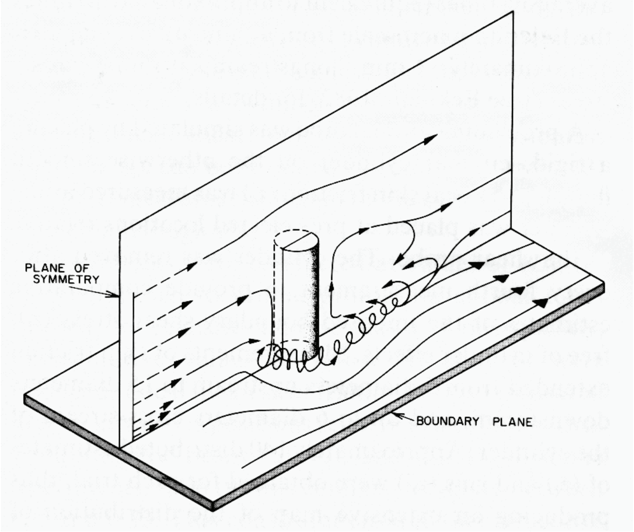
My name is: ____________________

COMMENTS ON THE DEVELOPING BL AND FLOW AROUND A TUBE

The purpose of the assignment was to take a closer look at a growing, flat-plate boundary layer now that you have seen the fully developed smooth-turbulent boundary layer in the test section on the flume bottom a couple of times. The "waving blanket" effects you saw in dye between the viscous sublayer and the turbulent log layer are regions of neutral stability (balanced viscous and inertial forces). A major source of instability is episodic impingement of large eddies from the log layer on the viscous sublayer, and when the viscous sublayer gets thick enough, they can rip it apart. These impinging eddies are what can move the dye out and the corn starch away from this region that lacks a permanent viscous sublayer. The clearing of the region more rapidly than anywhere else hides the fact that strong eddies are not present all the time there. Even in their absence, the viscous sublayer under a fast flow would grow large enough to rip itself apart through shear and vorticity. Be sure to read about growing boundary layers in Vogel, Ch. 8; be sure that you understand his Fig. 8.3. On the plate, the boundary layer first is laminar and very thin. Fast-moving fluid is very close to the no-slip layer, so shear is very high at and near the leading edge. Said another way, velocity at the plate is zero, but is very high close by, so *du* is large and *dz* is very small, so shear (*du*/*dz*) is huge. As the boundary layer grows, it gets thick enough to get fully rough-turbulent (no viscous sublayer). A little further downstream, a laminar sublayer starts to grow within it. The rear end of the plate would provide better protection from high shear, but the leading edge would provide a greater rate of mass exchange (*e.g*., dissolved material supply to a bacterial scum). Convince yourself that the lowest shear is near the rear of the plate, not in its middle. If you fixed a plate in a tidal current, the lowest mean shear would be near the middle of the plate because the current switches directions. Turbulence you visualized with dye near the upstream edge is advected from the turbulent flow upstream. The plate generates no turbulence until you reach the transition from a laminar to turbulent boundary layer. Water properties (viscosity and fluid density) do not change.

Looking at boundary layers, in turn, prepared you for examining the behavior of a short cylinder embedded in a boundary layer. The basic patterns that you saw would occur around any "bluff" body on the seafloor, but the distance that the object projects above the bed is important in the quantitative aspects of the flow effects.



Note: A purist would draw the grey arrow (net force on the tube) through the center of mass of the tube. The major point is that the force is mostly down¬stream but with a slight upward component due to lift from the low pressure over the top.

The figure here (minus the *p* and the gray arrow) comes from Eckman, J.E., and A.R.M. Nowell. 1984. Boundary skin friction and sediment transport about an animal-tube mimic. *Sedimentology* **31:** 851-862. Dashed arrows represent oncoming velocities, whereas solid lines with arrows represent streamlines. The "horseshoe vortex" or "roll vortex" formed (of which half is on the illustrated side of the plane of symmetry) occurs for cylinder Re defined by tube diameter and by velocity at the height (but upstream) of the tube top between about 90 and 900. You can see that as the tube stalls the oncoming flow, higher pressure will be created further up on the upstream face where oncoming velocity is greater. The highest pressure, however, won't be right at the top, because the pressure there can be (and is) relieved by flow going over as well as around the tube. The maximum in pressure will occur about where the p is shown on the diagram. You recognized the pressure maximum on the front face as the point from which dye spread in all directions. That maximum in pressure drives flow both around the tube and upward and toward the bed, where it runs, literally, into a wall. That stall, in turn, produces enough pressure (and another local maximum at the foot of the front face of the tube) to drive flow upstream a short distance before it is turned upward and to the side by the oncoming flow (as the radial flow from the tube spreads), generating the spiral.

I asked about the forces produced by the flow on the object (which must be exactly balanced by the forces that the object exerts on the flow unless the object or flow is accelerating). The strongest forces that contribute to the net force are the fluid pressure pushing on the upstream face and the negative pressure pulling on the downstream face, together with the shear forces pulling downstream along both sides and the top. Pressures on both sides and on the top of the cylinder are low, but because the flow is symmetric in the plane, there is no net, time-averaged, cross-stream force from the low pressures pulling on both sides. A modest lift force results from the reduced pressure over the top, giving a net force vector (gray arrow) at a slight upward incline relative to the horizontal. A smaller, mostly rotational force (torque) from small shears (because of small spatial extent and not very fast flows) on the front and back faces is trying to tip the tube upstream. The exact angle of the net force will be determined by the geometry of the tube and the structure of the upstream boundary layer. Some of you got confused by trying to include all the forces. It is especially confusing in the vertical, where gravity, lift and compressive or tensile stresses on the flume bottom and silicone grease all can get involved, depending on the relative magnitudes of lift and gravity. If we unglued the tube, however, it would be dragged downstream, with lift reducing the retarding friction. If we turn up the flow enough to erode the cylinder, it will tip forward into the flow, lift and head downstream.

Both on the boundary-layer component and on the tube component, some of you were misled by interpreting dye transport away from a spot as mean streamlines. Dye moves by molecular diffusion and in a turbulent flow follows instantaneous, not mean, streamlines. We'll get to diffusion soon.

Remember when you invoke a Reynolds number to indicate which Reynolds number you mean. Dimensional analysis of this particular problem (Eckman and Nowell 1984) indicates that to reproduce the flow pattern quantitatively requires matching of the roughness Reynolds number (Re_*) upstream of the tube, the body or cylinder Reynolds number formed from the tube diameter (or radius) and the mean flow speed at the top of the tube and the nondimensional height of the tube (its height relative to the boundary-layer thickness). So this 3D flow you visualized with dye is not simple, but knowing Bernoulli's law let you figure it out. Now you are doomed to see it everywhere around you, especially in winter.