment will also conform to the EUR as well as to the Generation IV safety criteria.

4.1. Drywell
In addition to the RPV and the three main steam and feed-water lines, the following components are located within the drywell: four hydraulically linked flooding pools, the emergency condensers and containment cooling condensers for passive heat removal and the flooding lines for passive flooding of the RPV. In addition, the drywell is equipped with two 100%-capacity re-circulation air-cooling systems. Also the lines of the residual LP injection/heat removal system are located inside the drywell.

The main steam lines and feed-water lines connected to the RPV are each equipped with two isolation valves, one located inside and one outside the dedicated containment penetrations.

It is planned to install the residual heat removal pumps and heat exchangers in separate compartments located underneath the containment, which are designed to withstand containment pressure. They are accessible from outside at all times for maintenance and servicing.

4.2. Pressure Suppression Pool
The pressure suppression pool performs the following tasks:
• Acts as heat sink in the event of accident conditions
• Provides a water inventory for active RPV makeup via the LPCI-residual heat removal system.

As part of the pressure suppression system, the pressure suppression pool is located between the outer and the inner cylinder below the core flooding pools. The pressure suppression pool is connected to the drywell via vent pipes, which are concrete embedded into the inner cylinder. In addition, the pressure suppression pool and core flooding pools are connected to each other via submerged water overflow pipes, which are not shown in Fig. 2.

4.3. Core Flooding Pools
The core flooding pools act as a heat sink for the emergency condensers and the safety relief valve system. In addition, owing to the pool elevation, the water in the core flooding pools is used for passive flooding of the reactor core following RPV depressurization in the event of a LOCA and in cases after automatic depressurization. In this function spring check valves open the flooding lines automatically. Passive flooding is expected to serve as a diverse long-term supplementary function to the active injection systems for core cooling. Specifications for the interventions have not been specifically defined at this stage of the design.

In the event of a serious core melt accident; the water inventory in the core flooding pools is used for cooling the RPV from the outside.

The core flooding pools are located above the pressure suppression pool. The physical separation of the core flooding pools is achieved via four plant compartments in which components, piping and ventilation units are located. Each core flooding pool houses an emergency condenser, a containment cooling condenser (above the water level), a RPV flooding line connection, and the relief lines of the safety relief valves with steam quenchers. In addition, a flooding line for RPV cooling from the outside leads into the
4.4. Containment and Safety Concept

Concerning the containment design, the proposal is to consider a modern BWR containment and to introduce passive features into the design; the containment should be provided with a core flooding pool, containment cooling condensers, and emergency condensers. The safety systems configuration should be modified in two essential areas in relation to considered modern BWR: (1) the auxiliary feedwater pumps should be omitted, (2) a passive core flooding pool with emergency condensers should be provided. The reason for this modification is that the mass of water within the RPV is about 1/10 of that of a BWR or PWR. Therefore, in case of LOCAs and transients like “loss of offsite power”, the safety philosophy of such reactors to maintain the primary pressure and consequently the heat capacity of the existing water is not appropriate in case of an HPLWR. Instead of using a high-pressure feedwater injection with all the complications mentioned above, it is proposed to initiate the automatic depressurization system (ADS) and use the existing low-pressure injection system and the passive flooding system.

With this proposed containment and the safety concept it is considered that an extensive use of passive systems is reached by integration of water capacity outside the RPV, that compensates for the lack of large water mass and natural convection within the RPV of an HPLWR. This safety concept is compatible with the guidelines of the EUR and of Generation IV reactors, as it will be presented in Section III.

III. General Application of Some Safety Requirements

Since the HPLWR is considered to be a long term development project which is expected to be realized in the far future (by approximately 2020, similarly to the Generation IV nuclear reactors that are now being assessed by the U.S. DOE and the Generation IV International Forum (GIF)), it is somewhat difficult to foresee the requirements which will be appropriate at that time. Therefore, it was decided to take into account as a general guide, the European Utility Requirements (EUR), which are currently considered to be most advanced and most complete in Europe and have been applied in the design of advanced LWRs such as the EPR and the SWR 1000 (detailed designs of which are very advanced). Additionally, the trends of future requirements, as expressed in the requirements known from the Generation IV initiative, was considered in order to include further advanced ideas.

The major objectives of the EUR document have been to develop requirements addressed to the LWR plant designers and vendors. It is a tool for promoting the harmonization of the most important plant features that were often too country specific. The main items considered in this convergence process are the safety approaches, targets, criteria and assessment methods, the standardized environmental design conditions and design methods, the performance targets, the design features of the main systems and equipment, and—at a lower level—the equipment specifications and standards.

Since the potential safety features of the HPLWR are based on preliminary plant and core design information, the full conformance assessment required by EUR could not be carried out. Instead a general evaluation for some important and selected items in the EUR safety requirements is presented in some detail in table form. A short summary of the results of these tables will be described in this paper. A more detailed evaluation of the conformity of the HPLWR against the EUR could be pursued concurrently with the completion of a more detailed design of the HPLWR. In addition, the HPLWR potential safety features are also compared in general terms with the Generation IV Safety and Reliability Requirements, and resulting conclusions are presented.

1. Estimation of the HPLWR’s Potential to Meet the EUR Safety Requirements

Some of the EUR requirements were considered and compared with the HPLWR general features. A comparison is made between some quantified (i.e. numerical values) of the EUR top tier requirements and the HPLWR. The objective of this comparison is to show that we estimate that the HPLWR has a potential to meet these requirements, considering the qualitative arguments made in two tables formed for the primary system and containment system.

However, as already mentioned above, it should be realized that the task of comparing the HPLWR to the EUR is quite substantial. Such a comparison can only be made after the HPLWR design becomes more mature and includes adequate detailed description of the entire power plant. On the other hand, it is advantageous to examine carefully the EUR requirements during the design stage, in order to assure the fulfillment of these requirements later on. Presently, it is necessary to continually monitor the preliminary basic design in relation to the EUR safety requirements. Thus it is clear that such a process is iterative, and a design of a new power plant such as the HPLWR can create substantial savings by considering the requirements in every step from the very beginning.

The HPLWR is being evaluated with particular emphasis on improved economics while maintaining the safety and reliability level achieved by advanced LWR. As mentioned above, it will rely on passive safety features to flood the core when necessary and to cool the containment. As the design of the HPLWR progresses and matures, additional evaluations will also be performed to assess the potential for new passive safety systems in the HPLWR design. In addition, the HPLWR design relies in part on existing proven technologies (e.g. supercritical fossil power plants).

As a further difference to current BWR, the HPLWR will have stainless steel fuel cladding instead of Zr, thus the consequences of Zr-water reaction are eliminated and the potential consequences of severe accidents are reduced. A demonstration that a severe accident could be contained.
within the containment building could eliminate the need for offsite emergency response. In general, substantially smaller hydrogen quantities, due to severe accident, are expected for the HPLWR.

A special attention is paid to detailed and reliable neutronics/thermal-hydraulics analyses of the HPLWR that will result in a safe and reliable core design with acceptable reactivity coefficients.

In summary, the HPLWR will use existing European severe accident design strategy for advanced LWR that has the potential to eliminate the need for offsite emergency response, in particular when the potential consequences of a severe accident in the HPLWR are smaller. The HPLWR will satisfy the necessary design (e.g. EUR) and regulatory requirements, and will be subject to the scrutiny of the regulatory and other Government authorities thus fulfilling this goal.

2. Generation IV Technology Goals in the Safety and Reliability Area vs. HPLWR

The Generation IV goals are defined in the broad areas of sustainability, safety and reliability, and economics. Sustainability goals focus on fuel utilization, waste management, and proliferation resistance. Safety and reliability goals focus on safe and reliable operation, investment protection, and essentially eliminating the need for emergency response. Economics goals focus on competitive life cycle and energy production costs and financial risk. The detailed discussion of each goal is given in [7]. Only, the safety and reliability related aspects of the Generation IV technological goals in relation to HPLWR are specifically elaborated in this sub-section.

Since many aspects of conceptual HPLWR design are not known in detail until the completion of the basic design and the related research and development efforts, general guidelines for the Generation IV technology goals in the safety and reliability area vs. HPLWR are provided in some detailed tables [9]. This comparison indicates that the present preliminary design of the HPLWR has the potential to meet most of these goals. It is also to be noted that, in general, the Generation IV requirements are generally compatible with the top tier EUR document [5, 6]. This is an important observation, since by using the EUR as a guide for the detailed design of the HPLWR, it will also insure the conformity of the HPLWR with Generation IV goals.

IV. Transient Safety Analyses

The supercritical HPLWR reactor represents a challenge for best-estimate safety analysis codes like RELAP5, CATHARE and TRAB since such codes were developed for two-phase or single-phase coolant at pressures far below the critical point. These codes were improved to be appropriate for some of the preliminary HPLWR safety analyses. Thus, the steady-state conditions and some selected transients, in which the system pressure remains above the critical pressure, were predicted by RELAP5, CATHARE and TRAB. The RELAP5 code was also used to evaluate the impact of losing the thermal insulation of the water rods and to study the feasibility of substituting solid moderator rods instead of water rods.

As an example the following transients were analyzed with the RELAP5/MOD3 code [9, 11]: (1) loss of feed water heating, (2) reduction of coolant flow, and (3) loss of off-site power. The TRAB (reactor dynamics) code of VTT was used to analyze the following power excursion transients [16]: (a) inlet temperature transient (280 to 260 °C in 1 sec), (b) inlet mass flow transient (1816 to 908 kg/s in 1 sec), (c) outlet pressure increase transient (25 to 27 MPa in 1 sec), (d) outlet pressure decrease transient (25 to 23 MPa in 1 sec). The results of the TRAB analyses indicate that the code can, in principle, analyze the HPLWR dynamics and showed that the HPLWR system behaves as expected at super-critical pressures and that the transients reach almost stable conditions after 10-20 seconds. Additional modelling effort is needed to improve the code capabilities.

For the RELAP5 analysis, the sequence of events, the initial and boundary conditions as well as the assumptions for the calculations were mainly taken from previous studies performed by the University of Tokyo [2, 12, 13] using codes especially developed for this type of reactors. For the transient analysis, a simplified plant model was developed for RELAP5 [5, 11]. This model uses a point kinetics model with the reactivity coefficients taken from [14] in order to account for the feedback between neutronics and thermal-hydraulics.

From the performed investigations, results of the second transient (reduction of coolant flow) are presented here. As initiating event, the feed-water flow reduction from 1816 kg/s (nominal value) to 908 kg/s within 1 s is assumed. This leads to an increase of the coolant temperature and thus to a strong coolant density reduction. In Fig. 3, the development of the core averaged coolant density and fuel temperature are given. As a result of two competing reactivity feedbacks (Doppler and moderator) the resulting total reactivity rapidly decreases until about 2.5 s. Later on, it steadily increases stabilizing at around –0.1 $. The core power follows the trend of the total reactivity. At the end of the transient the power also stabilizes at about 63% of its nominal value, see Fig. 4. For this transient the maximum cladding temperature amounts to 975 K, which is below the transient criteria of 1113 K for cladding material based on Ni-alloy.

The results obtained for the other transients using RELAP5 code are similar to those obtained by the University of Tokyo [13]. It has to be mentioned that in case of fast de-pressurization transients (e.g. blow-down phase of LOCAs), RELAP5 still encounters difficulties that must be remedied. Nevertheless, RELAP5 can, at this stage of the project, be used for some core design optimisation studies.
CATHARE is usually used for pressures in the sub-critical region, but after introducing steam tables including properties up to 26MPa, it was possible to develop a modified version of the standard CATHARE (version V1.5a) code, which is able to simulate transients where both supercritical and sub-critical regimes are encountered. The “reference concept” of the HPLWR 2) has been modelled with CATHARE. Two transients were analysed using a very simple model of the HPLWR 9, 15). These transients are: feed-water line break and steam line break. In both cases, the transient behavior appears to be well calculated from supercritical to sub-critical regimes and without numerical problems (Figs. 5 and 6). In fact, the supercritical regime lasts one or two seconds only. However, additional effort is necessary to improve the physical models in the code, to verify it and to validate it against experimental data, as it is also the case for RELAP5.

From the HPLWR investigations to-date it can be concluded that the codes that are mentioned above have the potential to be used as a reliable safety analysis tools within the framework of the HPLWR project. However, additional improvements of numerical method and physical models as well as further code qualifications are necessary to fully cover the analyses of postulated HPLWR transients and accidents.

V. Conclusions

The safety philosophy of the HPLWR is based on existing advanced LWR designs and it follows the EUR and Generation IV guidelines and criteria. Whereas the Generation IV criteria are more general and set the safety principles, the EUR guidelines are comprehensive and numerous, more specific and compatible with Generation IV. In order to be able to assess the safety readiness of the HPLWR, three conditions must be satisfied: (1) the HPLWR design must be completed and all safety systems must be finalized, (2) analytical safety tools must be verified against experimental data and validated, (3) the regulations that the HPLWR is expected to fulfill must be defined, and understood for application.

At the conclusion of the HPLWR project under the 5th FP, the HPLWR design has not been completed in sufficient details to perform accurate safety analysis, the expected regulations have not been explored and the computer codes that could be used to perform safety analysis have not been
fully validated and verified for supercritical water conditions. However, despite these shortcomings, the qualitative safety information presented, supports the contention that the HPLWR can be designed to operate safely and is expected to reach the safety level of advanced LWRs. Furthermore, the information and experience obtained on the use of transient analysis codes clearly demonstrates that reliable well-known computer codes that are currently being used in the safety analyses of LWRs will be able to analyze the HPLWR after additional development and verification. The preliminary results shown also indicate that these codes, in their present preliminary status, can already be used to help define and optimize the necessary safety systems of the HPLWR.

Nomenclature

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>ABWR</td>
<td>Advanced Boiling Water Reactor</td>
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<tr>
<td>ALWR</td>
<td>Advanced Light Water Reactors</td>
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<td>AC</td>
<td>Alternate Current</td>
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<td>ADS</td>
<td>Automatic Depressurization System</td>
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<td>BWR</td>
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<td>Framework Program of EC</td>
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<td>GIF</td>
<td>Generation IV International Forum</td>
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<td>HP</td>
<td>High Pressure</td>
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<td>HPLWR</td>
<td>High Performance Light Water Reactor</td>
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<tr>
<td>I&amp;C</td>
<td>Instrumentation and Control</td>
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<tr>
<td>LOCA</td>
<td>Loss Of Coolant Accident</td>
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<td>LP</td>
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<td>Reactor Pressure Vessel</td>
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<td>Zr</td>
<td>Zirconium</td>
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