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2024 Finite Element Thermal Analysis of a P-48 UF6 Overpack to Support Transport Re-certification

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Abstract

This paper provides an overview of the thermal evaluation performed as part of the safety analysis validation of the P-48 overpack Certificate of Compliance to support various projects requiring transport of 48-inch diameter UF6 cylinders. The P-48 is an insulated transport overpack designed to protect various types of UF6 cylinders previously deployed at the Portsmouth and Paducah former enrichment facilities in the U.S. Revalidation of the P-48 certificate required supportive safety analysis including a detailed thermal evaluation to meet existing transport regulations. In particular, a detailed finite element thermal analysis (FEA) of the P-48 package is performed to confirm these overpacks, when loaded with UF6 cylinders, meets the requirements of U.S. 49 CFR 173.420 (3) (iii). The controlling thermal condition in these requirements is the fire accident condition defined in U.S. 10 CFR 71.73 (c) (4). A description of the three dimensional detailed thermal FEA model and the application of the initial conditions are covered. The package internal structure is also evaluated for the additional heat generation produced during the fire condition. Due to the large thermal mass of the package and the limited conductivity of the insulation and internal structure, maximum cylinder temperatures are achieved at a time significantly beyond the end of the fire condition. Sensitivity studies are included to confirm the stability of the thermal transient solution. The evaluation demonstrates that the maximum temperature of the UF6 cylinder is achieved and the stability of the package and its confinement barrier is maintained.

Introduction

The P-48 Overpack was designed to provide transportation for a variety of cylinders containing non-fissile uranium hexafluoride (UF6). A picture of the P-48 Overpack in the transport configuration is shown in Figure 1. The total weight of the overpack package with a filled cylinder is approximately 43,000 pounds and has a total approximate length of 190 inches. The coated carbon steel package is designed with interior insulation to provide a crushable support for the cylinder for the drop conditions. The interior insulation also provides a thermal barrier for the 48 series cylinder. Since the contents heat generation is minimal the thermal barrier does not affect the thermal performance for the normal conditions of transport.

Figure1. Overall View of the P-48 Overpack for Transport

The cylinders of interest in this paper are those which are fully compliant in terms of wall thicknesses (no wall reduction due to corrosion) or other possible damage to the cylinder. The overpack is designed to withstand the conditions in 49 CFR 173.420 [1]. One of the efforts of the Re-certification for the P-48 Overpack is a thermal evaluation. The most severe thermal condition is the fire accident condition. While 49CFR 173.420(3) (iii) requires the thermal evaluation for the fire accident condition, the thermal conditions are actually defined in 10CFR71.73(c) (4). This particular section in 10CFR71 [2] addresses only the thermal accident condition and is for packages with fissile contents. However, it is being applied to an overpack which is for transporting nonfissile material. An important aspect of this requirement in 49CFR 173.420 is that it does not explicitly require accident conditions to occur prior to the fire accident condition. This is in contrast to 10CFR71.73 (a) which does require sequential evaluations of the drop conditions followed by the fire condition. The evaluation in this paper considers the fire accident to be a standalone event using the undeformed overpack geometry.

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Thermal Loading Conditions

The accident condition is initiated from the normal condition of transport. While 10CFR71.73(c) (4) does not specify the initial conditions, Section 71.71 is considered as defining the initial conditions for the accident. The normal condition is defined in terms of the terms of the ambient condition of 100°F and the solar insolance. A table in Section 71.71 provides energy to the surface applied over a 12 hour time frame for different surface orientations. Since the package is considered to be in equilibrium with the ambient, the absorptivity is taken to be the emissivity determined for a surface, which is applied as a factor to the specified solar insolance. The steel coated surface in the as fabricated condition was taken to be 0.8. These were applied to the P-48 Overpack. The heat generation of the UF_6 is considered to be negligible, and in a steady state condition the temperature of the UF_6 would be determined by the shell temperature. If the package surface temperature was uniform, the UF_6

temperature would be the same temperature. In a thermal transient condition such as the fire, the UF6, being in a liquid form and having a weight ranging from approximately 46,000 pounds to 61,000 pounds [3] would act as a large heat sink. Since the fire condition is only 30 minutes, the liquid could actually reduce the average cylinder temperature. To identify bounding conditions for the presence of a minimal amount of UF6 after the emptying operation, an empty cylinder was used in the fire accident condition.

The fire condition in 10CFR71.73(c) (4) is defined in terms of an ambient temperature of 1475°F to represent the average flame temperature in conjunction with an emissivity (absorptivity) of 0.9. This condition was applied to entire package surface to comply with the fully engulfed condition. A general requirement for including the effect of convection is also mentioned. The method to include the additional heat flux due to the convection is not specified in the regulations. In this paper, the correlation provided in [4] is used. To ensure that it is conservative, it was increased to bound the heat flux produced in [5] for a package subjected to regulatory pool fires. The diameter of the package in [5] (used for the fire test) was 55 inches as compared to the 70 inches for the P-48 overpack. Results for the [5] are considered to be applicable to the P-48 application. The convection computed from [4] was combined with the radiation heat transfer using a common methodology as identified in [7].

Thermal Criteria

The actual criteria for the cylinder due to the fire condition is based on the cylinder rupture pressure as determined by autoclave tests of the cylinder. For this cylinder, the burst condition corresponds to a cylinder temperature of 280°F. To ensure an adequate margin of safety to the burst pressure, the target temperature limit was set at 235°F. The requirement therefore is not based on a peak temperature, but rather an average temperature of the shell. The analyses performed for this evaluation are considered to be conservative and provide bounding temperatures

P-48 Overpack Finite Element Thermal Model

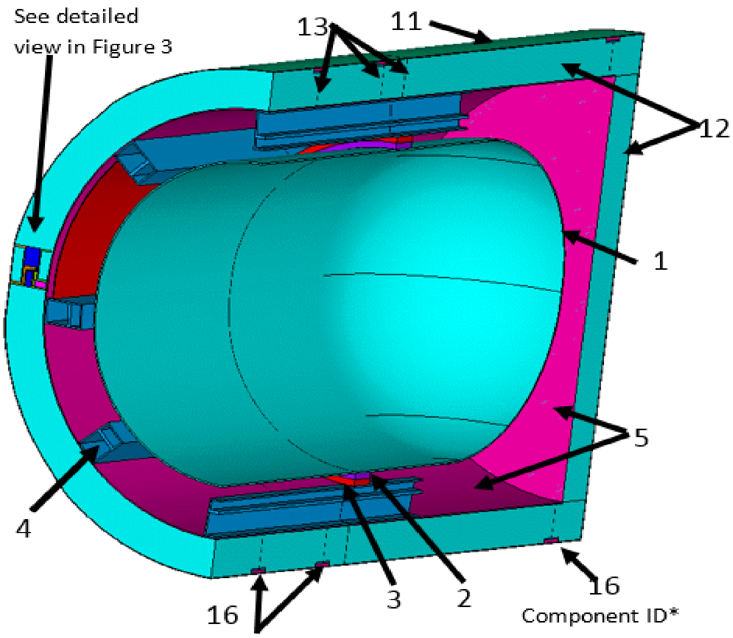
The P-48 overpack is designed to maintain the integrity of the cylinder for the drop conditions as well to insulate the cylinder for the fire condition. As such the design is comprised of structural members to transmit the inertial loading for the drop conditions. In addition the design provides sufficient thermal resistance against the heat applied of the surface of the overpack for the fire condition.

Table 1 lists the different components and their corresponding material and basic shape. As shown in Table 1, the material list is comprised of a variety of materials including structural steel, insulation, neoprene materials and wood. To minimize the size of the finite element model, a quarter symmetry was used.

Table 1. P-48 Overpack Components

Component ID*	Component Description
1	UF_6 Vessel
2	Neoprene support bands
3	Steel support band between the neoprene and the support tubes
4	Steel support tubes (4x4 & 2x4 tubes)
5	Steel Inner shell of Overpack
6	5" Steel channel on inside attached to the Overpack lid inner shell
7	6" Steel channel on outside attached to the Overpack lid outer shell
8	Braided seal
9	2.5"x2.5" Steel angles attached to Overpack inner & outer shells
10	Wood thermal break between the channels and between the angles
11	Steel Outer Shell of Overpack
12	Insulation between inner & outer shells and inside of the two channels
13	Steel gussets between the inner and outer Overpack shells
14	Steel thermal heat shield
15	Steel bands on the outer edge of the steel gussets
16	Laminated wood bands between the steel bands and Overpack shell

While there are minor variations in the different cylinders which could be transported by the P-48 Overpack, the quarter model shown in Figure 2 contains the necessary details to adequately simulate the fire conditions for any cylinder to be transported. The model in Figure 2 is comprised of hexahedral elements, shell elements and radiation matrices and the total number of elements in the quarter model is approximately 80,000.



*Component IDs are defined in Table 1.

Figure 2. Finite Element Model of P-48 Overpack

Heat transfer from the overpack surface to the cylinder is by conduction and radiation. Conduction though the components utilized temperature dependent material properties. Convection and conduction through the air in the gaps inside the overpack are considered to be insignificant and were not modeled.

The insulation (Item 12 in Figure 2) provides resistance to heat transfer over the largest area. Other components, such as Items 2, 8 and 10, are included to mitigate the higher conductivity of the structural components (Items 7, 9, 6, 4). Items 7, 9, 6, 4 provide a path of conduction from the surface to the cylinder during the fire condition. The most critical component in the thermal analysis is the closure. Figure 3 shows a detailed view of the closure joint. The use of wood for Item 10 in the closure mitigates the heat conduction across the closure joint. Due to the temperature of the components, radiation can be significant across the various gaps. In the area of the closure, Item 14 acts as a radiation shield to reduce radiation from the inner shell (Item 5) and the cylinder (Item 1).

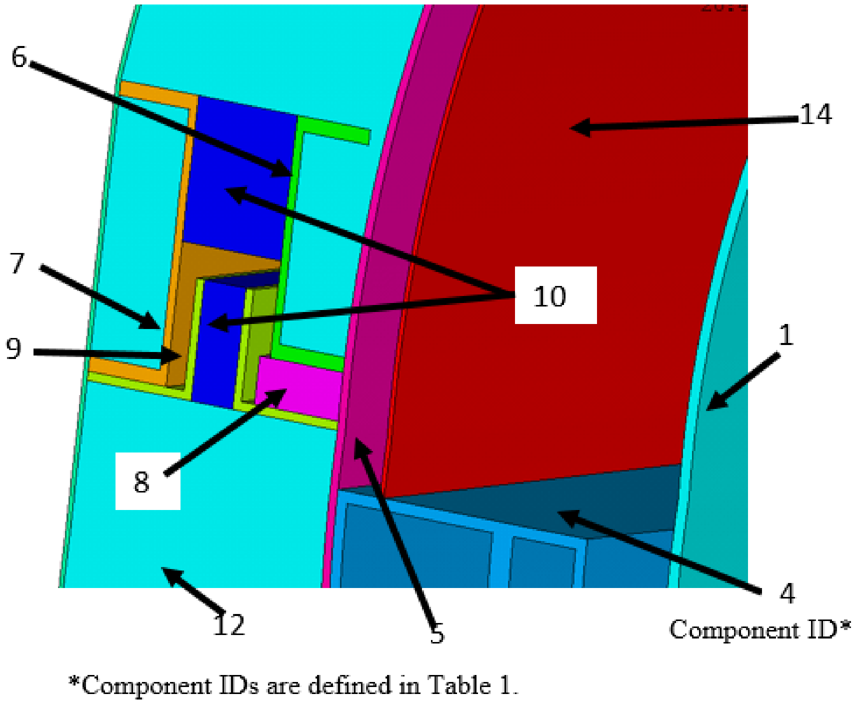


Figure 3. Detailed Finite Element Model of the Joint

Since the enclosures correspond to relatively complex surface shapes, three separate radiation matrices are generated to model the radiation across these air gaps.

These included

1) A radiation matrix across the air gap between inner surfaces of the Overpack (Item 5 in Figure 2) and the outer surface of the cylinder (Item 1 in Figure 2).
2) A radiation matrix across the gap between the outer surface of the thermal shield (Item 14, Figure 3) and the inner surface of the Overpack inner shell (Item 5, Figure 3).
3) A radiation matrix across the air gap between the inner surfaces of the channels and braided seal (Items 6 through 9 in Figure 3) inside of the closure assembly.

Since internal overpack air convection was to be neglected, finite element methodology was used to perform the evaluations. The thermal modeling capability using conduction and radiation finite elements in the commercially available ANSYS Program [6] was used to generate, solve, and post process the results.

Thermal results for the Base Condition (without Wood Combustion)

The initial solution for the fire condition did not consider the wood combustion. A solution for the steady state condition using an ambient temperature of 100°F with solar insolance from [2] was used as the initial conditions for the fire transient condition. Since the UF6 has negligible heat generation the steady state condition results in a uniform temperature of 141°F throughout the package. The fire condition is applied as a stepped condition and it was removed as a stepped condition also at the end of 30 minutes. The results are shown in Table 2 below for the cylinder.

Table 2 Average Cylinder Temperature without Wood Combustion

Time Period	Average Cylinder Temperature (°F) for the model without outer band wood combustion
Steady State Initial Condition	141
End of 30 minute Fire	143
Cooldown	222

Figure 4 shows the temperature distribution in the overpack at the end of the fire. As shown in Figure 4, the heat from the fire condition has not penetrated into the overpack, and not even though the closure joint.

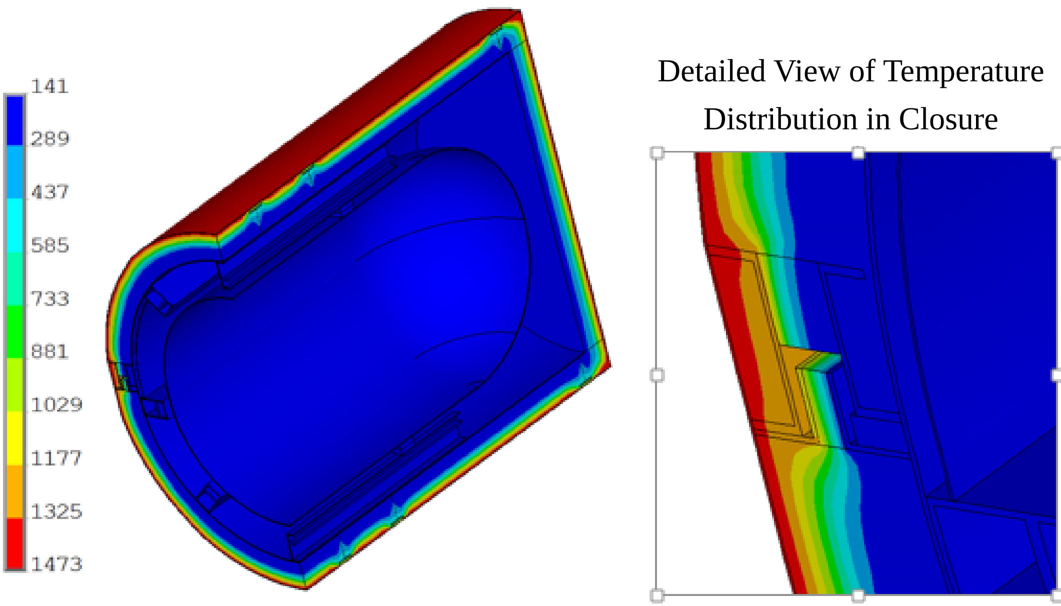


Figure 4 Overpack Temperature (°F) Distribution at 30 minutes-Base Case

This is consistent with the average cylinder temperature at the end of the fire condition is 143^{0}F. The average cylinder temperature is computed for each time step in the solution which is shown in Figure 5. It shows that the peak temperature of 222°F occurs during the cooldown period at 3.6 hours or 3.1 hours after the fire condition has ended. Figure 6 shows the overpack temperatures distribution at 3.6 hours. At this time, the residual heat is in the insulation which is in the process of being rejected back to the surface.

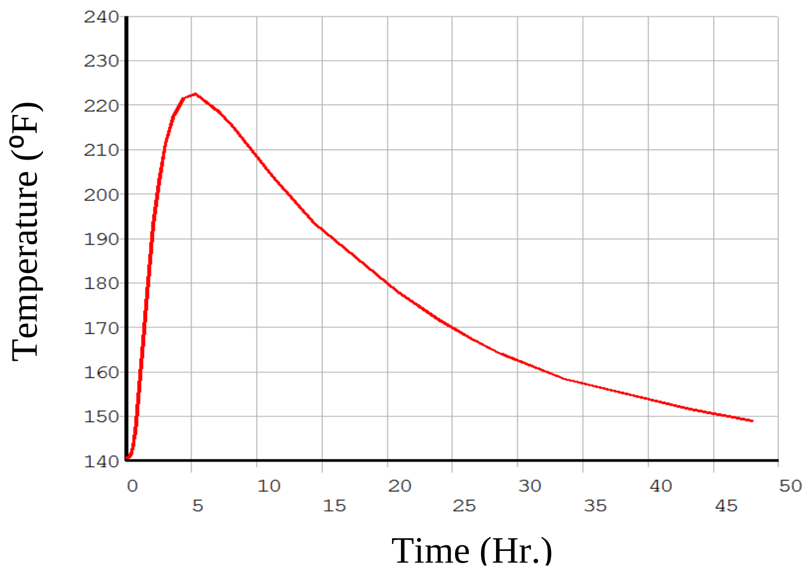


Figure 5 Average Cylinder Temperature (^{0}F) History - Base Case

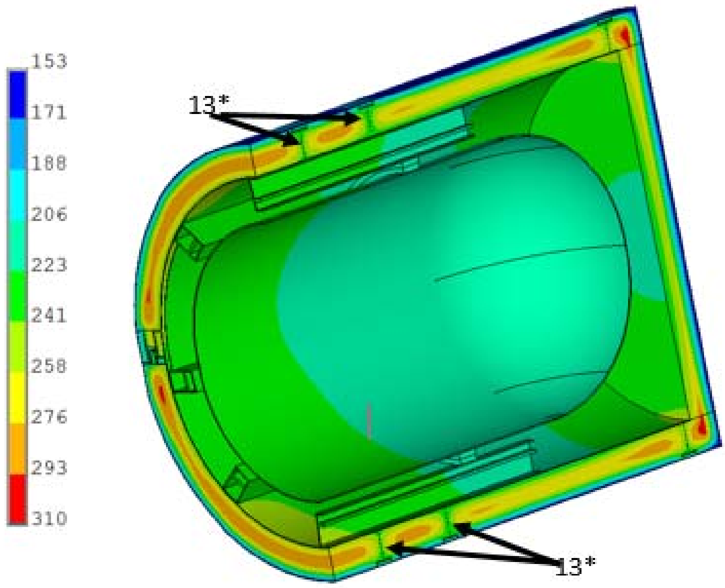


Figure 6 Overpack Temperature (°F) Distribution at 3.6 Hours – Base Case

Thermal results with Wood Combustion

As noted in Figure 4, the temperature of the wood bands at the overpack outer shell (Item 16 in Figure 2), are basically at the surface temperature of 1473°F. Reference [8] indicates that wood can combust spontaneously at 573°F. While the wood bands are covered it was assumed that the wood bands would have sufficient air to combust and result in additional heat generation during the 30 minute fire. Item 10, which is in the closure joint, has a small portion of wood which is above the ignition temperature. The wood in the closure joint is also treated with a fire retardant chemical. As the wood contained within the closed volume of the closure joint begins to combust, the char layer develops limiting the combustion. Since this is more effectively insulated than the outer wood bands, the additional heat developed by the closure joint was considered to be insignificant. Reference [9] reports that the heat generated from burning of typical dry, non-resinous wood is approximately 6,300 BTU/lbs. This corresponds to the energy released due to the wood combustion. Reference [8] also reports the char rate which is dependent on the time of combustion. Manufactures of the fire retardant also report an efficiency factor for burning of wood treated with fire retardant which can reduce the heat generation. Using the band wood mass in conjunction with the char rate, the internal heat generation can be determined which is directly input into the model to the wood band. As in the initial fire transient solution, a solution for the steady state condition using an ambient temperature of 100°F with solar insolance from [2] was used as the initial condition. During the 30 minute fire condition, the additional heat generation of the in the outer wood bands, is also applied. At the end of the 30 minutes, the conditions used in the initial solution are repeated. The post processing of the cylinder temperatures are shown in Table 3 below.

Table 3 Average Cylinder Temperature with Wood Combustion

Time Period	Average Cylinder Temperature (°F) for the model with outer band wood combustion
Steady State Initial Condition	141
End of 30 minute Fire	144
Cooldown	233

At the end of the fire condition the change in the cylinder temperature is 1°F. Due to the thermal mass, the peak average cylinder temperature increases 11°F. While the outer band (Item 16, Figure 2) is on the outside of the overpack, these wood bands are in contact with the steel stiffeners (Item 13, Figure 2) and a conduction path to the cylinder exists through Items 13, 4 and 3. The average cylinder temperature time history for this condition is shown in Figure 7. The shape is slightly different due to the additional energy generated by the wood.

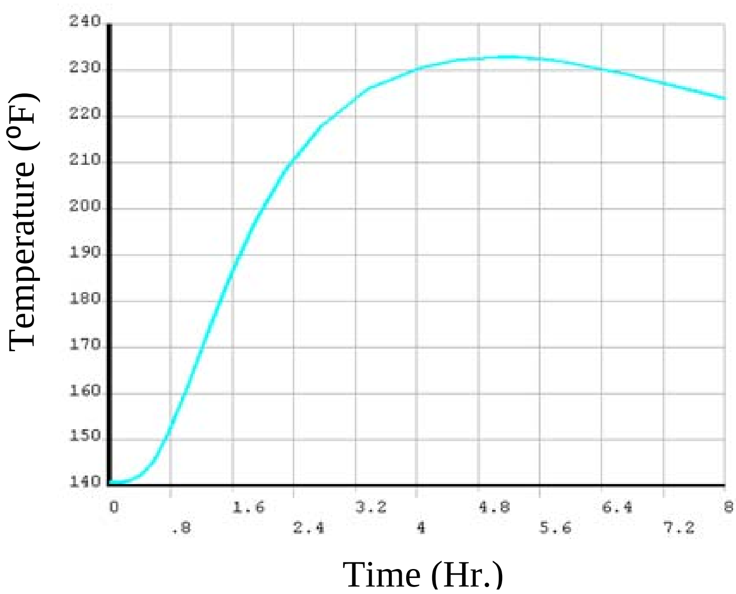


Figure 7. Average Cylinder Temperatures (^{o}F) History with Wood Combustion

Thermal results for Additional Sensitivity Studies

An additional solution was generated to determine the effect of using a low emissive paint. This coating would serve to reduce the lower initial steady state temperature. The surface coating has a temperature limit of 1000^{o}F, and since the surface temperature rises to beyond this limit in two minutes or less, the standard regulatory of 0.9 is applied during the fire condition. After the coating is removed. The results for the cylinder are shown below in Table 4. The coating does decrease the initial condition by 11°F, but the decrease from the initial condition does not carry over into the fire and cooldown. The lower initial temperature results in a slight increase in the flux due to the fire, resulting in 9°F difference from the previous case.

Table 4 Average Cylinder Temperature with Wood Combustion & Low Emissive Paint

Time Period	Average Cylinder Temperature (°F) for the model with outer band wood combustion and Low Emissive Paint
Steady State Initial Condition	130
End of 30 minute Fire	133
Cooldown	224

An additional study was also performed using a refined time step during the fire and immediately after the fire condition ended. The stepped application of the boundary condition results in large surface fluxes to the overpack, which determines the energy stored in the overpack during the fire condition. The stored energy then affects the subsequent peak temperature occurring during the cooldown period. To observe any sensitivity of the peak temperatures shown in Table 2 (base case), the initial solution was reperformed. The initial number of time steps for the stepped fire condition was increased by 40% over the initial solution. The peak average cylinder temperature was determined to be 222°F also. While the numerical testing was not extensive it did confirm that a sensitivity of the peak temperatures to the initial time steps during the fire boundary condition was not an issue.

Conclusion

This paper describes the thermal evaluation of the P-48 overpack for the fire accident condition. The three dimensional finite element model of the P-48 Overpack contained the details of the different heat conduction and radiation paths from the overpack surface to the cylinder. Surface flux generated by the fire used the regulatory based parameters and included the effect of convection. Combustion of the wood bands, which are attached to the overpack outer shell, was also incorporated and was shown to increase the cylinder temperature. The evaluations confirmed that the temperature limits for the empty cylinder satisfy the temperature limits established by autoclave testing of the cylinders.

References

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