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WUFI[*]: Barking Up the Wrong Tree?

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Maybe not. For years I have said that dog won't hunt.[†] I have come around. The engineer in me likes tools. I can't help it; it is a genetic defect we engineers are born with. With therapy we engineers have learned that tools come with limitations; Clint Eastwood comes to mind.[‡] I think WUFI has turned into a useful modeling tool and is getting progressively more useful. I never thought I would ever write those words.

WUFI is the brainchild of Hartwig Kunzel, aka "The Konig of WUFI," from the Fraunhofer Institute for Building Physics, and it is a software tool for calculating coupled heat and moisture transfer in building assemblies. It has gone through two decades of refinements. I think its time has come. For the record, I have always said the problem has never been the model, but the modeler. A tool is only as useful as the skill of the person using the tool.[§]

The physics has proven to be daunting. We know how to model heat flow and have known for a long time. Moisture flow? Not so much. The problem, among other things, is that water exists in four phases: vapor, liquid, solid and adsorbate. And these phases interact with each other in ways that are not clearly understood (*Figure 1*). There is no accepted theory of combined heat and moisture flow. Let me repeat: there is no accepted theory of combined heat and moisture flow. As such the interactions in models—not just WUFI—are currently phenomenologically based. We engineers build it, wet it and watch what

[*] Wärme und *Feuchte instationär.* (Note: I am not endorsing the product "WUFI." I am just describing how to make it work better.)

[†] For Canadians and Europeans and others who read this, the phrase is an American slang expression that means something will not fulfill its intended purpose. I first heard it in Texas, but folks from Arkansas and Kentucky claim it as theirs. The Canadian version is "hosed up," as in "WUFI is all hosed up," and it comes from Rick Moranis who grew up almost next door to me. We are both from Downsview, a suburb of Toronto. Rick is best known as Bob McKenzie, one of the McKenzie Brothers from "Great White North." In case you want to know how my mind works, check out my favorite clip, "the mouse in a beer bottle." Rick is credited with coining the phrase "hoser," but we all called ourselves "hosers" in my high school before Rick made it with Second City Television.

[‡] Harry Callahan played by Clint Eastwood from the 1973 movie "Magnum Force" gives one of the movie's best lines: "A man's got to know his limitations."

[§] I own a hammer and a saw; to say that I am a carpenter is a stretch. I built a deck once. I framed houses for a day before I got fired.

happens. Analysis is observation and experience based. We are still waiting for the physicists to figure out the theory.[#] In the meanwhile we have got things to design and build.

We guess—educated guesses—but guesses nevertheless. And we simplify. We take *Figure 1*—we ignore the solid phase—and then we apply it to a porous material. We get the transport processes and driving potentials in *Table 1*. Why does WUFI ignore the solid phase? You're kidding, right? Well, because including the solid phase interactions makes things way too complicated. Go back and check out "Thick as a Brick" *ASHRAE Journal,* May 2010, and "Double Rubble Toil and Trouble" *ASHRAE Journal,* April 2010. WUFI then ignores osmosis. Why? Same reason as the solid phase thing—only worse. Why porous materials? Non-porous materials are easy to figure out. You don't need a model for them. They don't absorb moisture. They don't get wet—except on the surface. Easy.

Now what? We need to figure out how to model the transport processes and driving potentials in *Table 1* (less osmosis). Remember, we don't have theory to work with. Well, we start by wetting a porous material and see what happens (*Photo 1*)? Get a good watch. And spend some quality time—about a decade—and play with some gamma rays. And oh, by the way, work with a bunch of smart folks and share.[||] Once you figure it out it gets easy (*Photo 2*). Well, not really. It took years to figure it out more or less in a single material (*Figure 2*). It took the Konig and his colleagues in Germany more years

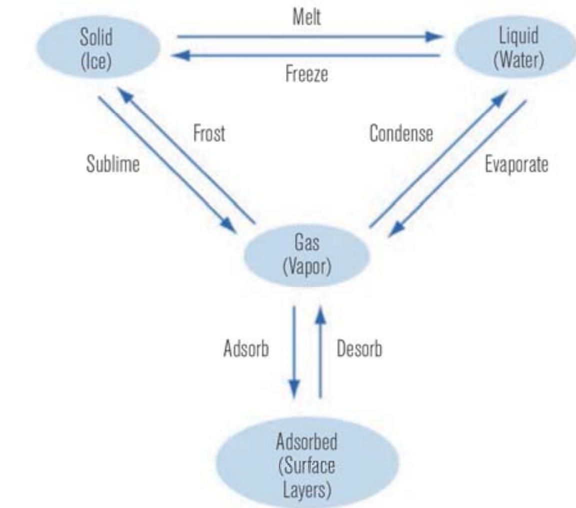
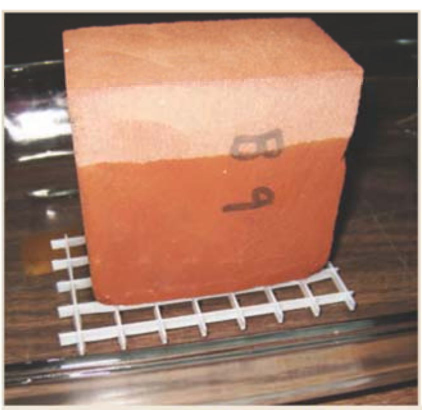


FIGURE 1 **Phases of Water. Water exists in four phases: vapor, liquid, solid and adsorbed. These phases interact as shown.**

TABLE 1 Moisture transport in porous media.

PHASE	TRANSPORT PROCESS	DRIVING POTENTIAL
Vapor	Diffusion	Vapor Concentration
Adsorbate	Surface Diffusion	Concentration
Liquid	Capillary Flow Osmosis	Suction Pressure Solute Concentration

We take *Figure 1*—ignore the solid phase—and apply it to a porous material. We get the listed transport processes and driving potentials.



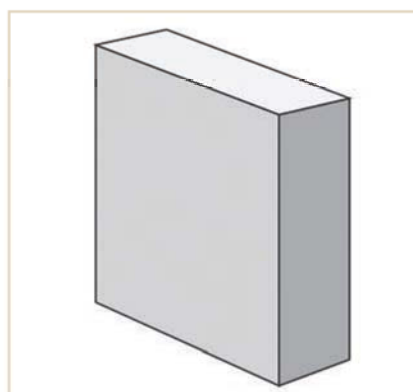


PHOTO 1 (LEFT) **Wetting "Take 1." Wetting a porous material to see what happens. Get a good watch.** PHOTO 2 (CENTER) **Wetting "Take 2." How an old guy does it.** FIGURE 2 (RIGHT) **Single Material. Addressing the dynamic interactions in a single material is challenging on its own.**

[#] Similarly, we are still waiting for them to figure out the friction thing. Physicists still to this day cannot derive frictional forces from the fundamental forces of nature. Can't do it with Newtonian Mechanics, Einsteinian Mechanics, Quantum Electrodynamics, or String Theory. We engineers don't care. We use fudge factors. We don't call them that because that would upset civilians. We call them "coefficients." We use the "coefficient of friction" because we don't have time to wait for the physicists to catch up to us. So, in the meantime, we engineers live in the coefficient world coupled with judgment and safety factors. And because of this you all have the good life. Cars, planes, trains, electric motors. You are welcome.

[||] Kumar Kumaran and Gint Mitalas and Mark Bomberg: the "Dream Team" who shared stuff with a young German—young at the time—Hartwig Kunzel and his colleagues.

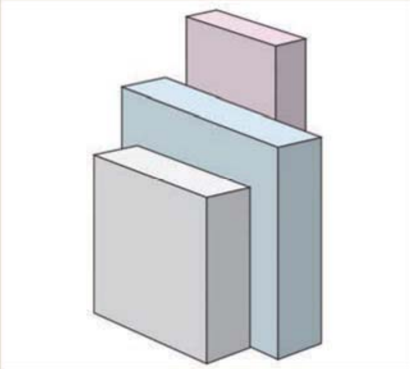


FIGURE 3 Several Materials in Contact. Addressing the dynamic interactions in several materials simultaneously proved to be an order of magnitude more difficult. Where the materials are in contact with each other, one-dimensional combined heat and moisture flow models provide reasonable correlation with real-world examples and measurements.

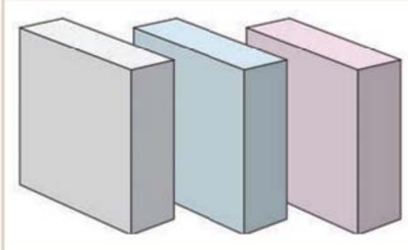


FIGURE 4 Several Materials not in Contact (Air Gap). Where the materials are not in contact with each other, one-dimensional models tend to break down as they are ill-equipped to handle airflow and the resultant convective flow.

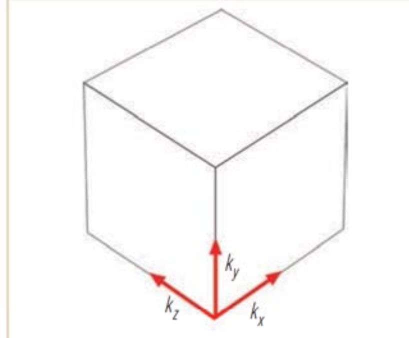


FIGURE 5 Material and transport properties based on orientation.

PHOTO 3 Oriented Strand Board "Take 1." Note the layered mats of aligned strands prior to heat and pressure. PHOTO 4 Oriented Strand Board "Take 2." Finished product—an engineered "structural use panel."

to figure it out when several different materials were in direct contact with one another (*Figure 3*).

But when the materials were not in direct contact with each other the models tended to break down (*Figure 4*). Again, all the models, not just WUFI. The problem was airflow. Airflow is a 3-D phenomenon. The models were one-dimensional. Oops. This was not a big issue with the Germans. Huh? Well, the Germans are Europeans, and European building assemblies historically tend to be solid mass systems with little or no convective airflow. As such, one-dimensional combined heat and moisture flow models (that ignored airflow)—the early versions of WUFI—proved useful in analyzing performance and predicting performance—in European assemblies.

It didn't work on the other side of the Atlantic—our side. North American building assemblies are multilayer systems with complex 3-D airflow pathways. One-dimensional combined heat and moisture flow models broke down in these types of assemblies due to the inability to model the airflow component. And worse, many North American building materials themselves are 3-D and are a bear to model one-dimensionally. They have different material and transport properties based on orientation (*Figure 5*). Check out oriented strand board (*Photos 3* and *4*) and its material and transport properties (*Figure 6*).

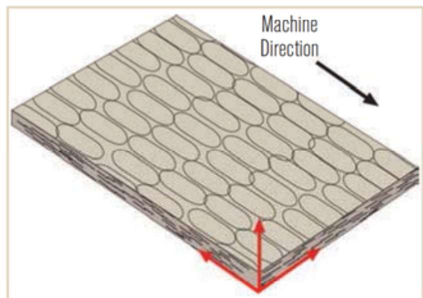


FIGURE 6 Oriented Strand Board. OSB material and transport properties are orientation based.

Add a half decade to figure out how to "fool" a one-dimensional model into giving reasonable results with materials that have orientation-based properties, and you get us to the two current remaining problems. The airflow piece we have already mentioned—and we will get back to it. But we have not yet talked about rainfall—the second of the remaining problems.

Both European and North America building assemblies are exposed to rain—this, of course, is obvious. That rain is a significant moisture load is also obvious. As such, this moisture transport mechanism needs to be considered by hygrothermal models for the models to be useful. Modeling the rain transport mechanism—a 3-D phenomenon in a multilayer system—adds significant complexity.

We needed a "hoser" of German ancestry for this one.** And then some guesses and judgment. The key question to answer is how much rainwater hits the wall. A simple question, but not one that is simple to answer. WUFI software adapts the rainwater exposure models developed by John Straube to determine the amount of rainwater that impinges on the wall. Some of this rainwater bounces off the wall. Some of this rainwater penetrates the cladding, and finally some of this rainwater penetrates the water control layer. This is summarized in *Figure 7*.

The Germans figured out that 30% of this water bounces off the wall and 70% stays on the wall. The 70% that stays on the wall ("retained water") is addressed by liquid conductivity (capillary flow) and vapor diffusion. In multilayered assemblies, folks at ASHRAE figured out that about 1% of the 70% (the "retained water") penetrates the cladding.†† It is important to apply this penetrating water to the backside of the cladding.‡‡ But this does not go far enough. I (and others) further assume that 1% of the 1% penetrates the water control layer and enters into the sheathing.§§

I know you all know this, but I thought I would say it to make a point, the retained water is affected big time by the amount of solar radiation incident on the wall. We all know that solar radiation affects the liquid conductivity and vapor diffusion (*Figure 8*)—except when we forget. Anyway, it should be obvious that model orientation plays a significant role.

Back to the airflow issue. The challenge is to model a complex 3-D phenomenon in a one-dimensional model. There are 12 typical airflow pathways that need to be considered in multilayer systems (*Figure 9*). These airflow pathways arguably can be combined for modeling purposes as shown in *Figure 10*. Note the cladding ventilation component that has been added. The flows in *Figure 10* can further be simplified as shown in *Figure 11*.

In 2003, probably in a Bavarian beer garden, and after getting a letter from the "hoser" of German ancestry, the Konig acknowledged the existence of North America and its particularly bizarre multilayer airflow dominated method of assembly construction. The "hoser"

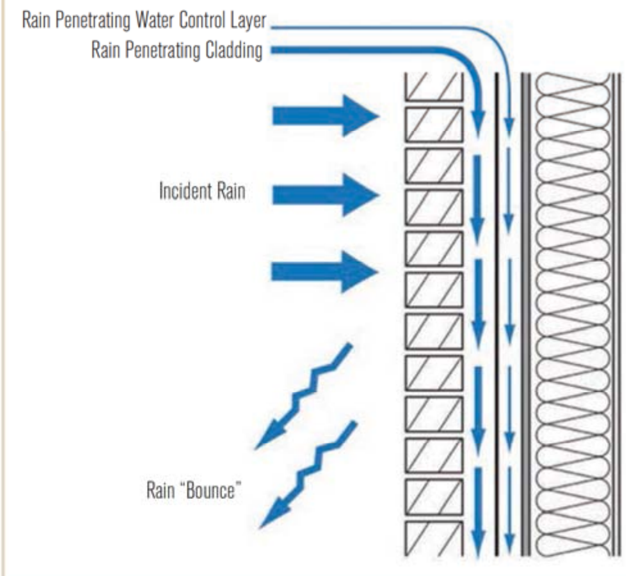


FIGURE 7 **Rainwater Penetration in a Wall. Some of the rainwater bounces off the wall. Some of the rainwater penetrates the cladding, and finally some of the rainwater penetrates the water control layer.**

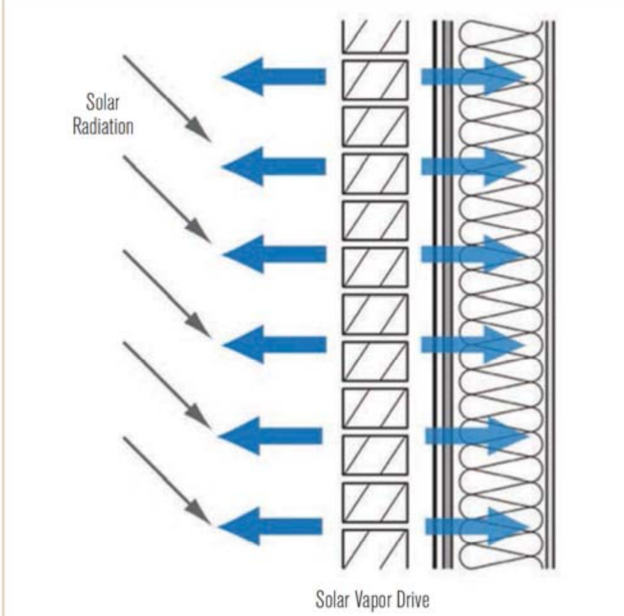


FIGURE 8 **Solar Radiation on a Wall. The retained water is affected by the amount of solar radiation incident on the wall. We all know that solar radiation affects the liquid conductivity and vapor diffusion—except when we forget. Anyway, it should be obvious that model orientation plays a significant role.**

** John Straube did his doctoral dissertation on the rain wetting of façades, and WUFI incorporates his work in providing a reasonable estimate of how much water falls on a wall. Also, as background, ASHRAE Standard 160-2009, *Criteria for Moisture-Control Design Analysis in Buildings*, uses the Straube rain model. Well done, John.

†† Big hat tip to the ASHRAE Standard 160 committee for this. Don't know who it came from specifically, but thanks to all of you. It has proven to be a very reasonable number. Let me know where this number came from? There has to be a story behind it. There always is a story.

‡‡ Standard 160 says apply the penetrating water to the face of the water resistive barrier (WRB). I and others (see Schumacher) think this is wrong because if we have a reservoir cladding and it is applied to the face of the WRB, it does not get into the reservoir.

§§ Standard 160 also should go the route of assuming 1% of the 1% penetrates the water control layer and enters into the sheathing.

recommended a "source" and "sink" method to approximate the effect of cladding ventilation and moisture transport. Within a year, WUFI software became capable of modeling cladding ventilation. Jawohl, endich ist das Tor fur unsere Mannschaft gefallen!##

With this airflow element added, WUFI allows us to approximate the flows in *Figure 11* as shown in *Figure 12*.

Note that WUFI software is unable to address "through the assembly airflow." The "source" and "sink" approach does not work. But the "through the assembly airflow" can be approximated as follows. Inner lining leakage moves air-transported moisture from the interior to the backside of the outer lining and vice versa. Outer lining leakage moves air-transported moisture from the backside of the outer lining to the exterior and vice versa. To make the modeling work, two arbitrary 5 mm (3/16 in.) airspaces are set up at the back side of the outer lining. One airspace is coupled to the interior. The other airspace is coupled to the exterior. The airspaces create an unintentional capillary break that needs to be compensated for.

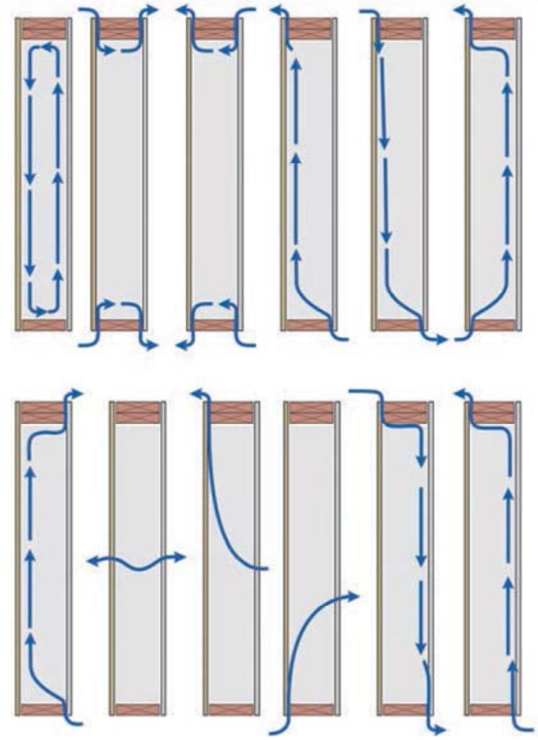
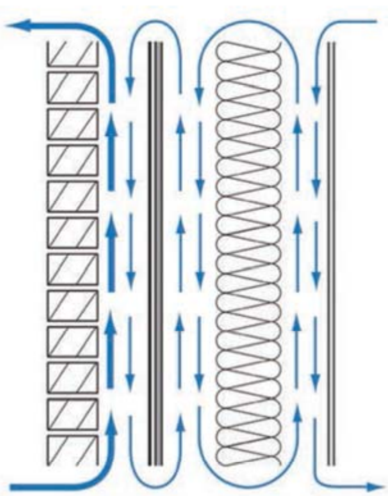
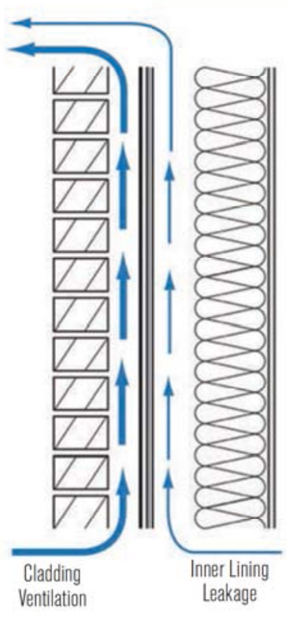


FIGURE 9 Airflow Mechanisms in a Wall. There are 12 typical airflow pathways that need to be considered in multilayer systems. The challenge is to model a complex three-dimensional phenomenon in a one-dimensional model.

Yes, finally the goal for our team has fallen! (www.translate.com)





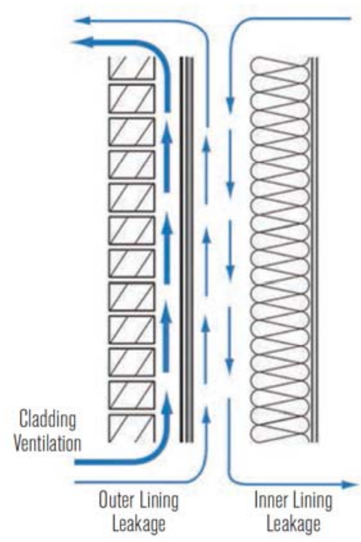


FIGURE 10 Combined Airflow Pathways (full level of complexity). The airflow pathways arguably can be combined for modeling purposes as shown. Note the cladding ventilation component that has been added. FIGURE 11 Further Simplification of Airflow Pathways. The operative phrase is "further simplification of airflow pathways."

FIGURE 12 Approximation of Flows (for purposes of modeling). A "source" and "sink" method to approximate the effect of cladding ventilation and convective (air transported) moisture transport.

Multiple layers can be addressed in a similar fashion (*Figure 13*).

So what should the flow rates, gap sizes and air changes per hour be for these elements? Check out *Table 2*. The information in *Table 2* comes from a combination of published work (ASHRAE 1091-RP, work done at Oak Ridge National Laboratory, work done at the University of Waterloo) and unpublished work.***

So where are we? We have "tuned" the WUFI model so that it works for multilayered North American assemblies. We took the old WUFI—something similar to a "Porsche 993"—and modified it to get a race car: a WUFI version of a "Porsche 996" Turbo. The real deal. Handles rain, handles airflow, handles OSB. You still need to learn how to drive it correctly. You do not require the skill of a Michael Schumacher to drive a "tuned" WUFI model—but it is good to have a Chris Schumacher around to occasionally check with, so you don't run it off the road.

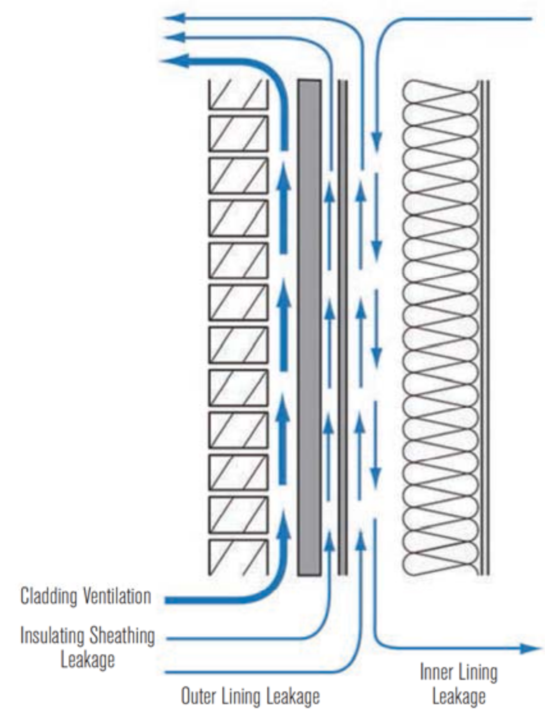


FIGURE 13 **Multiple Layers. Air space coupling to address through the assembly airflow in WUFI.**

TABLE 2 Cladding ventilation/sheathing ventilation.

	FLOW RATE	GAP	ACH
Wood Siding	0.1 cfm/ft^2	3/16 in.	20
Vinyl Siding	0.5 cfm/ft^2	3/16 in.	200
Brick Veneer	0.15 cfm/ft^2	1 in.	10
Stucco (Vented)	.01 cfm/ft^2	3/8 in.	10
Stucco (Direct Applied)	None	None	0
Sheathing Flanking Flow	0.05 cfm/ft^2	3/16 in.	10

Flow rates, gap sizes and air changes per hour for listed elements are given. The information in *Table 2* comes from a combination of published work (ASHRAE 1091-RP, work done at Oak Ridge National Laboratory, work done at the University of Waterloo) and unpublished work.

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