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# A Study on Fire Modeling of Main Control Benchboard Fire Scenarios for Evaluation of Main Control Room Habitability Conditions

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## 1. Introduction

A fire event probabilistic safety assessment (PSA) is performed on a fire scenario basis. In other words, fire-induced risk, primarily represented as core damage frequency (CDF) for the level-1 PSA and large early release frequency (LERF) for the level-2 PSA, is assessed for each unique fire scenario. A fire scenario in a fire PSA is generally modeled as a progression of damage states of targets such as equipment and cables over time that is initiated by a postulated fire involving an ignition source. A fire modeling analysis in a fire PSA is a tool used to determine the damage states of targets and the associated time, which are essential data for quantifying final fire-induced risk, i.e., the CDF and LERF. [1].

Fire scenarios in the Main Control Room (MCR), especially induced by ignition of Main Control Benchboard (MCB) panels are generally identified as one of the major contributors to the fire-induced risk. This study focuses on the fire modeling analysis of the MCB fire scenarios in the MCR especially for evaluating conditions and probabilities that evacuation from the MCR i.e., abandonment and plant shutdown outside the MCR i.e., alternate shutdown are required. Therefore, the output parameters of interest in this study are those related to habitability of the MCR. Input parameters of interest in this study are those used to generate a heat release rate (HRR) profile of the MCB fires. The HRR profile, which describes fire intensity as a function of time, is the most important element characterizing the fire scenario itself and significantly affecting the results of fire modeling [2] such as properties of fire plume, ceiling jet and hot gas layer (HGL); target response to heat and smoke; and thus habitability conditions of a fire compartment as well.

The objective of this paper is to analyze how the different input parameters for the HRR profile affect the main results such as habitability conditions and timing of forced abandonment of the MCR for the risk-significant MCB fire scenarios.

## 2. Methods and Results

### *2.1 Design features of the reference Main Control Room*

Fig. 1 shows a floor plan of the reference MCR. As shown in Fig. 1, the reference MCR contains various electrical enclosures including the horse shoe type multiple electrical enclosures, called MCB. The MCB is composed of 2.9 m high eleven (11) panels (PM01 – PM11). Each MCB panel is classified as an open large electrical enclosure containing a large number of thermoset cables. A fire in a single MCB panel may spread or propagate to one of adjacent MCB panels. Any fire in the MCB panels may directly lead to function failures or spurious operations of the safety systems related to the corresponding MCB panels. Therefore, the MCB panels are recognized as the most risk-significant fixed ignition sources and intervening combustibles in the MCR.

Main design features of the MCR are as follows:

- Size of compartment:
  W = 21.4 m, D = 18.4 m, H = 3.6 m
- Floor, ceiling and walls: 0.4 m thick concrete
- Mechanical Ventilation:
  24 for injection with a total of 7.08 $m^3/s$,
  16 for extraction with a total of 6.98 $m^3/s$
- Natural Ventilation:
  Six (6) doors closed during normal operation

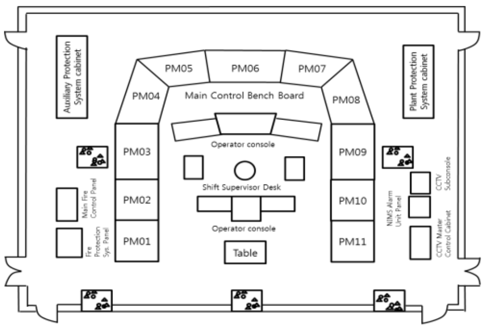


Fig. 1. Floor Plan of the Reference MCR.

### *2.2 Fire scenario and assumptions*

In this study, both CFAST (Consolidated model of Fire And Smoke Transport) [3] and Fire Dynamics Simulator (FDS) [4] were used as tools for the fire modeling analysis. The CFAST is a representative "multi-room two-zone fire model" that can provide quick and simple prediction of fire environments for two control volumes, a relatively cold lower layer and a relatively hot upper layer, conditions within each of which are considered as uniform at any given time. The FDS is a representative "Computational Fluid Dynamics (CFD) model" for fire-driven fluid flow that can provide more accurate and detailed prediction of fire environments especially under more complex and real conditions.

As described above, the main results of fire modeling analysis of this study are habitability conditions and timing of forced abandonment of the MCR at which any of the following abandonment criteria [1] is satisfied.

(1) The incident heat flux at 1.8 m from the floor exceeds 1 kW/m²;
(2) The HGL temperature exceeds 95 °C, which could generate the heat flux condition mentioned above;
(3) The HGL boundary descends below 1.8 m from the floor, AND the optical density (OD) of the smoke is greater than 3 $m^{-1}$.

MCB Fire scenarios are expected to follow the steps shown below:

(1) an initial fire in one of eleven MCB panels;
(2) fire propagation to one of the adjacent cabinets.

A single fire in the MCB panel PM02 (S); and an initial fire in the MCB panel PM02 followed by propagation to the MCB panel PM03 (P) were selected as two representative fire scenarios to be analyzed. The following are bases for this selection.

(1) First, the MCB panel PM02 is related to the CCWS, ESWS, which are safety-critical support systems by themselves, and failures of which cause more challenging fire environment to the MCR by making HVAC system unavailable.
(2) Second, the MCB panel PM03 is related to the ESFs, which are safety-critical frontline systems by themselves, and a fire in the PM03 causes more challenging fire environment to the operators likely to be located near the main operator console.

We conservatively assumed that mechanical ventilation is unavailable from the beginning of the fire in the PM02. We also assumed that a front door near the PM01 is open at 15 min after the initial fire occurs, which makes natural ventilation to the MCR.

Major conditions and assumptions for the HRR profile used in this study are as follows:

- HRR timing profile of the MCB panel fire follows the model shown below [1,5]:
  (1) t-squared growth from zero to peak for 12 min.
  (2) steady burning at peak for 8 min.
  (3) linear decay from peak to zero for 19 min.
- Peak HRR value of a single MCB panel was set either to 702 kW [1] or 400 kW [6].
- Time to fire propagation to an adjacent MCB panel was set either to 15 min [1] or 10 min [1, 7].

Other input parameters including combustion and thermal properties of EPR/CSM cable and structural materials were specified in accordance with the references such as SFPE Handbook 4th ed. [8], NUREG-1805 [9], NUREG-1934 [2], and reference plant design information. The chemical formula of XLPE/Neoprene cable, i.e., $C_3H_{4.5}Cl_{0.5}$, was used for that of EPR/CSM cable because the composition of EPR/CSM cable used for the reference plant is unknown.

The peak HRR value is an important variable as much as, or even more important variable than timing profile i.e., duration time of each stage (growth, steady burning, decay) for determining the fire environments. Recommended HRR values for electrical enclosure fires vary widely by the reference. NUREG/CR-6850 [1] Table G-1 recommends 702 kW as the 98th percentile HRR value of the ignition source category 2, "Vertical cabinets with qualified cable, fire in more than one cable bundle" to which the MCB panel corresponds. According to more recent data NUREG-2178 Vol.1 [6] Table 4-1, the MCB panel corresponds to the classification group 4a, "Large Electrical Enclosures > 1.42 m³" with Fuel Type "TP" and Fuel Loading "Default". The 98th percentile HRR value of classification group 4a with "TP" & "Default" recommend by this table is 400 kW. In this study, we analyzed effects of the peak HRR value of the MCB panel fire by varying it from 702 kW to 400 kW.

Sometime after ignition of a single electrical enclosure, fire may propagate to adjacent electrical enclosure. NUREG/CR-6850 [1] provides recommendations for fire propagation from an exposing cabinet to adjacent exposed cabinets as follows:

- If fire propagation to adjacent electrical cabinets cannot be ruled out given the guidance provided, assume that no significant heat release occurs from the adjacent cabinet for –
  (1) 10 min. if cables in the adjacent cabinet are in direct contact with the wall; or
  (2) 15 min. if cables in the adjacent cabinet are not in direct contact with the wall.

According to NUREG/CR-6850, conservative assumptions including a composite fire comprised of three or more enclosures, 10-min propagation, and instantaneous 98th percentile peak HRRs have typically been used by analysts. Both actual in-plant experiences and insights from testing indicate that this type of fire propagation is not realistic. The most recent data NUREG-2178 Vol.2 (Draft) [7] provides new recommendations for fire spread from an exposing enclosure to an adjacent exposed enclosure as follows:

- Fire spread should be limited to one adjacent enclosure.
- If fire spread to an adjacent electrical enclosure cannot be ruled out given the guidance provided, assume that fire spread occurs 10 min after ignition of the exposing enclosure based on the 'go/no-go' criteria.
- Therefore, the exposed enclosure will begin its 12-min growth stage concurrent with ignition at 10 min. Consistent with the treatment of the exposing enclosure, the exposed enclosure should be assumed to maintain its peak intensity for 8 min, after which it will begin a decay phase that will last no more than 19 min.
- The probability of fire spread from an exposing to exposed enclosure is 0.02, conditional on fire ignition in the exposing enclosure.

In this study, we analyzed effects of this "time to fire propagation to an adjacent enclosure" by varying it from

15 min to 10 min. This parameter is used to generate the HRR profile, which is, as already mentioned, one of the most important elements in fire modeling.

### *2.3 Results of fire modeling*

Fig. 2 shows 3D layout of CFAST model for the MCB fire scenario. Fig. 3 shows 3D layout of FDS model for the MCB fire scenario. CFAST version 7.4.1 (released in August 2019) and FDS version 6.7.0 (released in June 2018) was used in this study.

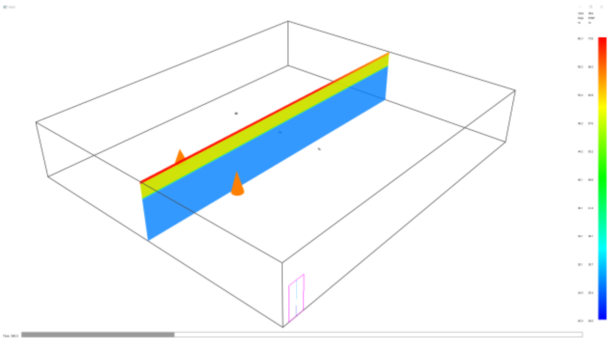

Fig. 2. 3D View of CFAST Model for the MCB Fire Scenario.

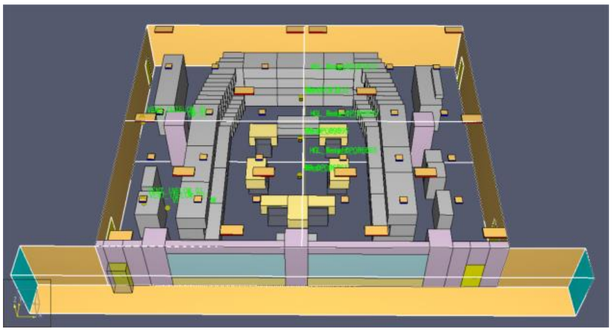

Fig. 3. 3D View of FDS Model for the MCB Fire Scenario.

Fig. 4, 5, and 6 show the HRR profiles of the single MCB fire scenario (Fig. 4), the 15-min MCB fire propagation scenario (Fig. 5), and the 10-min MCB fire propagation scenario (Fig. 6) for the peak HRR value of 400 kW and 702 kW.

It is obvious that the fire propagation results in a higher peak as well as a larger area under the HRR curve because it overlaps two single fire HRR curves. As shown in Fig. 5 and 6, with the fixed peak HRR value, the area under the curve, i.e., total amount of heat released remains unchanged regardless of the propagation time but the shape of curve become steeper as the propagation time decreases. On the other hand, as expected, changes in the peak HRR value from 702 kW to 400 kW lead to the dramatic reduction of the area under the curve as well as the height of the curve.

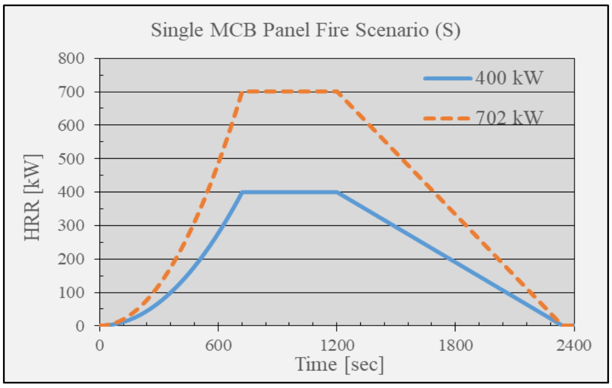


Fig. 4. HRR Profile of the Single MCB Fire Scenario (S) Depending on Peak HRR

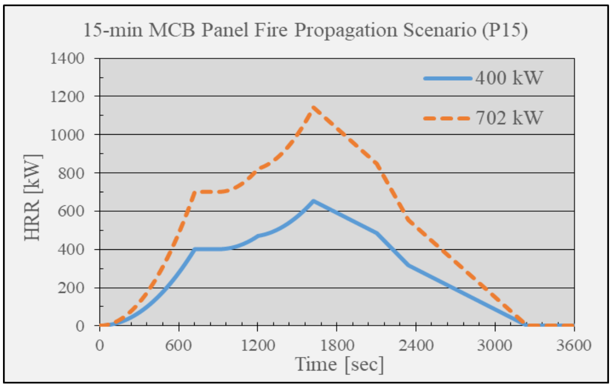


Fig. 5. HRR Profile of the MCB Fire Propagation Scenario at Time to Propagation = 15 min (P15) Depending on Peak HRR

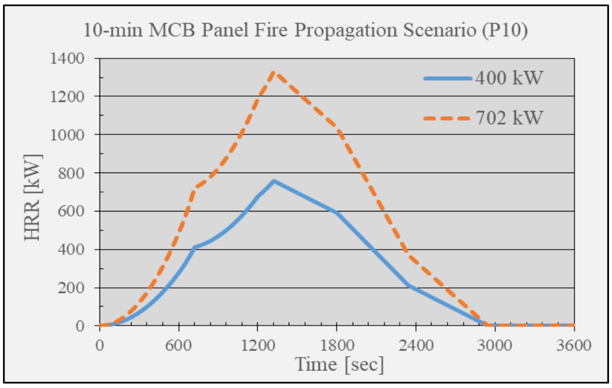


Fig. 6. HRR Profile of the MCB Fire Propagation Scenario at Time to Propagation = 10 min (P10) Depending on Peak HRR

Fig. 7 - 12 show time evolution curves of the HGL height and temperature of the single MCB fire scenario (Fig. 7 & 10), the 15-min MCB fire propagation scenario (Fig. 8 & 11), and the 10-min MCB fire propagation scenario (Fig. 9 & 12) for the peak HRR value of 400 kW and 702 kW.

Table I & II summarized changes in the abandonment time i.e., time at which OD & HGL height meet the associated criteria. Note that the incident heat flux and HGL temperature meet the associated criteria much later than the OD & HGL height do, or even do not exceed the associated criteria. Also, note that the OD always satisfies the criterion sooner than the HGL height does. In other words, the HGL height changes practically govern the habitability and determine the abandonment of the MCR.

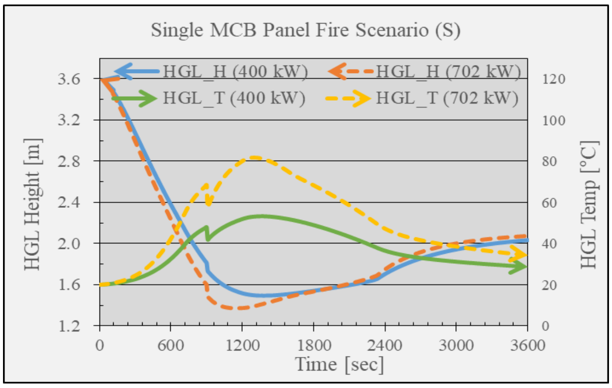


Fig. 7. HGL Height and Temperature Changes of the Single MCB Fire Scenario (S) Depending on Peak HRR Evaluated Using CFAST

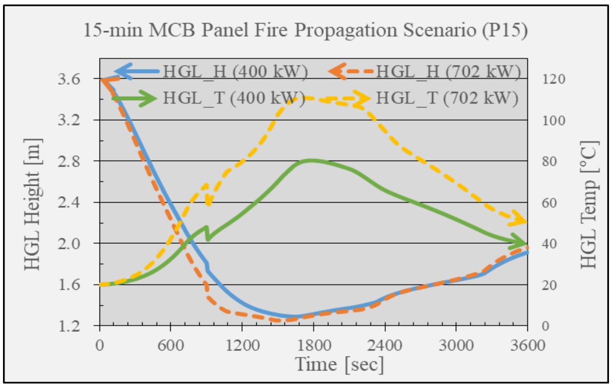


Fig. 8. HGL Height and Temperature Changes of the MCB Fire Propagation Scenario at Time to Propagation = 15 min (P15) Depending on Peak HRR Evaluated Using CFAST

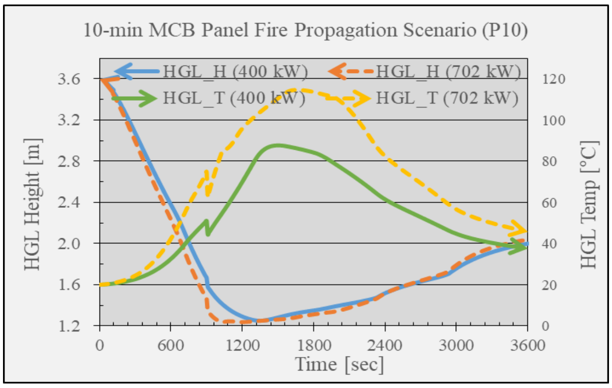


Fig. 9. HGL Height and Temperature Changes of the MCB Fire Propagation Scenario at Time to Propagation = 10 min (P10) Depending on Peak HRR Evaluated Using CFAST

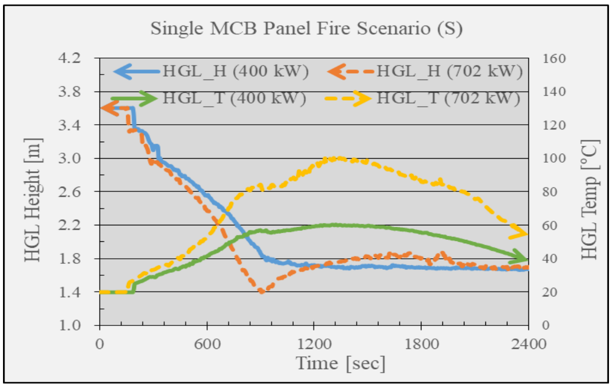


Fig. 10. HGL Height and Temperature Changes of the Single MCB Fire Scenario (S) Depending on Peak HRR Evaluated Using FDS

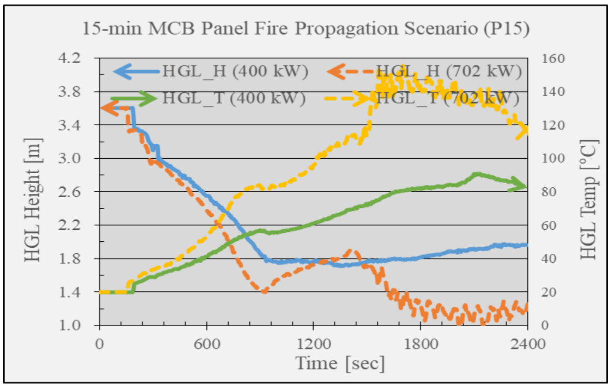


Fig. 11. HGL Height and Temperature Changes of the MCB Fire Propagation Scenario at Time to Propagation = 15 min (P15) Depending on Peak HRR Evaluated Using FDS

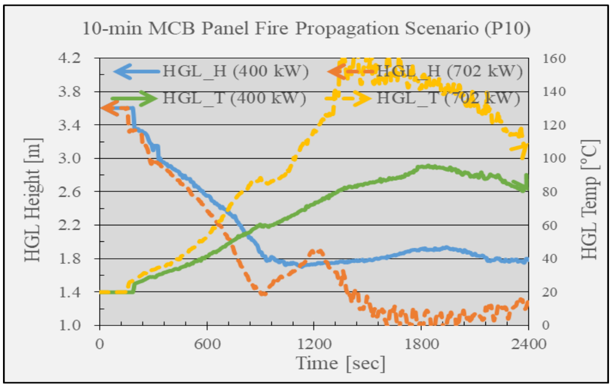


Fig. 12. HGL Height and Temperature Changes of the MCB Fire Propagation Scenario at Time to Propagation = 10 min (P10) Depending on Peak HRR Evaluated Using FDS

The CFAST results (Fig. 7 - 9 and Table I) show that the HGL boundary descends below the criteria, 1.8 m from the floor, in the representative MCB fire scenarios, irrespective of changes in the peak HRR value as well as the propagation conditions. The CFAST results indicate that change of the peak HRR value from 702 kW to 400 kW delayed the abandonment time from 790 sec to 910 sec by 120 sec, 15% (based on the single MCB fire scenario and the 15-min MCB fire propagation scenario). The CFAST results also indicate that time to the abandonment reduces from 910 sec to 840 sec by 70 sec, 8% (based on the peak HRR value of 400 kW) as the propagation condition changes from the single fire through the 15-min propagation to the 10-min propagation. Note that additional heat and smoke generated by the fire propagation in 15 min does not advance the abandonment time of the single MCB fire scenario. This is because the OD & HGL height conditions meet the abandonment criteria around 2 min before the fire propagation at 15 min (based on the peak HRR value of 702 kW) or almost at the same time with the fire propagation at 15 min (400 kW).

The FDS results (Fig. 10 - 12 and Table II) indicate that the fire propagation does not affect the abandonment time irrespective of the propagation time. The OD & HGL height conditions meet the abandonment criteria approximately 2 min before the fire propagation at 15 min (based on the peak HRR value of 702 kW) or only 30 sec (400 kW) after the fire propagation at 15 min. On the other hand, the results indicate that time to the abandonment is extended from 770 sec to 930 sec by 160 sec, 21% in all scenarios as the peak HRR value changes from 702 kW to 400 kW.

Table I: Abandonment Time of MCB Fire Scenarios Depending on Peak HRR and Time to Fire Propagation Evaluated Using CFAST

| Fire Scenario (Prop. Time [min]) / Peak HRR [kW] | Abandonment Time [sec] (HF) / (HGL_T) / (OD & HGL_H) Criteria |
|---|---|
| S / 702 | ( - ) / ( - ) / (160 & ***790***) |
| P15 / 702 | (1630) / (1430) / (160 & ***790***) |
| P10 / 702 | (1490) / (1190) / (160 & ***760***) |
| S / 400 | ( - ) / ( - ) / (210 & ***910***) |
| P15 / 400 | ( - ) / ( - ) / (210 & ***910***) |
| P10 / 400 | ( - ) / ( - ) / (210 & ***840***) |

Table II: Abandonment Time of MCB Fire Scenarios Depending on Peak HRR and Time to Fire Propagation Evaluated Using FDS

| Fire Scenario (Prop. Time [min]) / Peak HRR [kW] | Abandonment Time [sec] (HF) / (HGL_T) / (OD & HGL_H) Criteria |
|---|---|
| S / 702 | ( - ) / (1190) / (660 & ***770***) |
| P15 / 702 | ( - ) / (1190) / (660 & ***770***) |
| P10 / 702 | ( - ) / (1070) / (655 & ***770***) |
| S / 400 | ( - ) / ( - ) / (775 & ***930***) |
| P15 / 400 | ( - ) / ( - ) / (775 & ***930***) |
| P10 / 400 | ( - ) / (1800) / (770 & ***930***) |

## 3. Concluding Remarks

This study conducted fire modeling analysis for evaluation of habitability conditions and timing of forced abandonment of the MCR for the two representative MCB fire scenario: a single fire in the MCB panel PM02 (S); and an initial fire in the MCB panel PM02 followed by propagation to the MCB panel PM03 (P). Comparative analysis was conducted by changing the peak HRR value of a single MCB panel from 702 kW to 400 kW and “time to fire propagation to an adjacent MCB panel” from 15 min to 10 min.

Through the comparative analysis, we found that loss of MCR habitability, and thus, forced abandonment occurs in the representative MCB fire scenarios, regardless of changes in the peak HRR value as well as the propagation conditions. The results of comparative analysis indicate that the peak HRR value slightly affects habitability conditions and timing of forced abandonment of the MCR despite of its wide variation depending on the reference. The results also indicate that effect of the propagation time is smaller than that of the peak HRR value or the fire propagation could have no effect in the calculation using a CFD model like FDS.

Further detailed studies are required to examine the effect of mechanical or natural ventilation and combustion characteristics of the MCB panel for a more realistic evaluation of the habitability conditions and timing of forced abandonment of the MCR.

## Acknowledgements

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