RealShear™ F- AND M-SERIES SENSORS

USER GUIDE

v.070712

LENTERRA

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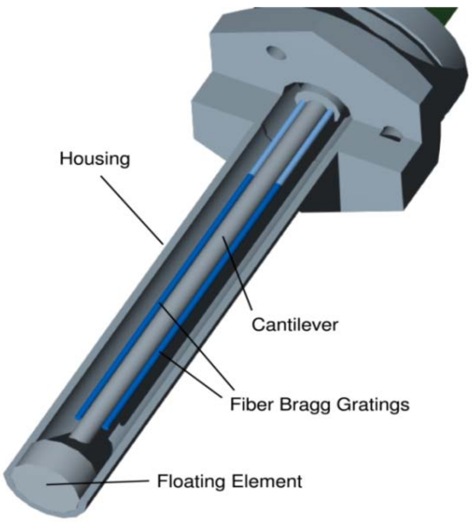
DESIGN

RealShear ™ sensor

Lenterra's RealShear™ family of shear stress sensors/inline viscometers enable direct measurement of wall shear stress induced by fluids on construction walls in mixers, pipes, turbines, pumps, extruders and other devices employing flowing fluids and gases. The sensor is mounted flush with a pipe or vessel wall, or rotor-stator workhead, to provide in-line measurement with no disruption of process flow. When paired with a LOC-F Optical Controller, the RealShear™ sensor comprises an efficient, fast and reliable sensing device useable in a wide range of applications.

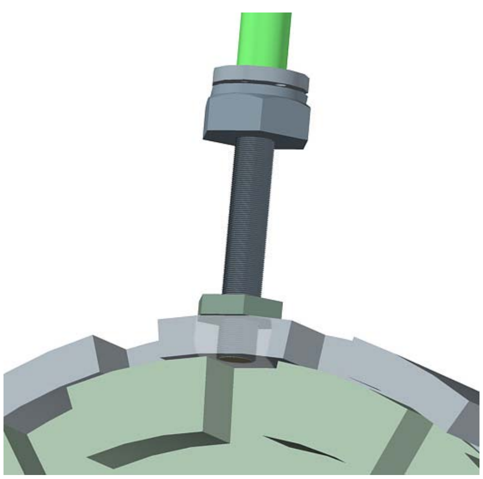


Rendering of RealShear™ sensor

RealShear™ sensors are direct measurement force sensors employing a floating element that is brought in contact with the flow and a mechanical cantilever system which bends in response to shear stress applied to the sensor's surface. This bending is detected by two optical strain gauges called Fiber Bragg Gratings (FBGs), attached to either side of the cantilever beam. Bending causes strain in the FBGs which shifts their optical resonance frequencies. Infrared light is used to interrogate these FBGs, and the intensity of the reflected light is a function of the degree of overlap of their spectra which shift in opposite directions when bending occurs.

The cantilever and micro-optical resonators are inside a finely-threaded stainless steel cylindrical housing, with a hexagonal head and ruggedized fiber optic cabling. The cable terminates with a LC/PC type duplex fiber fiber-optic connector (as shown), or two FC/APC connectors.

INSTALLATION

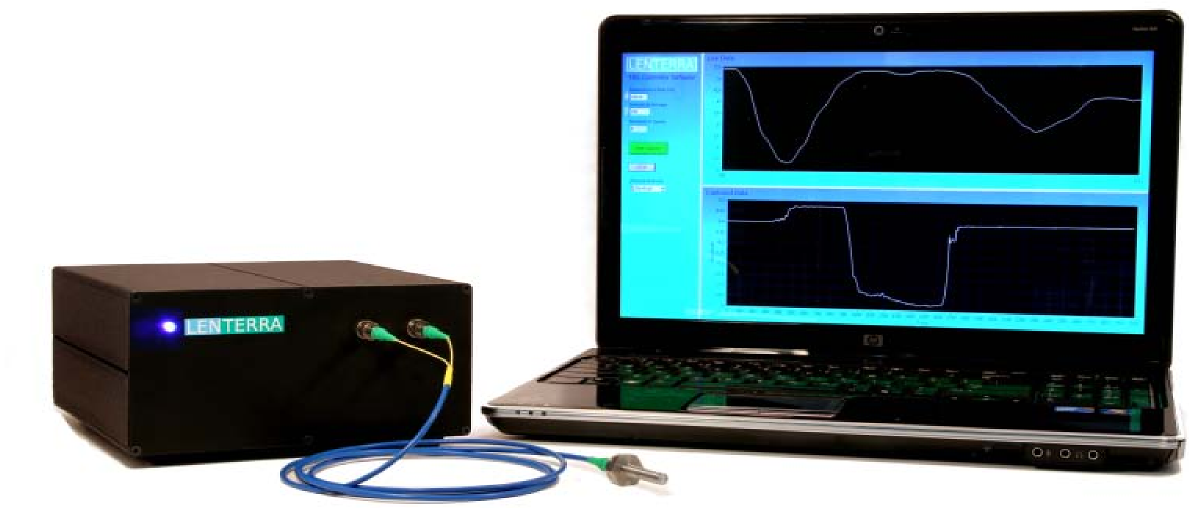


RealShear™ sensor installed through stator in a high shear mixer

Typical installation consists of following steps:

- In a desired place of the construction wall, tap a thread to accommodate the sensor (1/4-80 for an F-series and 6-80 for an M-series sensor)
- Trying not to damage the fiber-optical cable, screw the sensor into the hole such that the floating element is flush with the surface. Teflon tape could be used to seal the thread
- Align the sensor sensitivity axis with the expected flow direction. Sensitivity axis is indicated on the hexagonal portion of the sensor housing with an indentation, such that a positive response results from flow emerging from this side
- Secure the sensor with a nut

TOTAL MEASUREMENT SYSTEM



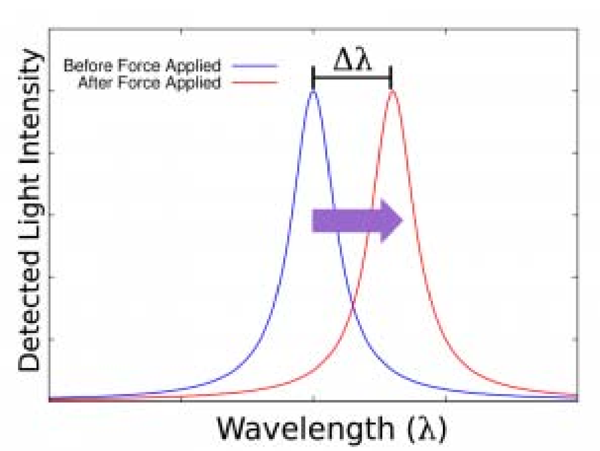
A complete system for measuring shear stress/viscosity

Includes :

- A probe with connecting fibers
- Controller combining optical components and data acquisition electronics
- Computer
- Measurement Software

The Lenterra LOC-F Controller includes an optical source for interrogation of the FBGs. The unit interfaces with a PC through USB for measurement display and analysis. The controller is capable for fast measurement rate to capture high frequency periodic effects and transients (up to 10 kHz). Refer to the LOC-F Controller documentation for further detail about the controller and measurement software.

PRINCIPLE OF OPERATION



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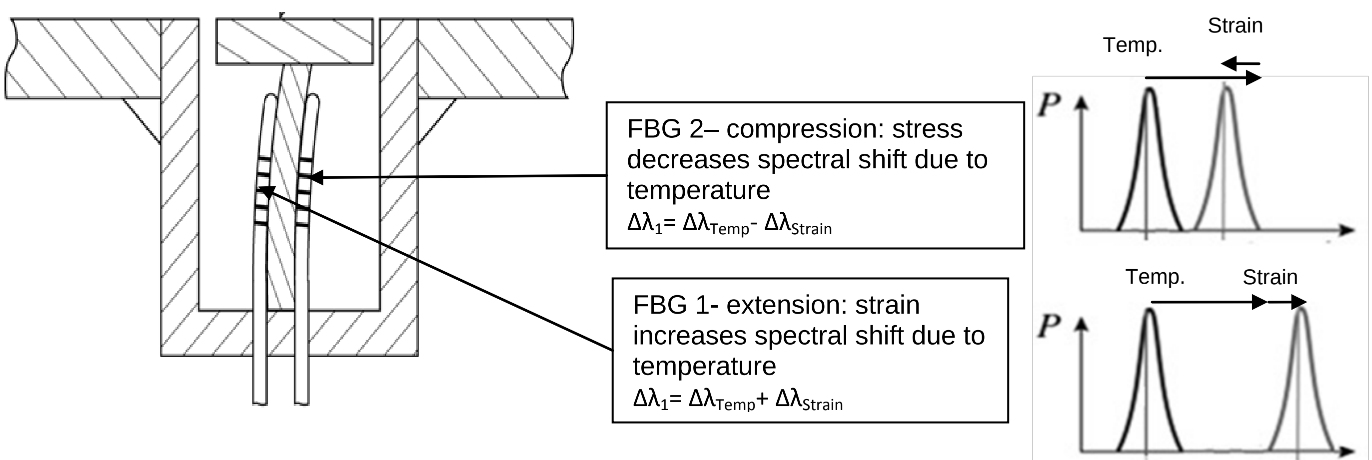
MICRO-OPTICAL STRAIN GAGES

Fiber Bragg Gratings are resonant periodic structures inside optical fiber in which the index of refraction varies along the fiber. Like other optical resonators, light of a particular wavelength is reflected from the grating while light of other wavelengths passes through forming a characteristic absorption or reflection spectrum. The FBG is attached to the side of the cantilever and experiences longitudinal strain (or stress) when the cantilever is deflected, which alters the spatial structure of the grating causing a change in the wavelength of light that is reflected from it. By illuminating the fiber with light and detecting the reflected spectrum, the shift in the optical resonance wavelength, Δλ, can be measured and related to strain of the FBG. Therefore, shear force on the floating element can be measured by tracking the shift in the resonant wavelength. This optical detection of the force applied to the cantilever allows for small footprint of the sensor, provides high sensitivity combined with ruggedness, durability and insensitivity to electromagnetic noise.

TEMPERATURE COMPENSATION AND TEMPERATURE MEASUREMENT

Two micro-resonators are housed inside the sensor so that temperature effect can be compensated for. Strain shifts FBG spectrum, but so does temperature. To get information about strain independently from temperature, and measure temperature independently from strain, two FBGs are attached to opposite sides of the cantilever. The differential signal (shift of FBG 1 spectrum less shift of FBG 2 spectrum) is independent from



Spectrum shifts due to strain and temperature

temperature, while the average signal (shift of FBG 1 spectrum plus shift of FBG 2 spectrum) is independent from the strain:

$$\Delta\lambda_{Strain} = \left(\Delta\lambda_{FBG1} - \Delta\lambda_{FBG2}\right)/2 \qquad \Delta\lambda_{Temp} = \left(\Delta\lambda_{FBG1} + \Delta\lambda_{FBG2}\right)/2$$

SPECTRUM SHIFT MEASUREMENT AND WALL SHEAR STRESS COMPUTATION

Spectrum shift $\Delta\lambda$ is measured using an optical circuit that is a part of the controller. Wall shear stress is found from $\tau_w = k\Delta\lambda$**,** where *κ* is the calibration coefficient. Sensors are calibrated by applying a varying mechanical force *F* to the tip of the cantilever and measuring $\Delta\lambda$**:** while shear stress is calculated from the known applied force as $\tau_w = F/A$ (*A* is the area of floating element).

MEASURING VISCOSITY AND SHEAR RATE

Shear stress and viscosity are interrelated through the shear rate (velocity gradient):

$$\tau = \mu \frac{\partial u}{dy} = \mu \dot{\gamma}$$

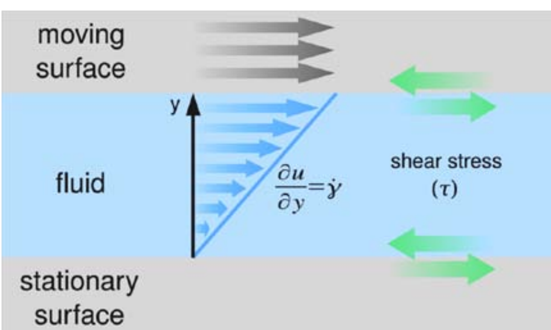
Here τ is the shear stress, $\dot{\gamma}$ is the shear rate, μ is the dynamic viscosity, u is the velocity component of the fluid tangential to the wall, and y is the distance from the wall.

When the viscosity of a fluid is not a function of shear rate, the fluid is described as Newtonian. In non-Newtonian fluids the viscosity of a fluid depends on the shear rate (or in some cases the duration of stress). Certain non-Newtonian fluids behave as Newtonian fluids at high shear rates and can be described by the equation above. For others, the viscosity can be expressed with certain models. RealShear™ sensors directly measure shear stress at a wall (τ_w at y = 0). To determine viscosity the value of the shear rate at the wall must be independently known. The viscosity or shear rate can then be calculated from:

$$\mu = \frac{\tau_w}{\dot{\gamma}_w} \qquad \text{or} \qquad \dot{\gamma}_w = \frac{\tau_w}{\mu}$$

If the shear rate is known or can be modeled, a RealShear™ sensor can be used as a real-time, in-line viscometer. Measuring viscosity in this way uses the same principle as "cup-and-bob" viscometers in which a cylinder is rotated inside a cup, submerged in the fluid under test. This powerful capability removes the need for further costly instrumentation when viscosity needs to be monitored in-line.

VISCOSITY AND WALL SHEAR RATE MEASUREMENT IN HIGH-SHEAR MIXERS



High-shear mixers are used across numerous industries, including for the production of pharmaceuticals, food, and cosmetics. HSMs are often of the rotor-stator type, in which one element (the rotor) rotates in close proximity (fraction of a millimeter) to a stationary element (the stator). Mix components that pass between them experience high shear stress. For high-shear mixers, the known rotor geometry and rate of rotation can be used to calculate the velocity gradient. Following assumptions can be made in this case:

- A "no slip" condition exists (the fluid velocity at each surface is equal to the velocity of that surface)
- The velocity gradient profile is linear, i.e. the shear rate is same for all distances from the wall y. This is typically a good assumption for HSMs due to the very small gaps between rotors and stators

With these two assumptions, the shear rate at the stator is simply the tangential velocity of the rotor (the "tip speed") divided by the gap distance between it and the stator:

$$\dot{\gamma}_w = \frac{u_{rotor}}{y_{gap}}$$

The rotor velocity can be calculated from its diameter, d, and the rate of rotation (RPM):

$$u_{rotor} = \pi \frac{RPM}{60} d$$

Using the direct wall shear stress measurement from a RealShear™ sensor, the viscosity therefore can be calculated as:

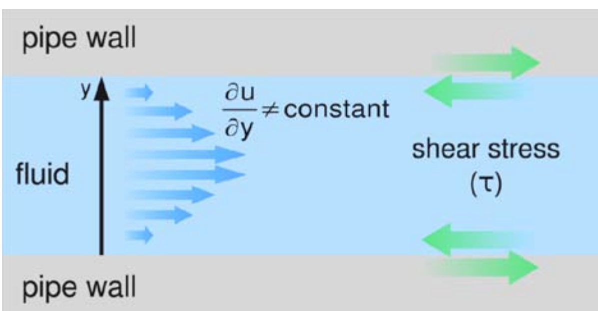
$$\mu = \frac{\tau_w y_{gap}}{\pi d} \frac{60}{RPM}$$

VISCOSITY MEASUREMENT IN PIPES AND OTHER CHANNELS

Measurement of the wall shear stress can also be used to determine the viscosity of fluids flowing through pipes or other channels. Just as in the case of high-shear mixers, in order to calculate the viscosity from the measured wall shear stress, the wall shear rate must be known. Formulas exist that implicitly incorporate the wall shear rate for various channel geometries and can be used to calculate the viscosity based on the measured wall shear stress. Simple formulas are known for the following conditions:

- The flow is laminar
- The flow is fully developed (the velocity gradient no longer changes as the flow continues along a channel). This condition can be assumed to occur at a distance into a pipe equal to several pipe diameters, or a distance into a thin channel equal to several channel heights

CIRCULAR CROSS-SECTION PIPES



Viscosity (μ) can be calculated from the wall shear stress (τ_w) for flow in a pipe with a circular cross-section with the following formula:

$$\mu = \frac{\tau_w r}{4U}$$

Here U is the average flow velocity, and r is the inner radius of the pipe. To calculate the average flow velocity from the flow rate, simply divide the volumetric flow rate (Q) by the cross-sectional area of the pipe (A):

$$U = \frac{Q}{A}$$

THIN RECTANGULAR CROSS-SECTION CHANNELS

Viscosity can also be calculated in thin channels (in which the height of the channel is much less than the width), such as those found at the exit zone of extruders. For a rectangular thin channel the viscosity is

$$\mu = \frac{\tau_w h}{6U}$$

where U is the average fluid velocity, and h is the height of the channel.

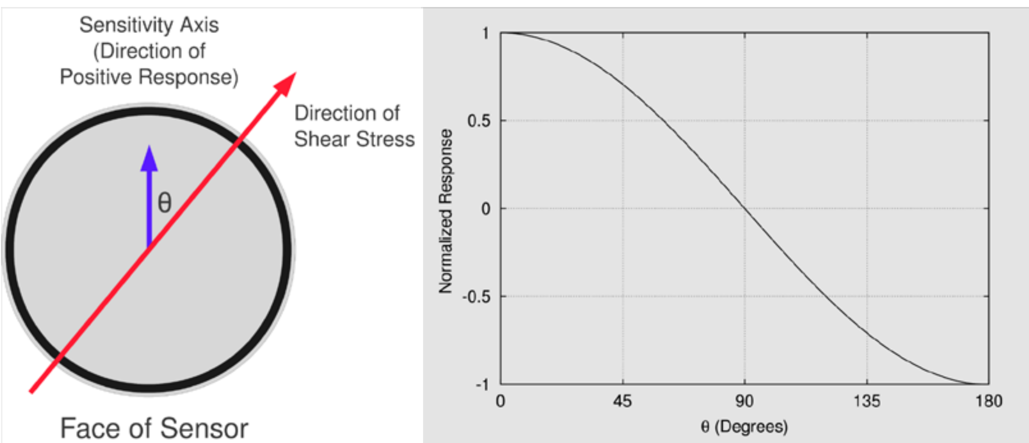
TEMPERATURE EFFECT

For both Newtonian and non-Newtonian fluids, viscosity is function of temperature. Depending on the particular fluid, even small changes of temperature can result in significant variation of viscosity. As a consequence, accurate interpretation of viscosity measurements should be accompanied by temperature measurements.

FACTORS THAT AFFECT THE SIGNAL

In addition to shear force incurred by the flow on the floating element, the sensor signal can be affected by several other factors:

SENSITIVITY TO OFF-AXIS SHEAR STRESS



RealShear™ sensors have a directional response and should be aligned in the desired flow/shear direction for maximum sensitivity. The Sensitivity Axis is indicated on the hexagonal portion of the sensor housing with an indentation that defines the start point of the Sensitivity Vector, such that a positive response results from flow directed from the indentation through the center of the floating element. Response of the sensor varies with angle Θ between direction of the flow and Sensitivity Vector as cosΘ.

ATTENUATION IN THE FIBER OPTIC SYSTEM

Bends in the fiber optic cable, material on the surface of the optical connector, or misalignment of the connector when attached to the controller can cause the infrared intensity to be reduced. This effect does not change the resonant frequencies of the FBGs. In order to minimize these effects, the following rules should be adhered to when working with the sensor:

- Clean the fiber connectors prior to connection to the controller using an appropriate cleaner (such as CLETOP optical fiber connector cleaner or compatible)
- Avoid tight bends in the cable
- Once installed, secure the cable so that it stays stationary during measurements

GRAVITY

Gravity will act on the cantilever and will bend it if the sensor is positioned at an orientation other than vertical. This will cause a change in the infrared intensity if the axis of sensitivity is not perpendicular to the direction of gravitational force. It will increase the signal if the sensor sensitivity vector and gravitational vector point in the same direction, and will decrease if they point in opposite directions. This effect does shift the resonant frequencies of the FBGs, in the same manner that shear stress acting on the sensor does. This effect is most pronounced for the more sensitive RealShear models (those below 5 kPa range) and can normally be neglected for less sensitive models. To avoid the gravity effect, try to install the sensor vertically.

CALIBRATION COEFFICIENT

During factory calibration, two coefficients are measured that are found in the sensor calibration sheet:

- γ_0 - gage coefficient for zero gravity effect, and
- γ_g - gage coefficient for maximum gravity effect

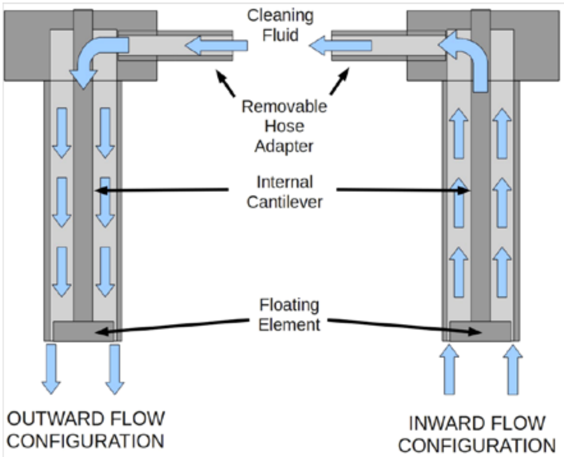
User needs to calculate and enter into the measurement software the effective gage coefficient $\gamma = \gamma_0 + (\gamma_g - \gamma_0)\cos\alpha$, where α is the angle between the sensor sensitivity vector and gravitational vector (in downward direction), before being able to record wall shear stress in units of Pascal (Pa).

CLEANING GUIDELINES

A floating element at the tip of a RealShear™ sensor is attached to a cantilever beam which deflects in response to shear stress applied to the floating element surface. To allow these deflections, a circular gap exists between the edges of the element and the inner wall of the threaded cylindrical housing of the sensor. Nominally this gap is 100 microns wide. This gap allows the material of the flow pass into the sensor. While the sensor is designed to operate normally when it is filled with fluid, it is often the case that after use it is necessary to clear this material out of the sensor. For example if the fluid has solid content that precipitates inside the sensor or in the gap it can affect calibration during subsequent use. Also, material remaining in the sensor can potentially contaminate future batches if not cleared out.

CLEANING CONFIGURATIONS

To facilitate cleaning out of the interior of the sensor, RealShear™ sensors are equipped with a threaded hole through which cleaning fluids can flow, and with a matching hose adapter. Using this flushing port, fluid can be pushed through the sensor and out through the gap at the face (“outward flow” configuration). Alternatively, fluid can be pulled up through the gap into the port (“inward flow” configuration). For the latter it is necessary for there to be cleaning fluid already in the tank or pipe. A combination of these two



methods can also be employed in which flow is reversed once or repeatedly during a cleaning cycle.

A variety of pumping equipment can be used to perform the cleaning:

- *Manual* - The simplest method is to use a squeeze bulb or bottle to manually push or pull cleaning fluid through the sensor. If the frequency of cleaning is low, this can be a simple and convenient solution.
- *Pressurized source* - If a pressurized cleaning fluid source is available, this can be connected to the sensor, typically with an in-line valve. Only outward flow can be used in this case, but in many situations this is adequate.
- *Mechanical Pump* – A pump, either unidirectional or reversible, along with a reservoir of cleaning fluid can also be used for either outward or inward flow.

CLEANING FLUIDS

The choice of cleaning fluid will depend on the nature of the test material. The following is a partial list of solvents for which the sensor was tested to withstand without damage to its internal components:

- Water
- Ethanol
- Isopropyl Alcohol

The maximum temperature of the cleaning fluid should not exceed the specified operating temperature of the particular model of sensor being used (currently 100 °C for standard sensors, and 200 °C for high temperature models). In general, strong acids or bases should be avoided if possible.

CHOOSING THE RIGHT METHOD

Ultimately the best cleaning method to use will depend on a number of factors unique to each process, including the type of material under test, the conditions of testing, and stringency of cleaning requirements. A Standard Operating Procedure (SOP) should be developed by the user for each situation. The following are some rough guidelines:

- **Highly soluble material (glycerol, shampoo etc.) with no solids content**

For these type of fluids, either inward or outward flow can be used. Depending on the flow rate of the cleaning fluid, as little as 30 seconds of cleaning can be sufficient.

- **Material with insoluble solids content (e.g. toothpaste, slurries)**

When the test material contains solids, outward flow can, in some cases, lead to a buildup of material at the gap which can constrict motion of the floating element. In these cases it is recommended to use inward flow to pull material away from the gap, up through the sensor, and out through the flushing port.

Notes:

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