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A CFD ANALYSIS OF EASTERLY WIND FLOW IMPACTING THE VEHICLE ASSEMBLY BUILDING

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ABSTRACT

In an attempt to explain the high loss of panels from the south face of the Vehicle Assembly Building (VAB) during Hurricane Frances, a three-dimensional computational fluid dynamics (3-D CFD) model was developed to simulate local velocity and pressure distributions resulting from such a storm. A preconditioned compressible Navier-Stokes flow solver [1] was used to compute the flow field around the VAB complex, including the Launch Control Center, the Low and High Bays of the VAB, and several outbuildings in the immediate LC-39 area. The mapping of the forces and velocities on and along the affected faces of the VAB correlated surprisingly well with the extensive damage areas realized on both on the south face and on the southeast section of the roof. The model results were also consistent with the minimal damage seen on the east, north, and west faces of the structure.

INTRODUCTION

The local wind environment resulting from Hurricane Frances varied in speed and direction throughout the course of the storm's track through the Bahamas, making landfall near Stuart, Florida (84 nm [97 statute miles] to the southeast), along its trek across Florida, and ultimately out of our area via Florida's western panhandle. Figure 2 shows the approach, landfall, and departure track of Frances.

Unfortunately, because of a loss of power at the Cape Canaveral Air Force Station X-Y building, all KSC wind information was lost at 1220Z on September 5, presumably very close to the occurrence of maximum winds as evidenced by other sources. A National Weather Service automatic water level station, located at the Trident Pier at Port Canaveral approximately 16 miles to the south-southeast, indicated maximum surface winds occurred between 1224Z and 1300Z. The winds at the port during this period were sustained at 41 kt, gusting to 57 kt and shifting (veering) rather quickly from 70° (true) to a more easterly direction. Over the next several hours, the wind direction eventually shifted to be from the east-southeast. The average wind speed continued to drop, but even 12 hours after the occurrence of maximum winds, they were still close to 30 kt steady-state and gusting to nearly 50 kt. Figure D-3 shows a 3-day time history plot of signicant winds as measured at the Trident Pier from 0000Z on September 4 to 0000Z on September 7 resulting from Hurricane Frances.

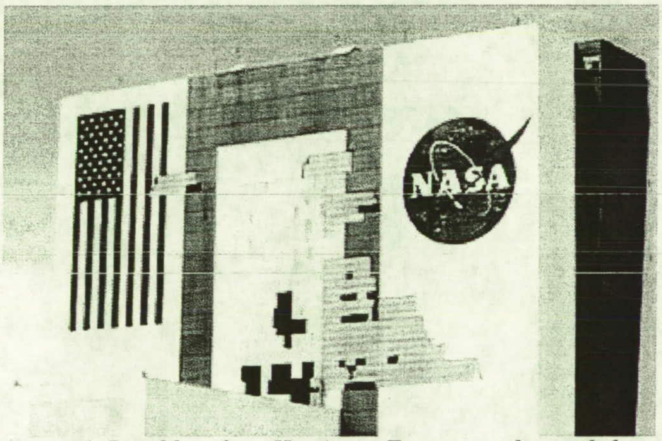

Figure 1. Panel loss from Hurricane Frances on the south face of the VAB

The Trident Pier wind data allows us to use the KSC wind tower data with some degree of con. dence that the worst part of the storm winds were captured prior to the loss of data at the Center. The 500-ft meteorological tower (Tower 313) provides a reasonable estimate of the vertical structure of the wind impacting the VAB because it is located 2.7 miles north-northwest of the VAB and has wind sensors at multiple levels. Sensors are installed at the 12-ft, 54-ft, 162-ft, 204-ft, 295-ft, 394-ft, and 492-ft levels and are located on both the northeast and southwest corners of the tower structure for "best" free-stream exposure.

Since it is not known exactly when any of the panels departed the building, we opted for three most likely wind flow scenarios for the CFD analysis. The first starting point was to select a wind speed and corresponding direction based on the maximum sustained velocity seen at Tower 313. We would then bias the direction ±10° about that direction.

Between 0930Z and 1200Z on September 5, the maximum sustained wind at the 492-ft level was about 70 kt, with a peak gust of 89 kt (see Figure D-4). The direction was between 062° and 077° and was rapidly veering (turning clockwise with time). At the 295-ft level, the maximum sustained wind was about 61 kt from a general direction of 64° to 78°, with a maximum gust of 78

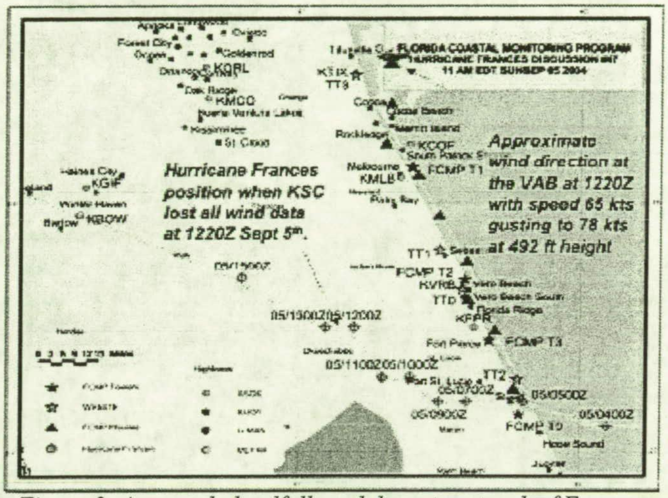

Figure 2. Approach, landfall, and departure track of Frances

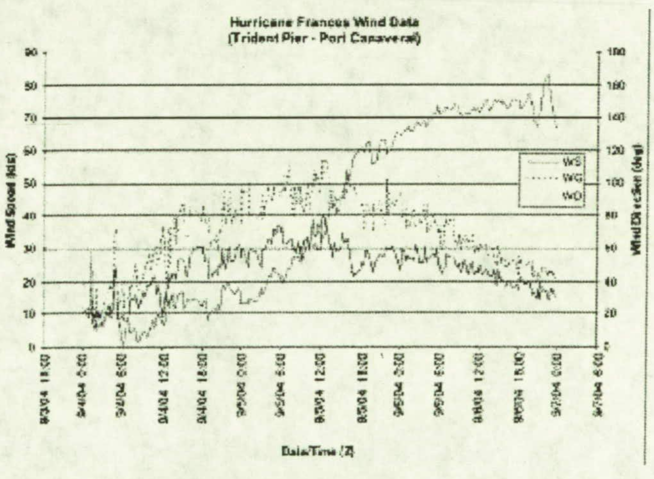

Figure 3. Hurricane Frances wind data from Trident Pier at Port Canaveral

Considering the variability of the measurements, terrain, and other uncertainties, we selected a working wind speed consistent with a minimal Category 1 hurricane (64 kt) and a general first-guess wind direction of 080°. With the VAB sited on a line biased 13.5° counterclockwise from true north, the initial CFD wind direction of 080° would be hitting the east face of the building nearly dead on—or at least within 3.5°. For simplicity, the CFD wind direction was selected to impact the east face directly and then varied ±10°.

All of the CFD model runs to date have been with a uniform vertical distribution, though in reality we know the wind speed in the planetary boundary layer increases nonlinearly with height. Even so, the analysis results show good agreement with what was seen in actuality in terms of location, area, and extent of damage on the VAB.

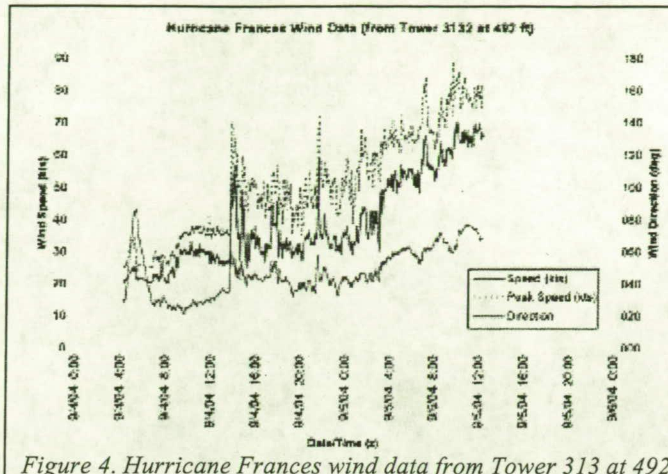

Figure 4. Hurricane Frances wind data from Tower 313 at 492 ft

ANALYSIS

Similar CFD analysis has been conducted for the wind flow simulation around the VAB [2]. In the present simulation, a viscous, Reynolds-averaged Navier-Stokes (RANS) with k-ε turbulence model was selected. The flow is assumed to be uniform, with wind speed and direction prescribed as the freestream boundary conditions. Due to the complexity of the building geometry and surrounding structures, an unstructured grid system was used. A grid-independence study was performed with two grid levels: *coarse mesh* with 501,025 cells, and *fine mesh* with 884,382 cells. To speed up the convergence, a multigrid scheme was also used. The computations were made on the Beowulf cluster using parallel processors at KSC's Launch Systems Testbed. Several case studies were made for different wind speeds and flow directions. Figure 5 shows the computational domain considered for the simulations. A parametric study was performed with different wind magnitudes and directions.

DISCUSSION OF RESULTS

Though the low-level surface winds at KSC never reached hurricane strength (74 mph) during Hurricane Frances, extensive panel failure occurred at wind speeds far below the 118- to 125-mph wind load limit reported in the literature. The maximum sustained winds measured at a nearby wind tower were 53 mph at a height of 54 ft and 80 mph at 492 ft. with such low-velocity winds actually seen along the similar 525-ft vertical extent of the VAB, we need to turn to the results of the CFD analysis to help explain the inordinate loss of panels from the south face. The final panel loss count was approximately 825 panels, or 20 percent of the total VAB side-surface area, with the majority of the damage occurring on the south face, above and toward the right of the low bay.

CFD model runs showed the only wind flow cases that would exceed an allowable pressure difference on the panels of 115 psf (190 psf less an allowable margin of safety) are those from Category 4 storms and higher (greater than 131 mph). We suspect something else at play here. A range of wind cases (wind speed and direction) was generated for a variety of additional, arbitrarily defined pressure differentials that would yield surface area disturbances near 20 percent or greater. Table 1 shows a range of wind conditions and calculated pressure differentials for a quick-look assessment. The threshold areas are integrated over the south face of the VAB, which has a total surface area of 220,014 sq ft.

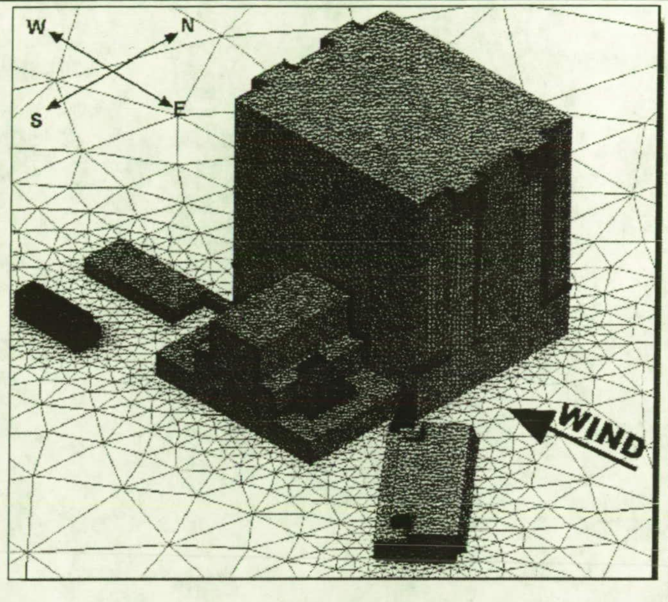

Figure 5. VAB computational geometry

Table 1. Surface area affected at prescribed pressure differential (Max ΔP)

Hurricane Category	Wind Speed (mph)	Wind Directi on	Max ΔP (psf)	Potential Damage Area (sq ft)	Percent of Total Area Damage
1	74	90°	23	42,518	19.3
2	96	90°	38	65,829	29.9
3	120	90°	60	73,777	33.5
3	120	80°	60	48,771	22.2
3	120	100°	60	157,250	71.5
3	120	100°	67	69,077	31.4
4	155	90°	118	64,608	29.4
5	200	90°	180	64,354	29.3

This analysis shows the potential damage area on the south face is sensitive not only to wind speed, but to relatively small changes in direction. The table shows four simulation that were made for a Category 3 hurricane: a wind directly impacting the east face, plus three of the same speed that were biased ±10° off the east face. The maximum pressure difference is encountered when the wind direction is 10° south of the building's east-west axis. This direction nicely corresponds to the period of the storm when the wind was at its maximum.

Figures 6 through 12 graphically show the CFD pressure distributions on the VAB for various wind intensities from the east. Figures 9 and 10 show the results when the wind is biased ±10° about the East face. The predicted streamlines in Figure 13 indicate strong vortices in the region between the low and high bays of the VAB. This indication is consistent with the fact that the most damage was confined to the south face. In addition, photographs taken after Hurricane Frances indicate that the panels in this region were peeled off the wall in two directions (i.e., either toward the upper left corner of the south face or toward the upper right corner). This two-directional flow phenomenon (Figure 14) is also predicted by the velocity vectors of the computational simulation (Figure 15), indicating a strong recirculation zone near the region where the panels were stripped off the surface. The CFD analysis also predicted flow separation around the top of the building, which again is consistent with the actual damage seen on the roof (Figure 16). The north side of the building only suffered minimal damage, as shown in Figure 17.

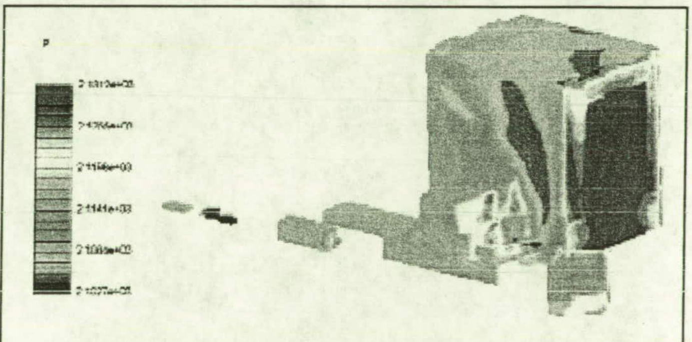

Figure 6. Coarse grids (high-wind case)

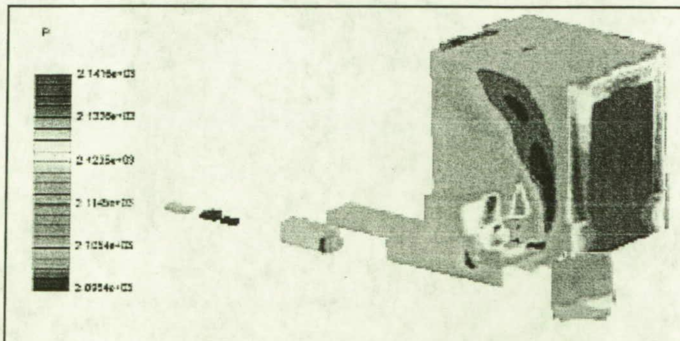

Figure 7. Coarse grids (high-wind case)

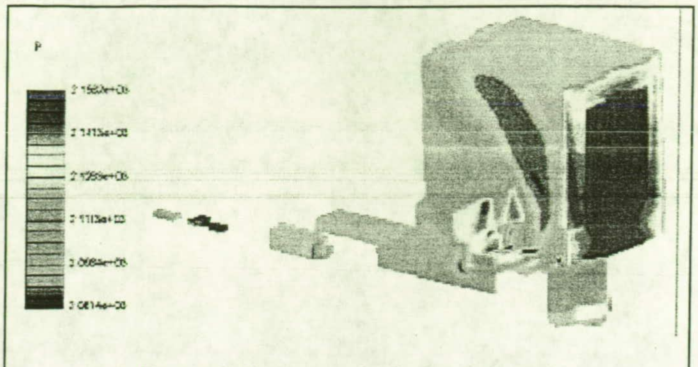

Figure 8. Coarse grids (high-wind case)

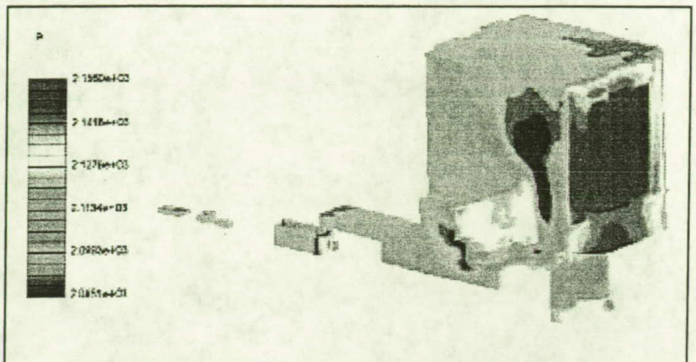

Figure 9. Coarse grids (high-wind case)

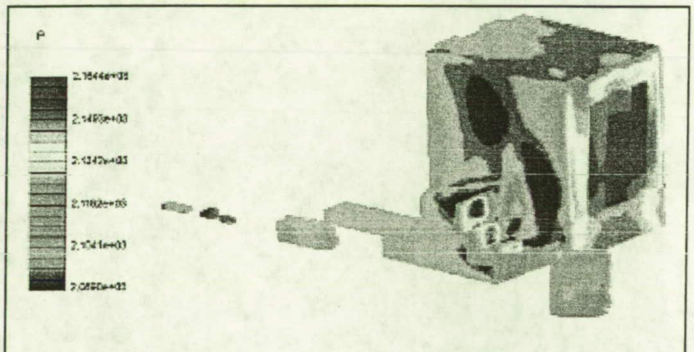

Figure 10. Coarse grids (high-wind case)

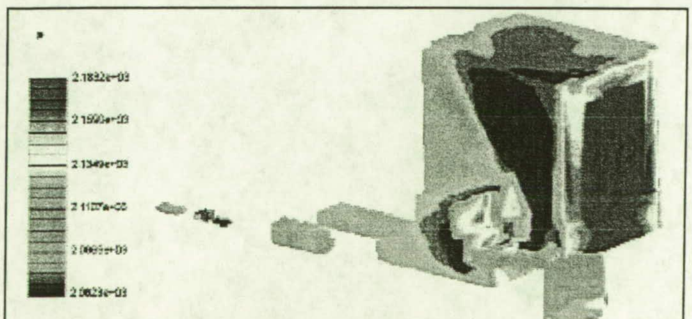

Figure 11. Coarse grids (high-wind case)

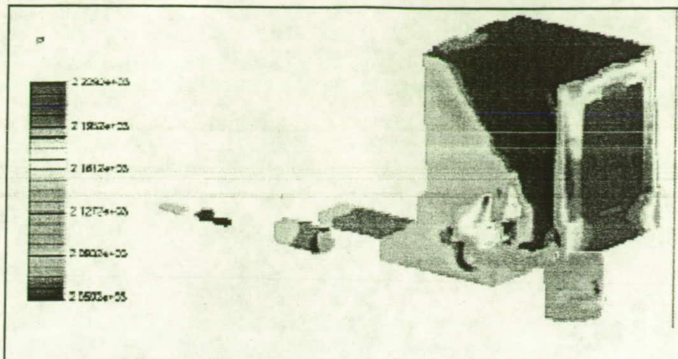

Figure 12. Coarse grids (high-wind case)

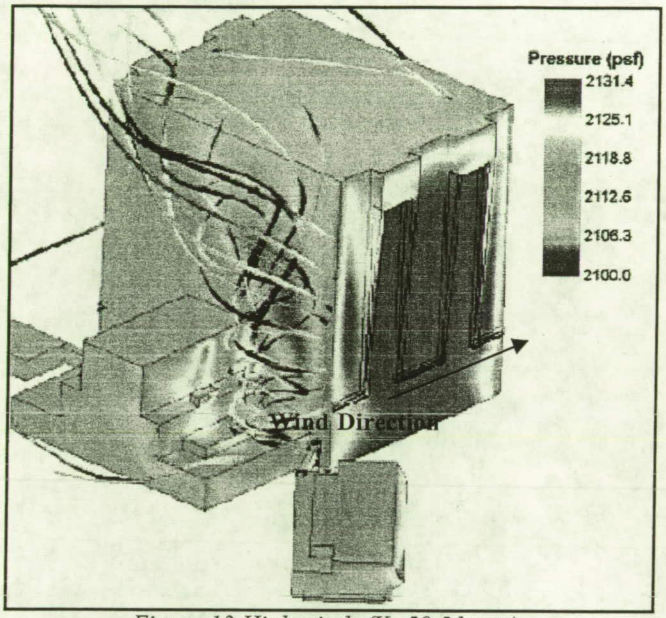

Figure 13 High winds (V=59.5 knots)

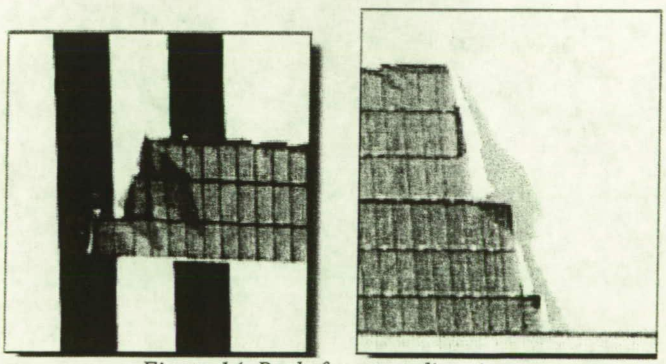

Figure 14. Peels from two directions

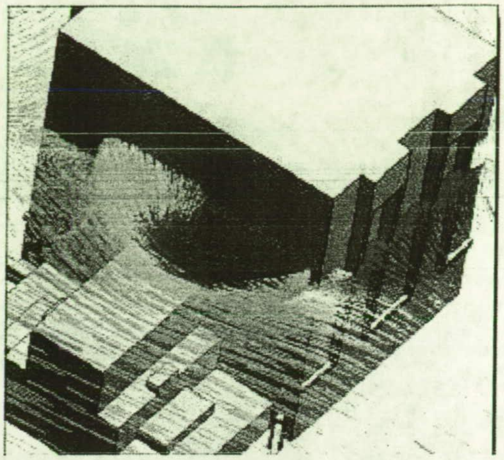

Figure 15. Flow separation around VAB (V=10 knots)

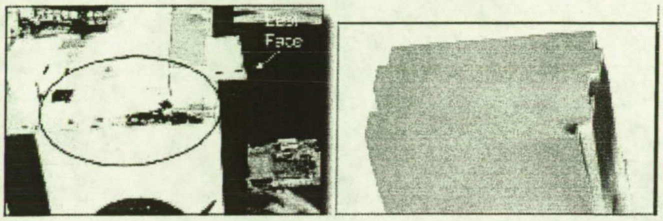

Figure 16. Roof damage (Category1, 74 mph East wind)

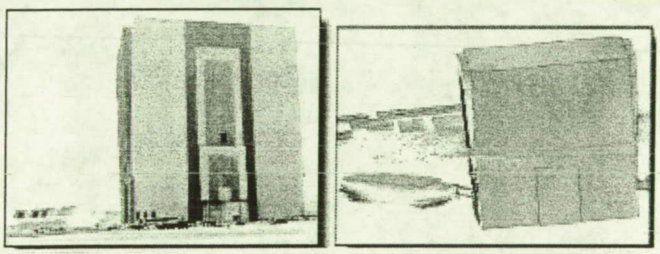

Figure 17. Comparison of damage on the north side of VAB

CONCLUSIONS

The CFD analysis explained the flow phenomena around the VAB. The results agree well with actual damage seen after the hurricanes. The south wall of the VAB sustained the most damage because of pressure interactions among surrounding buildings in the LC-39 area. Flow visualizations also help explain what actually happened during the hurricane; streamlines and velocity vectors reveal strong vortices near the south face of the VAB. The flow reversals, as seen in the velocity vectors, explain why the panels were stripped off the surface in two different directions. Finally, the area of the pressure gradients on the south face are consistent with the location and size of the area of failed panels, even though the magnitude of the wind was much lower than what was anticipated for failure. The combination of the pressure and velocity distributions suggests that the panel failures were caused by shear, peeling, and tension rather than compression. Inspection of the panels corroborated the failure modes, and corrosion of the panels and fasteners suggests material degradation may have played an important role in the panels' failing in winds far weaker than hurricane force. CFD analysis is an important tool to understanding potential or actual failure mechanisms because it can help facilities engineers plan their repair and reinforcement strategy in order to mitigate future damage to complex structures.

ACKNOWLEDGMENTS

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REFERENCES

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