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# Conceptual design studies for the European DEMO divertor: First results

J.H. You[a]*, G. Mazzone[b], E. Visca[b], Ch. Bachmann[c], T. Barrett[d], G. Brolatti[b], V. Cocilovo[b], F. Crescenzi[b], P. K. Domalapally[e], D. Dongiovanni[b], S. Entler[e], G. Federici[c], P. Frosi[b], M. Fursdon[d], H. Greuner[a], D. Hancock[d], S. McIntosh[d], A. v. Müller[a], M. T. Porfiri[b], G. Ramogida[b], J. Reiser[f], M. Richou[g], M. Rieth[f], S. Roccella[b], A. Rydzy[b], R. Villari[b], V. Widak[f]

*[a]Max Planck Institute for Plasma Physics, Boltzmannstr. 2, 85748 Garching, Germany*
*[b]ENEA, Unità Tecnica Fusione, ENEA C. R. Frascati, via E. Fermi 45, 00044 Frascati, Italy*
*[c]EUROfusion PPPT, c/o IPP, Boltzmann Str. 2, 85748 Garching, Germany*
*[d]CCFE, Culham Science Centre, Abingdon OX14 3DB, United Kingdom*
*[e]Research Cnter Rez, Hlavní 130, 250 68 Husinec – Řež, Czech Republic*
*[f]KIT, IAM, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany*
*[g]CEA, IRFM, F-13108 Saint Paul Lez Durance, France*

In the European fusion roadmap, reliable power handling has been defined as one of the most critical challenges for realizing a commercially viable fusion power. In this context, the divertor is the key in-vessel component, as it is responsible for power exhaust and impurity removal for which divertor target is subjected to huge high heat flux loads. To this end, an integrated R&D project was launched in the EUROfusion Consortium in order to deliver a holistic conceptual design solution together with the core technologies for the entire divertor system of a DEMO reactor. The work package 'Divertor' consists of two project areas: 'Cassette design and integration' and 'Target development'. The essential mission of the project is to develop and verify advanced design concepts and the required technologies for a divertor system being capable of fulfilling the physical and system requirements defined for the next-generation European DEMO reactor. In this contribution, a brief overview is presented of the works from the first project year (2014). Focus is put on the loads specification, design boundary conditions, materials requirements, design approaches, and R&D strategy. Initial ideas and first estimates are presented.

Keywords: DEMO, tokamak, divertor, plasma-facing component, conceptual design, Eurofusion

## 1. Introduction

In the recent European roadmap drafted for realizing commercially viable fusion power generation, reliable power handling was defined as one of the most critical missions [1]. In this regard, divertor is the key in-vessel component, since it is responsible for power exhaust and impurity removal via guided plasma exhaust. Due to the intense bombardment of energetic plasma particles, the plasma-facing targets of the divertor shall be exposed to extreme heat flux loads. In addition, neutron irradiation produces defects and damage in the materials leading to embrittlement. Pulsed operation causes fatigue owing to thermal stress variation. The complex and harsh loading environment a divertor is subjected to poses particularly challenging engineering issues that have to be solved for materializing a DEMO reactor. To this end, an integrated R&D program has been launched in the framework of the EUROfusion Consortium in order to deliver holistic solutions of full conceptual design together with the core elements of required technologies for the entire divertor system of a DEMO reactor. The essential mission is to develop and verify advanced divertor design concepts and technologies being capable of fulfilling the physical requirements and the system-level specifications defined for the early-generation European DEMO reactor (the so called DEMO 1).

In this article, a brief overview is presented on the project structure, objectives, rationales, approaches, and the first results obtained from the tasks carried out in 2014. The aim of this contribution is to provide readers with basic information on the current project activities and the background ideas of design approaches.

## 2. EUROfusion work package 'Divertor'

The divertor project (WPDIV) has been installed as a work package associated with the 'Power Plant Physics & Technology' Department (PPPT) of the EUROfusion. WPDIV consists of two project areas: 'Cassette design & integration' and 'Target development'. Fig. 1 shows the schematic work breakdown system. WPDIV is supported by a consulting panel of external experts who perform design progress review for the subproject Cassette (v.s.). The Project Board is mainly in charge of the surveillance of contractual progress and approval of major budgetary change or modification of scopes. As a part of PPPT, WPDIV is linked to other 12 work packages involved in PPPT via diverse technical interfaces. 6 leading research institutions in EU are participating in WPDIV. In total, a gross budget of 10 million euros were allocated for the first 5 years (2014-18), an extension of further 2 years is foreseen with additional budget. The delivery of the final Conceptual Design Report is due by end of 2020.

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*author's email: you@ipp.mpg.de (Jeong-Ha You)*

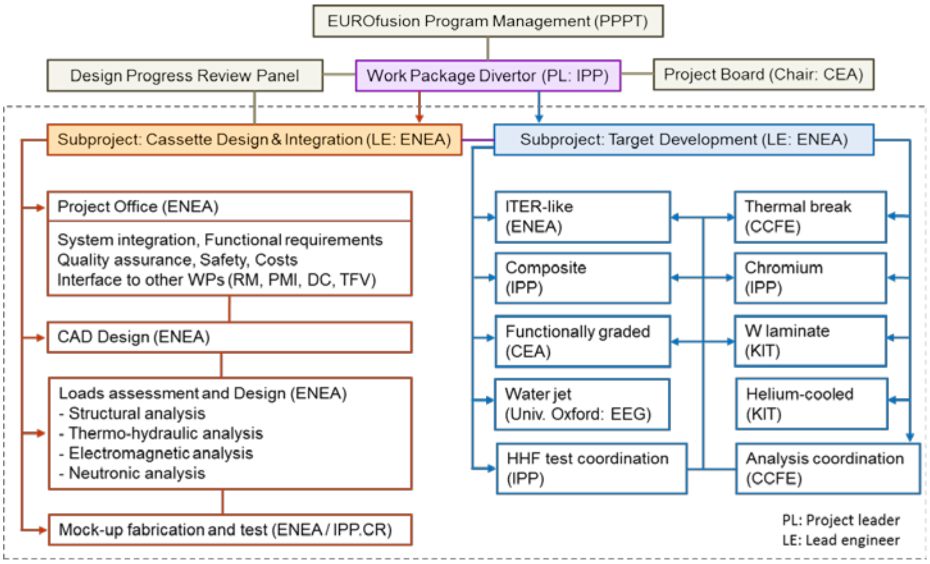


Fig. 1. Schematic project breakdown system of the EUROfusion work package ‘Divertor’.

## 3. Subproject: Cassette design and integration

### 3.1 Baseline CAD models

The first version of CAD contour model of a single divertor cassette was created in 2014. This starting draft was essentially based on the ITER divertor geometry as plotted in Fig. 2 (a). In 2015, the second version of CAD contour model was produced as illustrated in Fig. 2 (b). The interior details of the cassette are currently designed. Compared to the first version, the revised cassette model is characterized by a reduced volume. Both outboard and inboard baffle parts have been removed from the cassette while the breeding blanket has been extended instead. The tritium breeding ratio (TBR) is predicted to increase from 1.13 to 1.20 by the gain of the additional breeding areas. In case of a double null plasma configuration, the TBR is decreased, but not less than 1.13 with the revised configuration. The loss in TBR due to the divertor area is estimated to be 0.07.

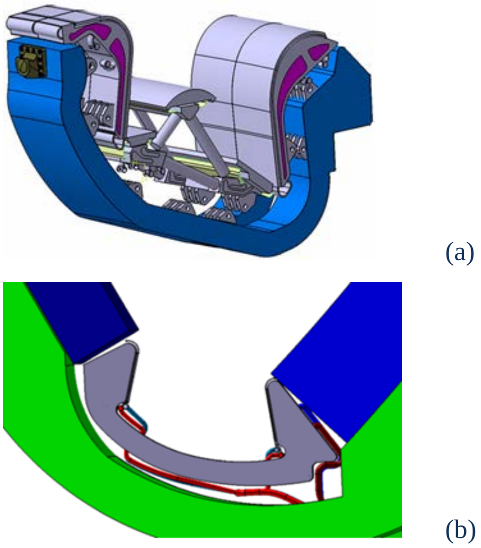


Fig. 2. CAD contour models of a single divertor cassette (a): 1st version of year 2014, (b) 2nd version of year 2015

For the time being the dome is not contained in the new CAD model for the sake of design simplification, but equipment of cassette with a dome is still considered as an option. A comparative study is ongoing to evaluate the impact of the absence of a dome. Decrease of neutral gas pressure, reduced efficiency of radiative cooling and pumping, potential gas flow toward the core plasma, and reduced shielding against neutron and heat flux are the primary issues. The issues are investigated together with the work package ‘Tritium fuelling and vacuum’.

### 3.2 Thermal loads: preliminary estimates

As the current subproject is still situated in an early stage, a rigorous estimation of the expected loads is very difficult. The main reasons for this are that the physical boundary conditions and the operational scenarios have not been identified yet for DEMO and that the design of cassette interior has not been finalized yet. Nevertheless, first estimates of basic load parameters were produced to get a rough indication about loading features. The loads were categorized into 5 types: thermal, electromagnetic, neutronic, and mechanical (static, dynamic). The atomic loads on the surface casing sputtering and blistering are handled in the dedicated work package ‘plasma-facing components’. As a starting basis thermal load parameters are assumed as follows [2]:

Total fusion power: 2037 MW
Power for external heating: 50 MW
Power carried by radiating neutrons: 1630 MW
9 % thereof in divertor cassette: 147 MW
Total power radiated from the core: 238 MW
10 % thereof on divertor PFC: 24 MW
Plasma power extracted via scrape-off layer: 220 MW
90 % thereof dissipated by gas radiation: 198 MW
30 % thereof on the divertor PFC: 66 MW
10 % exhausted by bombardment on target: 22 MW
67 % thereof on outer strike point: 15 MW
33 % thereof on inner strike point: 7 MW,

where PFC stands for plasma facing components.

Summing up the individual contributions to each part of a divertor segment, thermal load partition is obtained as follows:

| | |
|---|---|
| Total power imposed on divertor: | 259 MW |
| in cassette: | 147 MW |
| on PFCs: | 112 MW |
| 15 MW thereof on outer strike point | |
| 7 MW thereof on inner strike point | |

It should be noted that the strike points on the targets are subjected to the most intensive heat flux loads, since the thermal power density sharply peaks at these sites due to the narrow width (several millimeters) of the strike band. The heat flux profile on the divertor PFCs and the peak heat flux density at the strike point could not be exactly specified yet, as the operational scenarios have not been identified yet. As a starting basis, a maximum heat flux load of 10 and 20 MW/m² is assumed on the target for normal operation and slow transient events (i.e. loss of detachment), respectively. These heat flux values are the same as those of the ITER divertor target [3].

### 3.3 Nuclear loads: preliminary estimates

Due to the absence of design details of cassette interior and lacking data on plasma operation parameters, it was not possible to make a precise neutronics analysis in this early stage of project. A rough preliminary assessment was made of dpa dose and nuclear afterheat on the basis of the first CAD model of cassette and ITER type PFC. The loading condition considered was extrapolated from those of ITER divertor assuming a fusion power of 1600 MW, which is in the meantime obsolete.

The dpa of the copper heat sink and the tungsten armor of the PFC were predicted to reach up to 10 and 2 dpa on the target per a full power year (fpy), respectively.

The nuclear afterheat generated in divertor was predicted to amount to 161 MW in total, thereof 39 MW in inner target, 56 MW in outer target, 39 MW in dome, and 27 MW in cassette body.

Neutronics analysis is carried out repeatedly, if geometry or radiological data are updated by any design change. Regular revision of neutronics analysis is foreseen at the end of each calendar year coupled with the revision of the CAD model.

### 3.4 Materials and the operation temperatures

The baseline PFC armor material for DEMO divertor is tungsten. As baseline structural materials copper alloy CuCrZr has been chosen for the PFCs and ferritic steel Eurofer97 for the cassette body, respectively.

The selection of CuCrZr alloy (or Cu-base composites) as heat sink material of the PFC is owing to the excellent thermal conductivity and superior mechanical properties required for a structural application such as strength and ductility at envisaged operation temperatures [4]. Such an ideal combination is the unique and exclusive merit of copper alloys or copper-base composites. Thus, for the high heat flux region of the divertor PFCs

It is noted that each of these materials are subject to a recommended service temperature range to avoid critical embrittlement, when operated under neutron irradiation [5]. For CuCrZr alloy the lower service temperature limit under irradiation lies between 150 °C and 250 °C. The exact specification of this temperature limit depends on the specific structural design criterion to be applied for design. When uniform elongation is used as criterion, the limit should be 250 °C, whereas it is set 150 °C, in case total elongation criterion is considered. In this judgment, the guiding rationale is to assure the capability of plastic deformation to rupture with a sufficient strain margin for a given operation temperature range.

The allowable lower temperature limit of PFC operation is determined by three fundamental design factors: 1) the required thermohydraulic margin of cooling condition to prevent coolant burnout at the critical heat flux, 2) the degree of thermal recovery of irradiation damage which is measured as tensile strains and 3) the degree of design conservatism adopted for the structural design of the heat sink. The physical basis of the ductility requirement is the ability of irradiated CuCrZr alloy to undergo thermal recovery of lattice defects at relatively low temperatures compatible with pressurized water-cooling conditions as addressed above.

The allowable upper temperature limit of PFC operation is determined by the unacceptable loss of tensile strength of structural heat sink material due to thermal softening and irradiation creep. In case of the baseline heat sink material, CuCrZr alloy, the recommended upper service temperature limit is 350 °C for long term operation [5]. A further constraint related to the heat sink application of CuCrZr alloy is the issue of corrosion erosion which may occur on the inner wall of cooling tube to a serious degree, when the wall temperature is above 200 °C and the water chemistry is not properly controlled.

For massive cassette body, the reduced activation 9Cr steel Eurofer97 is considered as structural material. The motivation of using this steel for cassette is to exploit the essential benefits of the superior low activation feature to allow recycling of the material within a due period (say, a couple of centuries).

As structural material, Eurofer97 steel is also subject to a recommended service temperature range to avoid brittle failure caused by irradiation embrittlement or undesired creep-fatigue interaction. When irradiated, the ductile-to-brittle transition temperature (DBTT) of Eurofer97 steel is shifted up to 300 °C. Thus, it is generally desired to operate the steel cassette above the DBTT to prevent any brittle failure. But the lower temperature limit of Eurofer steel can be still decreased, if the peak stress intensity is not so strong or the irradiation dose is not high.

### 3.5 Cooling schemes

In the design framework of the early DEMO (also called DEMO 1), only a water-cooled divertor is considered as baseline design concept.

The conceptual layout design of the piping systems for the water cooling of cassette has been currently devised. Initially, two different options were under consideration. The first option is single coolant circuit applied in series to both the PFCs and cassette body. The second option is dual separate coolant circuits each applied independently to the PFCs and cassette body, respectively. Each option has its pros and cons. In the course of design evolution, it turned out that the cooling option with dual separate coolant circuits is advantageous in terms of mechanical performance of irradiated materials, pressure drop, and power exhaust efficiency.

### *3.5.1 Thermohydraulic analysis for the 2014 model*

In the first project year, where an ITER-like divertor was considered, a preliminary conception of cooling scheme was produced for the divertor version of year 2014. The single coolant circuit concept was adopted. A schematic drawing of the cooling scheme is illustrated in Fig. 3. In this scheme, the streaming sequence of the coolant is as follows: inlet at outboard cassette body, outboard target, outboard baffle, outboard cassette body, inboard cassette body, inboard target, inboard baffle, inboard cassette body, dome umbrella, and finally outlet.

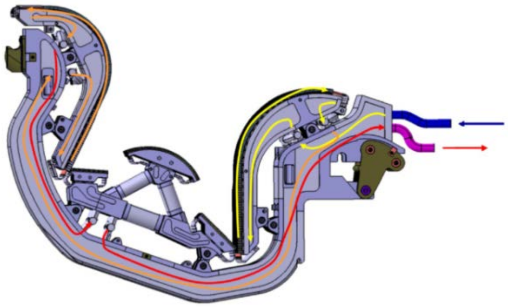


Fig. 3. Schematic drawing of preliminary cooling scheme devised for the ITER-like divertor (first version of year 2014). Single coolant circuit concept was adopted.

A preliminary thermohydraulic analysis has been carried out for the first cassette model of year 2014 by means of FEM-based computational fluid dynamics analysis. For this, three-dimensional FEM models were created for the tubular cooling channel and coolant distributor manifold. The estimated parameters are summarized in Table 1.

Table 1. Estimated thermohydraulic performance of the single coolant circuit cooling concept (the 1st cassette model in 2014).

| | OVT[1] | IVT[2] | Dome |
|---|---|---|---|
| No. of PFC units per cassette | 50 | 50 | 50 |
| Channel diameter (m) | 12 | 12 | / |
| Channel roughness (μm) | 1.4 | 1.4 | 1.4 |
| Power in the OVT (MW) | 92.8 | 59.5 | 46.5 |
| Swirl tape length (m) | 0.7 | 0.6 | / |
| Twist ratio | 2 | 2 | / |
| Tape edge (mm) | 0.8 | 0.8 | / |
| Water velocity (m/s) | 16-17.5 | 24-26 | 15.5 |
| Mass flow rate per pipe (Kg/s) | 1.67 | 1.67 | tbd. |
| Gross mass flow rate (Kg/s) | 4008 | 4008 | 4008 |
| Inlet pressure (MPa) | 5 | 3.93 | 1.92 |
| Outlet pressure (MPa) | 3.9 | 2.1 | 0.26 |
| Total pressure drop (MPa) | 1.1 | 1.8 | 1.84 |
| Pressure drop by swirl tape | 0.37 | 0.7 | / |
| CHF margin | 1.84 | 1.82 | tbd. |
| Inlet temperature (°C) | 150 | 155.4 | 158.8 |
| Outlet temperature (°C) | 155.4 | 158.8 | 161.5 |
| Temperature increase (°C) | 5.4 | 3.4 | 2.7 |

[1] OVT, [2] IVT: outboard and inboard vertical target

The input parameters of coolant at inlet are as follows:

- temperature: 150 °C
- pressure: 5 MPa
- velocity: 16 m/s
- tube diameter: 12 mm (with swirl tape)

These cooling parameters were derived primarily under the thermohydraulic condition to assure the minimum required power exhaust capability of the target for whole operational scenarios of divertor. The design goal was to reach a sufficient thermal margin to the local critical heat flux (CHF) to prevent bulk boiling and burnout accident even for slow transient events. The envisaged heat flux margin to the local CHF at the cooling tube of the target ranges between 1.3 and 1.6 depending on the target PFC geometry. It is noted that the current combination of the cooling parameters leads to the local CHF value of about 48 MW/m².

The results of thermohydraulic analysis manifest that the cooling via single coolant circuit is not adequate at least for the given cassette model due to the facts that:

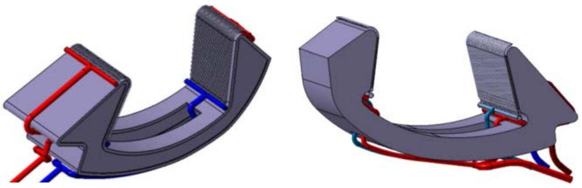
1. the total pressure drop is unacceptably large,
2. the coolant temperature in cassette body is too low for Eurofer steel to be operated in ductile regime.

To solve the issues, the coolant channels need to be laid out separately, each for the PFC and cassette body. Thus, the single coolant circuit option was abandoned, and the dual separate coolant circuit concept is further pursued. However, this decision has no major implication on the design of cassette contour.

### *3.5.2 Cooling scheme for the 2015 model*

In the second project year (2015) a revised CAD model of cassette has been created. A major design change was implemented: the outboard and inboard baffles were cut off from the cassette while the breeding blanket modules were extended to cover the previous baffle regions. The motivation of this design modification was to increase the TBR as much as possible by exploiting the high dose plasma-facing areas available for tritium breeding. The cassette body contour was shaped in accordance with the kinematic envelop required for remote maintenance.

Accordingly, a completely new cooling scheme has been devised based on dual separate coolant circuits. At the moment, two different piping schemes are considered as illustrated in Fig. 4 (a) and (b).
Cooling parameters are to be specified in near future for the PFCs and cassette body, respectively. The cooling condition for the PFCs will not be altered. In the case of cassette body, the DBTT of irradiated Eurofer steel will be taken into account for the specification.



(a) (b)

Fig. 4. Two different piping schemes for cassette cooling based on dual separate coolant circuits (model of year 2015).

## 4. Subproject: Target development

### 4.1 Design rules for the monoblock type target

As there is no suitable structural design rules being specifically applicable to a monoblock-type target with a brazed structure, dedicated elastic structural design rules have been developed together with analysis guidelines. Plastic structural design rules are currently being worked out. The objectives of the elastic structural design rules are to provide standardized criteria against major failure modes on the basis of characteristic loading natures and failure features being found in monoblock-type targets. In addition, a generic computational procedure has been defined for comparable FEM analysis. Strictly speaking, only the coolant tube is structural part, thus being subject to the structural design rules.

In the elastic rules, the copper alloy tube is assumed to be elastic while the copper interlayer is assumed to be elasto-plastic in order to take the significant plastic flow of soft copper into account. In this way, residual stress from manufacture process is calculated more accurately. Tungsten armor block is assumed to be elastic as non-structural part. It is only to be used for an initial design assessment (e.g. geometry optimization). More rigorous design assessment will be provided by the elasto-plastic analysis procedure and design rules due in 2017.

Two elastic rules were selected including ratchetting (3Sm) and fatigue (elastic stress range). These rules are found to remain valid irrespective of the residual stress. Further, three thermal rules were defined: maximum heat flux at the coolant tube wall, and the peak temperatures in the tube as well as armor. In case substantial residual stress is present, accurate computation of actual strains is hardly possible within the elastic framework. Due to this essential limitation, the elastic rules should be regarded as provisional design criteria.

### 4.2 Design concepts for target PFCs

One of the major challenges for developing a reliable target for DEMO divertor is to find a heat sink material that is able to fulfill the relevant structural design criteria at the irradiation dose level and the heat flux load range foreseen for DEMO divertor. It seems that CuCrZr alloy cannot fully meet the requirements. Thus, advanced Cu-base materials or novel design concepts are employed for target development.

Table 2. Design concepts for DEMO divertor target and dome being considered in EUROfusion WPDIV.

| Concepts | Heat sink materials |
|---|---|
| ITER-like | CuCrZr tube (baseline concept) |
| Thermal break | CuCrZr tube with Cu felt interlayer |
| Composite | W wire Cu composite ($W_f$/Cu) tube |
| Chromium | Cr monoblock, CuCrZr tube, W tile |
| FGM | CuCrZr tube with W/Cu interlayer |
| W laminate | W/Cu laminate, W/V laminate tube |

In Table 2, the design concepts for DEMO divertor target being currently employed in the WPDIV are listed with description of the respective heat sink materials. The underlying idea of innovation is either to enhance the material performance in terms of high-temperature strength (W wire-reinforced Cu composite tube, W/Cu laminate tube) or to reduce thermal stress (FGM, thermal break), DBTT (chromium), or heat flux concentration at tube (thermal break). The designs are based mostly on W monoblock geometry (except the chromium PFC).

For some target design concepts, the materials and test mock-ups have been successfully fabricated. Figs. 5 and 6 show two examples of such mock-ups equipped with either a W/Cu laminate tube or thermal break layer made of porous Cu felt, respectively.

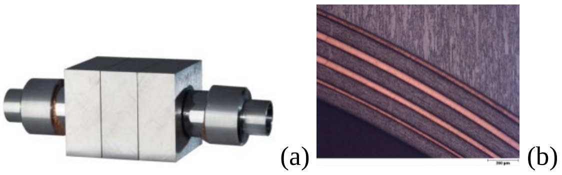


Fig. 5. Divertor target mock-up (a) with W/Cu laminate tube (b).

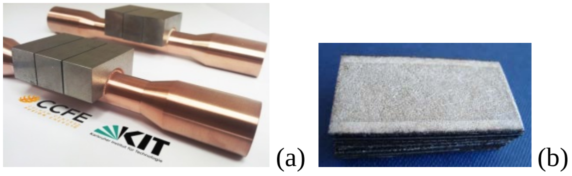


Fig. 6. Divertor target mock-up (a) with a thermal break interlayer made of porous Cu felt material (b).

## 5. Summary

In order to produce the conceptual design of DEMO divertor, an integrated R&D program WPDIV has been launched in 2014 in the framework of the EUROfusion Consortium. Design schemes and loading features have been identified. Technology development is on-going.

## Acknowledgments

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