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ANALYSIS OF NSTX UPGRADE OH MAGNET AND CENTER STACK

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The new ohmic heating (OH) coil and center stack for the National Spherical Torus Experiment (NSTX) upgrade are required to meet cooling and structural requirements for operation at the enhanced 1 Tesla toroidal field and 2 MA plasma current. The OH coil is designed to be cooled in the time between discharges by water flowing in the center of the coil conductor. We performed resistive heating and thermal hydraulic analyses to optimize coolant channel size to keep the coil temperature below 100 C and meet the required 20 minute cooling time. Coupled electromagnetic, thermal and structural FEA analyses were performed to determine if the OH coil meets the requirements of the structural design criteria. Structural response of the OH coil to its self-field and the field from other coils was analyzed. A model was developed to analyze the thermal and electromagnetic interaction of centerstack components such as the OH coil, TF inner legs and the Bellville washer preload mechanism. Torsional loads from the TF interaction with the OH and poloidal fields are transferred through the TF flag extensions via a torque transfer coupling to the rest of the tokamak structure. A 3D FEA analysis was performed to qualify this design. The results of these analyses, which will be presented in this paper, have led to the design of OH coil and centerstack components that meet the requirements of the NSTX-upgrade structural design criteria.

I. Introduction

The National Spherical Torus Experiment (NSTX) is being upgraded to operate with 2 MA of plasma current and 1 Tesla central toroidal magnetic field (Ref. 1). The upgrades include a replacement of the center stack and addition of a second neutral beam. The upgraded center stack will have an ohmic heating (OH) solenoid magnet coil that provides the initial inductive current drive in the plasma. This OH coil is a 1016-turn (4-layer, wound 2 in hand) solenoid that is cooled continuously by water flowing in a coolant channel in the center of the conductor (Figure 1). The cooling water is pumped in 8 parallel coolant paths in the coil. Figure 1 also shows one of the eight conductor paths in the OH winding. During each plasma discharge the current flowing in the OH coil results in heating in the coil. This heat is removed by the coolant flow. In section II of this paper we give details of the thermal-hydraulic analysis of the OH coil cooling and optimization of the cooling channel diameter.

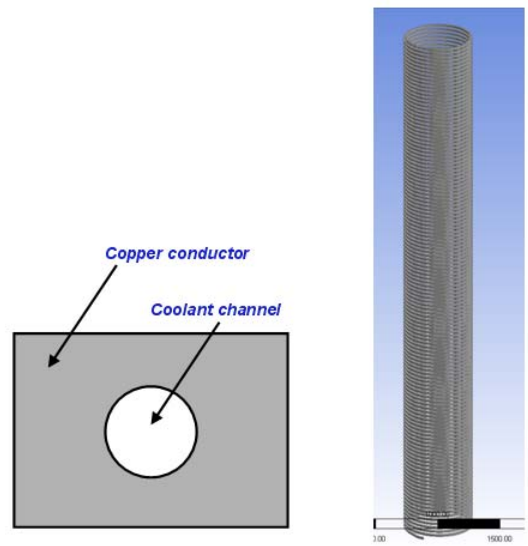

Figure 1: NSTX Upgrade OH Coil Conductor Cross Section and One of 8 Cooling Paths

The large currents (i.e. 24 kA peak) in the OH winding results in large EM (hoop and axial) forces on the coil. In addition, other coils (e.g. poloidal field coils) in close proximity of the OH coil exert localized forces on the OH winding. The structural design of the OH coil which is a fiberglass reinforced VPI epoxy system is required to withstand these loads. In the design of the NSTX upgrade, the OH coil is directly wound on the inner TF coil bundle without a tension tube. The OH is axially preloaded against the TF flag extensions using a series of Bellville spring washer stacks (Figure 9). In section III a model is presented to analyze the thermal and electromagnetic interaction of center stack components such as the OH coil, TF inner legs and the preload mechanism under all scenarios involving different combinations of TF and OH coil temperatures and energized states. This analysis tool helps in specifying Bellville washer stack requirements to keep OH coil from lifting during normal machine operation and fault conditions.

In the NSTX upgrade, the currents in the inner legs of the TF coils interact with the fields from the OH and the poloidal field (PF) coils resulting in torsional loads in the TF bundle which are transferred through the lower and upper lids to the rest of the machine structure. A "crown" part made of G-10 material is designed to engage the TF bundle and to transfer this torque to the lid and at the same time maintain electrical insulation. In section IV we show the structural analysis of this torque transfer mechanism and its interaction with the TF coil and insulation.

II. OH COIL COOLING

The OH coil in NSTX upgrade provides the flux swing necessary to drive the initial Ohmic current drive in the plasma. Detailed design of the OH coil including the number of turns, I^2t, and conductor size was based on maximizing the flux change in the plasma given constraints on the coil radial build, capabilities of power supplies and coil insulation. This optimization was performed separately from the analysis reported in this paper (Ref. 2). The resulting OH coil design parameters are listed in Table 1.

Table 1: OH Coil Design Parameters

OH Inner Radius (Copper)	0.2118 m
OH Outer Radius (Copper)	0.2757 m
OH Ground & turn insulation	0.0032 m
OH Height	4.2416 m
OH #turns	1016
OH #layers	4
OH Conductor width	0.0137 m
OH Conductor height	0.0136 m
OH Cooling hole diameter	0.0044 m
OH Packing fraction	0.75
OH Voltage	8103 V
OH Current Base	24000 A
OH Inlet Coolant Temp	12 °C
OH Maximum temp	100 °C
OH Copper Mass	2800 kg

Due to the nature of the VPI epoxy insulation the temperature of the OH coil has to be kept below 100 °C for peak coil currents of 24 kA and equivalent square wave pulse width T_{esw}=0.85 seconds. Additionally the NSTX upgrade design criteria calls for cooling time between pulses of less than 20 minutes and cooling pump pressure below 600 PSI. The coolant channel diameter is a parameter that can be optimized to achieve these requirements. Larger coolant channel leads to higher coil resistance and higher Ohmic heating and initial temperature in the coil. However it also leads to more efficient cooling and lower cooling time. Higher pressure drop leads to higher mass flow and shorter cooling time.

II.A. Analysis Tools

Two analysis tools were used to analyze the OH coil heating and subsequent cooling. The first was Ansys CFX computational fluid dynamics (CFD) code (Ref. 3). Ansys CFX is a hybrid finite-element/finite-volume CFD code that was used here to analyze the transient coupled electrical thermal and flow phenomena at the heating phase of the coil. The analysis took into account the cooling effect of the flowing entrained water in the coil during the discharge and the effect of the OH current pulse shape. The resistive heating of the coil due to the current flow during the discharge was input into CFX using a time dependent volumetric heat source. CFX accounted for the resistive heating, conductive heat transfer in the copper, and turbulent convective heat transfer to the coolant in the channel. Maximum coil temperature during the discharge was calculated using this analysis method. Figure 2 shows a portion of the computation mesh of the copper conductor and the coolant fluid channel used in the analysis. Finer elements were used near the coolant channel wall to better resolve the turbulent convective heat transfer.

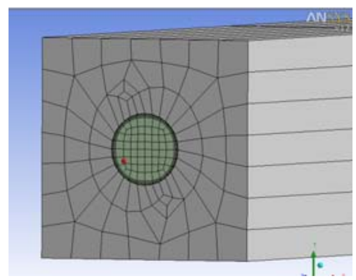

Figure 2: Finite Element Mesh of the OH Conductor

The second analysis tool used is a 1D finite-difference transient cooling simulation code called FCOOL developed at Princeton Plasma Physics Laboratory for use in design of magnet coil cooling. Fcool uses input about the current flow and pulse length, coolant flow length, available pressure drop, coolant channel size, and conductor size to model the initial heating and the cooling wave propagation in the coil. It does this by dividing the coil into small finite length sections and sequentially solving the cooling and hydraulic parameters using closed form equations in the length sections. However, Fcool does not treat the complete transient heating of the copper and the simultaneous cooling by the entrained water during the heating pulse. Fcool is much less computationally expensive than the CFX simulation of the entire coil. For this reason analysis of the cooling phase of the problem and predictions of cooling time vs. pressure drop across the coil were performed using Fcool.

II.B. Results

Using the analysis tools mentioned above, multiple coolant channel diameters were analyzed. It was determined that 0.175 inches (4.4 mm) was the optimum diameter for the coolant channel. Figure 3 shows the result of the analysis of the heating phase of the coil using CFX. The entrained water is shown being heated along with the copper during the current pulse. The maximum coil temperature reached is shown to be below 100 °C.

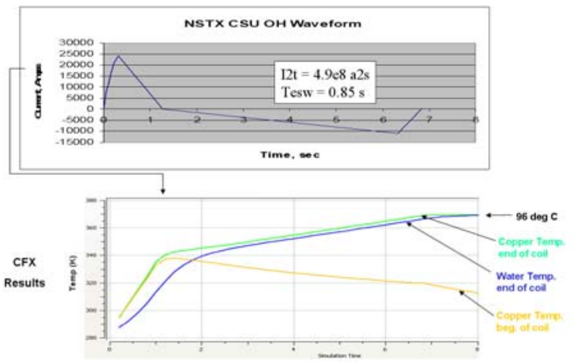

Figure 3: Simulation of the Heating Phase of OH Coil Including the Effect of Entrained water

Figure 4 is an Fcool plot of the coil conductor temperature at the coolant outlet end of the coil as a function of time for a 500 PSI pressure difference driving the coolant flow. Water enters the coil at 12 °C and due to the long length (i.e. approximately 200 meters) of the coil it quickly reaches the maximum coil temperature. For this reason the copper end temperature and the coolant exit temperature stay at the maximum until the coolant flow is able to remove enough heat so that cooler copper area can extend along and reach the end. This is commonly referred to as the cooling wave. Figure 4 shows that the cooling wave reaches the end of the coil in 15 minutes (900 seconds) and the coil is cooled entirely in 19 minutes (1140 seconds) thus satisfying the design criteria.

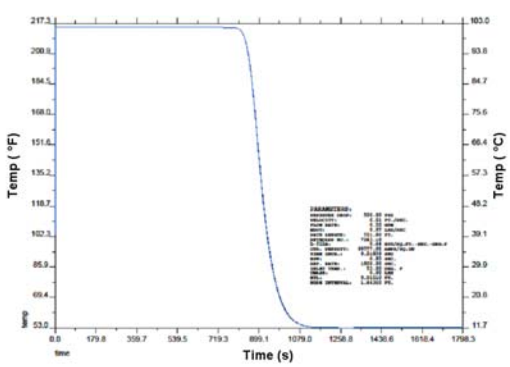

Figure 4: Simulation of the Cooling of the NSTX Upgrade OH Coil

III. STRUCTURAL ANALYSIS

The main structural loads on the OH coil and the center stack components are the results of electromagnetic (EM) forces and differential thermal expansion. The EM forces in the OH coil result from the hoop forces and the axial compression in the coil. In addition, the field from nearby coils especially the PF coils exerts force on the OH coil windings. To study these loads, an axisymmetric discrete-conductor finite element model of the entire OH coil was developed. Figure 5 is a section of this model showing the finite element mesh. Ansys Multiphysics FEA code was used to study the coupled EM-structural effects.

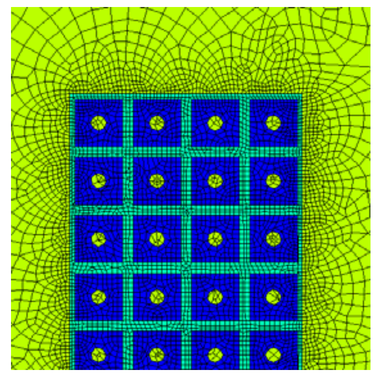

Figure 5: Finite Element Mesh Used in Axisymmetric Structural Analysis of the OH coil

Figure 6 is a plot of the mid-plane (Tresca) stress intensity resulting from the combination of hoop and axial stresses. The stress is below the 165 MPa limit in the copper and therefore acceptable. Figure 7 is a contour plot of shear stress in the coil epoxy insulation which is shown to be below the 22 MPa limit.

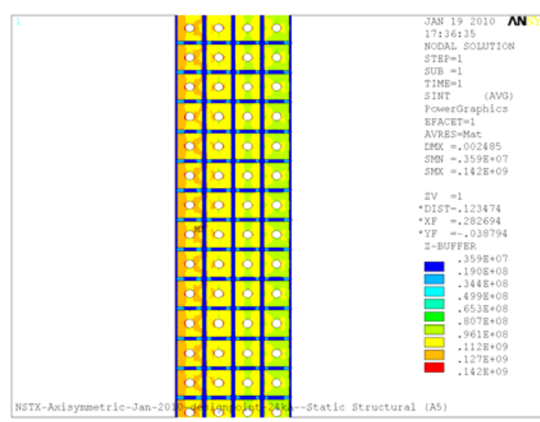

Figure 6: Mid-plane Stress Intensity in the OH Coil with I=24 kA

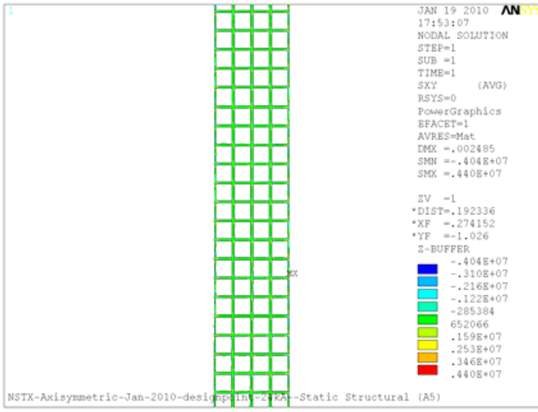

Figure 7: Shear Stress in the OH Coil Insulation

Figure 8 shows the stress intensity in the OH winding resulting from interaction with the poloidal field coils PF1A (Upper and Lower) which is housed close to the OH coil inside the center stack housing. The plot is for a case where the OH coil current is 13 kA and PF1A coils carry 16.6 kA current. The plot shows the stress in the copper is below the stress limit. From the results of analyses with this model we derived criteria limiting the currents that can flow in the OH and PF1A coils at any one time during the discharge in order to avoid damaging the OH coil.

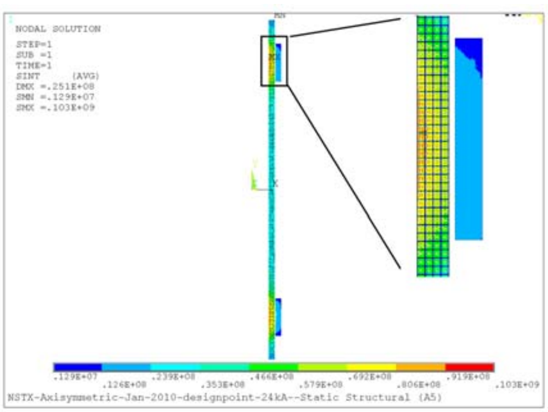

Figure 8: Stress Intensity in The OH Coil Due to Self Currents and Interaction with Current in Adjacent PF1A Poloidal Field Coil

As mentioned before, the OH coil in NSTX upgrade is directly wound on the TF inner legs bundle and preloaded against the TF flag extensions using Bellville spring washers. The spring washer stacks need to be designed such as to keep the OH coil from lifting (and breaking the leads in the bottom) under all possible machine operation scenarios. Figure 9 shows the center stack components and the axisymmetric FEA model used to analyze the thermal expansion and interaction of the center stack components. The Bellville washer stacks are modeled as axisymmetric spring elements in the FEA model.

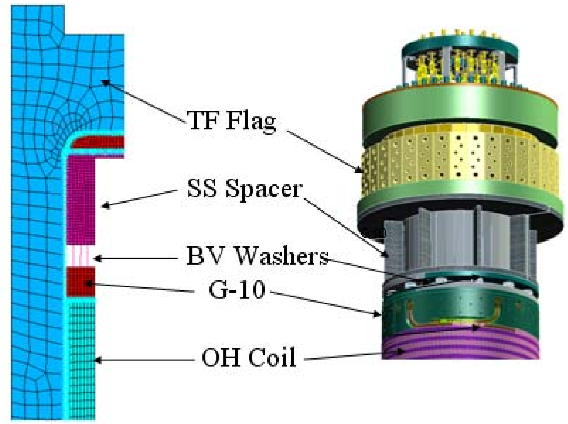

Figure 9: NSTX Upgrade Upper Center Stack Components and Axisymmetric FEA Model

Figure 10 shows the results of the FEA simulation of the interaction and stresses under two operation scenarios. Table 2 lists results of different scenarios involving: the on or off current states of OH and TF coils, temperature states of the different coil, and with or without the maximum OH launch force of 50,000 lbs. The launch force is caused by interaction of OH with all of PF coils. The table shows that with the right choice of Bellville washer stack stiffness and height we can maintain acceptable stresses in the OH and TF coils and prevent the OH coil from lifting under all operation scenarios.

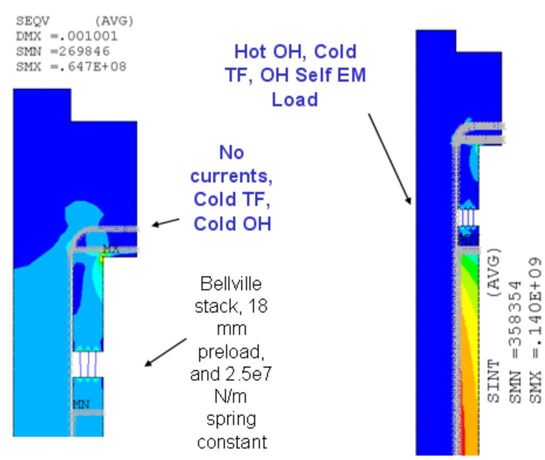

Figure 10: Stress on Center Stack Components under Two Operation Scenarios

TF Temp	OH Temp	TF Curr	OH Curr	Launch Force	Peak OH Stress MPa	Peak TF Stress MPa	OH Lifted?
COLD	COLD	OFF	OFF	OFF	7-14	7-14	NO
HOT	COLD	ON	OFF	OFF	102-115	38-51	NO
COLD	HOT	OFF	OFF	OFF	10-19	19-29	NO
COLD	HOT	OFF	ON	OFF	125-140	16-31	NO
COLD	HOT	OFF	ON	ON	123-138	16-31	NO
HOT	COLD	ON	ON	ON	117-132	15-29	NO
HOT	HOT	ON	ON	ON	110-134	15-19	NO

Table 2: Simulation Results of Different Operation scenarios

IV. ANALYSIS OF CENTER STACK TORQUE TRANSFSER MECHANISM

In the NSTX upgrade, the currents in the inner legs of the TF coils interact with the fields from the OH and the poloidal field (PF) coils resulting in torsional loads in the TF bundle. These torsional loads are transferred through the lower and upper lids to the rest of the machine structure. A "crown" part made of G-10 material is designed to engage the TF bundle and to transfer this torque to the lid and at the same time maintain electrical insulation between the TF conductors and the lid. Figure 11 shows the upper portion of the machine, the center stack, and the G-10 torque crown piece (in green).

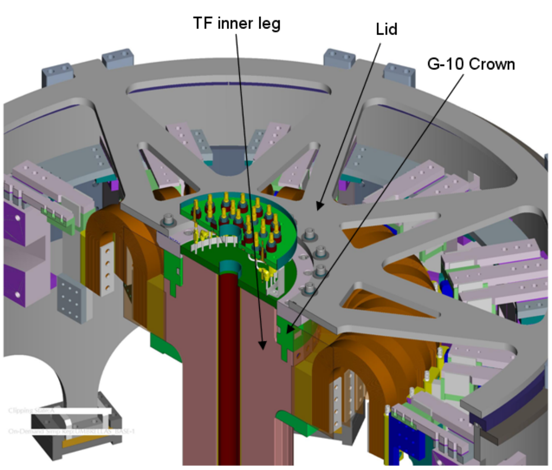

Figure 11: Design of the Upper Portion of the NSTX Upgrade and the Center Stack

Since the center stack TF bundle is made of 36 conductors (blades) with epoxy insulation bonding in between, an accurate analysis of the torque transfer mechanism would need to be done in 3D. However the cyclic symmetry nature of the geometry allows us to simplify this by doing the analysis on 1/36 of the problem geometry (or one TF coil conductor). The geometry also included the TF epoxy insulation bonded to the conductor (Figure 12). The design of the crown included stainless steel inserts to be used as nuts for bolting the lid to the upper portion of the crown.

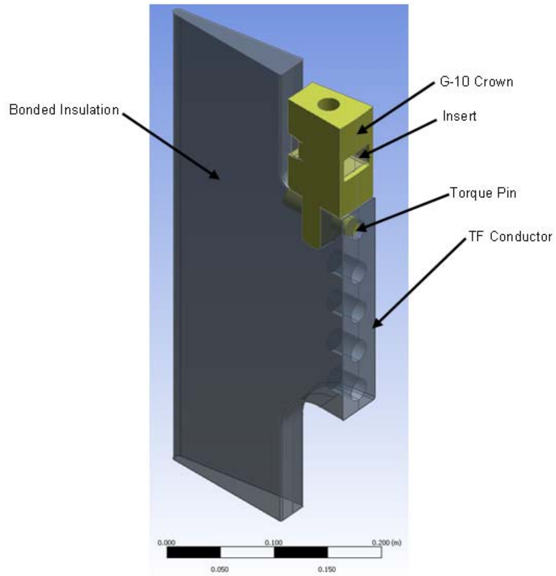

Figure 12: 1/36th Geometry of the Center Stack Torque Transfer Mechanism

The amount of torque expected to be exerted on the locking assembly was obtained from the global FEA model (Ref. 4). The worst case out of plane torsional load from the global model corresponded to 360,000 N.m of torque on the crown to TF bundle interface which results in approximately 9000 lbs force per blade. The load was applied to the top surface of the G-10 crown piece in the model analyzed (Figure 13). The model was held fixed on the bottom.

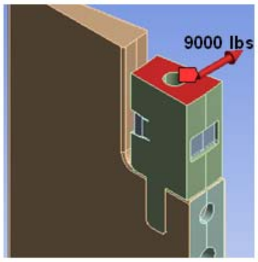

Figure 13: Load on the 1/36th Geometry Cyclic Symmetry Model

IV.A. Results

Figure 14 is a contour plot of equivalent stress on the components of the model resulting from the torsional load. As can be seen from the plot the stresses are below the limits for copper (233 MPa), and G-10 (130 MPa) (Ref. 5).

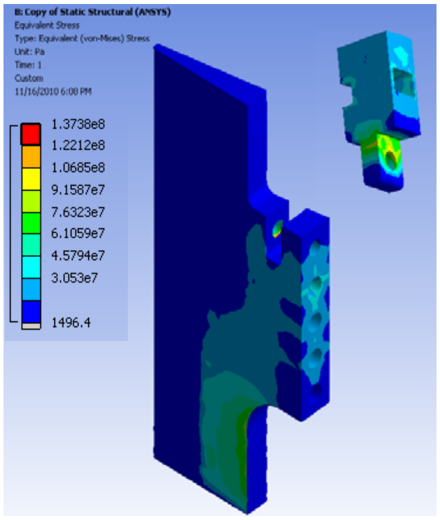

Figure 14: Contour Plot of Equivalent stress

The shear stress in the insulation shown in Figure 15 is, for all but a small area, below the (Cyanate Ester) bond strength of 25 MPa. In the areas where this limit is exceeded, delamination may occur which is benign due to its limited area. Figure 15 also shows the normal stress (in toroidal direction) in the epoxy filled fiberglass wrapped insulation. The normal stress in the insulation is safely below 10 MPa strength of epoxy.

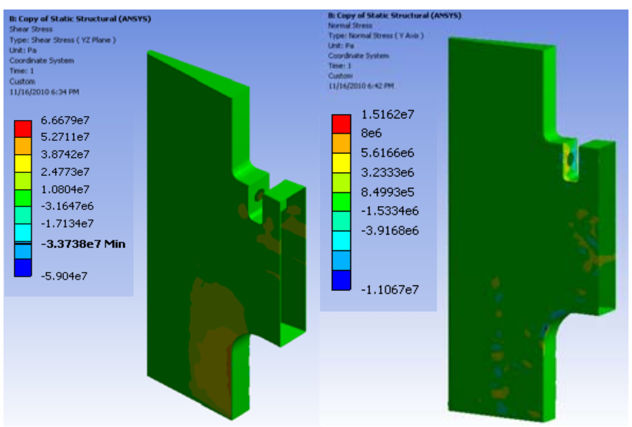

Figure 15: Contour Plot of Shear stress in the Insulation

It is concluded therefore that the center stack torque transfer mechanism can withstand and transfer the torsional loads to the lid.

ACKNOWLEDGMENTS

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