Industrial Water Division

Scale Formation: Biology, Boundary Dynamics, LSI and Sphagnum Moss

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Introduction

My career include 25 years as a vascular surgeon and 40 years of cellular biology research in the fields of cancer, wound healing, inflammation and hardening of the arteries (atherosclerosis). Over the last 10 years, Vance and I turned a portion of our research energy to the biology of Sphagnum moss and biocides, water, surfaces, organic contamination, scale formation, corrosion and disinfection by products (DBP). There are remarkable similarities between arteries, blood flow, boundary dynamics, laminar and turbulent flow and atherosclerosis; wounds and wound healing; pipes, flowing water and organic contamination, scale and corrosion. Our studies on the effect of the correct species of Sphagnum moss in water systems on organic contamination, scale and corrosion, support the hypothesis that the combination of organic contamination and the boundary fluid dynamics of laminar flow and turbulent flow significantly effects corrosion and scale formation.

Whether it's an artery or vein in your body, a pipe carrying water or another fluid, or a tank holding wastewater, the boundary layer between the fluid and the conduit or wall is an unusual and very dynamic microscopic world. It's an area where the physics of fluid flow intersects with cells, bacteria and matrix molecules to create a microenvironment that affects the conduit it sits on and the fluid that passes by.

We will look at the two systems, arteries and pipes, and see how they are remarkably similar in function, dysfunction and repair.

Boundary dynamics, laminar and turbulent flow

Laminar and turbulent flow

Fluid flows down a straight conduit in a laminar flow pattern. The fluid in the center of the conduit flows faster than that close to the wall as shown in Fig. 1. From a macroscopic viewpoint, there is flow in the entire conduit. From a microscopic viewpoint, at the boundary layer, there is very little flow.

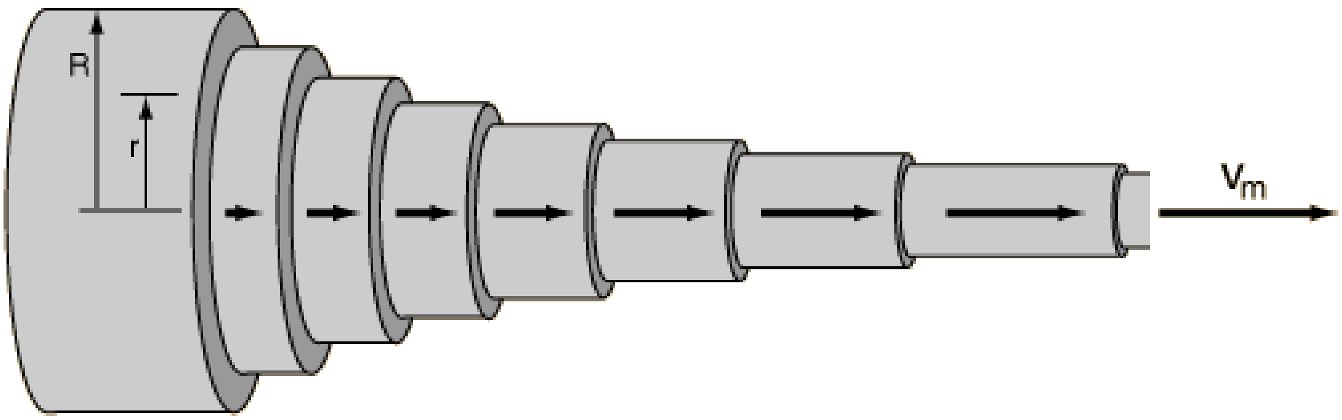
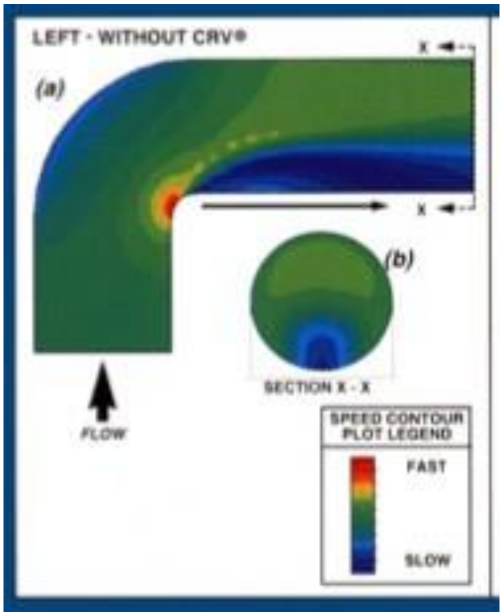


Figure 1. Laminar flow velocity down a conduit. Flows are highest in the center and decrease from the center to the edge. At the boundary layer flow almost stops.

As the fluid flow hits a curve, bifurcation or obstruction, flow in certain areas becomes turbulent while flow in other areas remains laminar. Depending on the severity of the curve or the obstruction, the area of turbulent flow, velocity of flow, and viscosity of the fluid changes in proportion as shown in Fig. 2 a-d.



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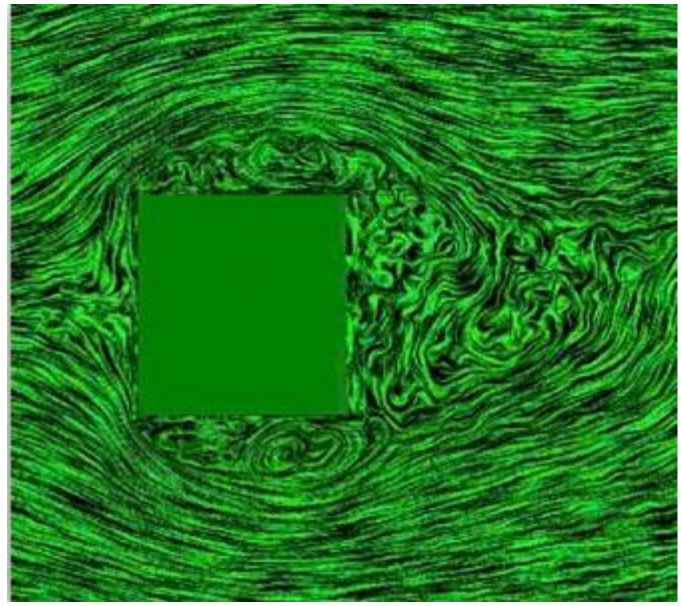

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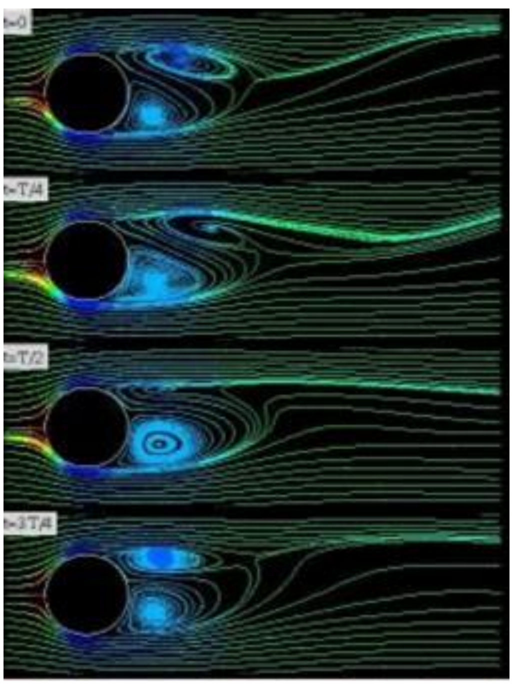

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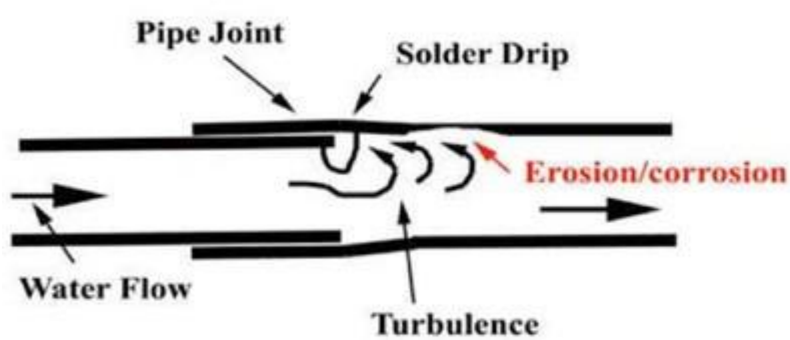


(d)

Figure 2. (a) Flow velocity around a 90^{o} turn. There is a large area of very slow flow just after the turn; (b) Turbulent flow around a square obstruction; (c) Flow profiles around a round obstruction; (d) Flow dynamics around a pipe joint.

Boundary dynamics

The interaction between a fluid and a conduit wall looks simple to the naked eye. It becomes very different when viewed on a microscopic scale. In healthy arteries, the boundary layer consists of plasma and endothelial cells. There is very little oxygen at the surface of the endothelial cells. When arteries become diseased and plaques form, there is turbulent flow, disruption of the endothelial boundary, and inflammation in the media just under the endothelial layer. Man made conduits have similar boundary dynamics with very little flow, increases in viscosity, and the deposition of organic contamination. Joints in the conduit, turns and bifurcations create turbulent flow that allows further accumulation of organic contamination, scaling and corrosion as shown in Fig. 3.

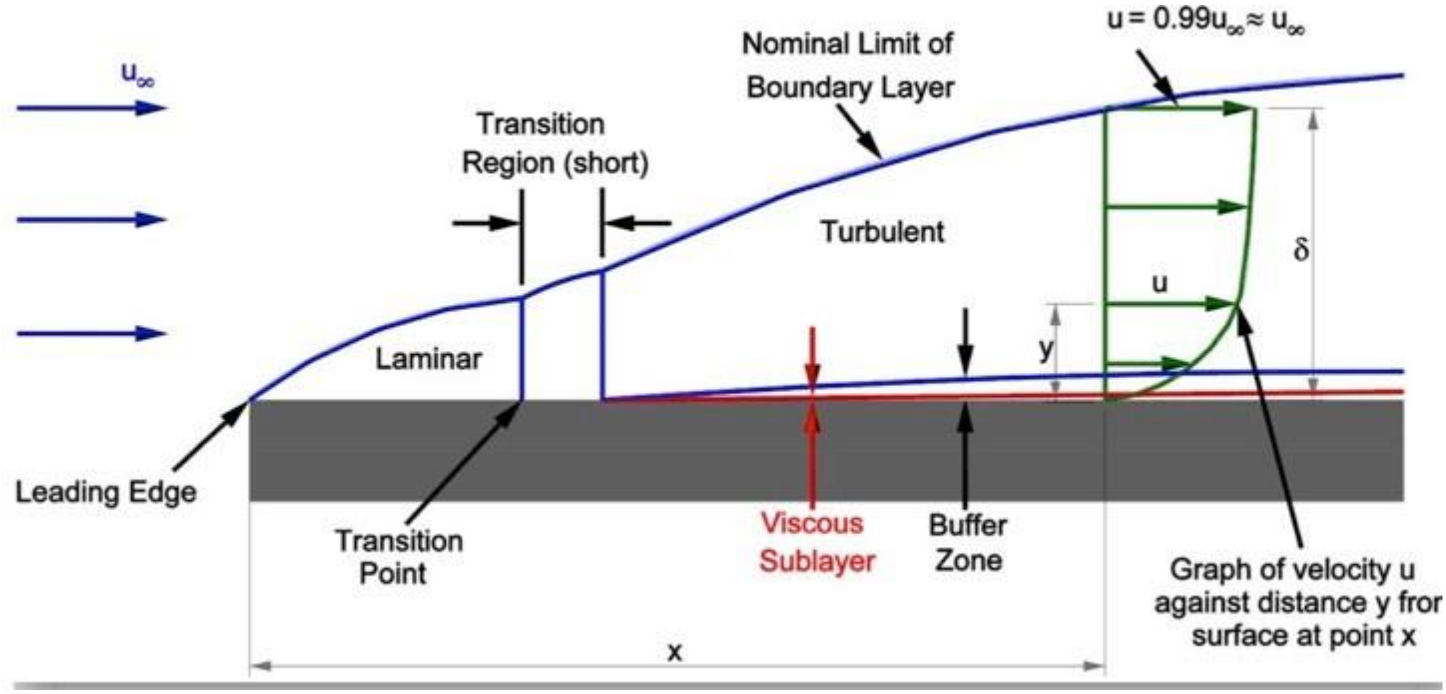
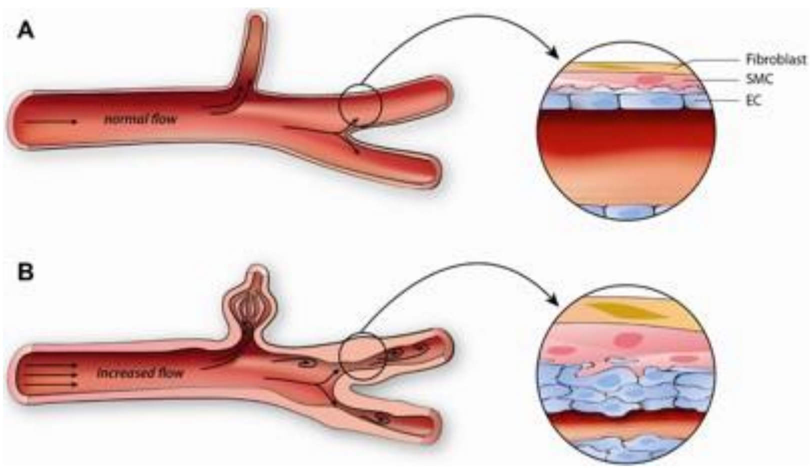


Figure 3. Diagram of boundary layer dynamics.

Cells and tissue – bacteria and organic contamination

Arteries

Arteries are semi-elastic tubes made from different types of collagen and populated with three major types of cells. Endothelial cells line the artery tube, smooth muscle cells give the tube the ability to contract, and adventitial cells give it its strength. The cells in arteries, as in all tissues, get old, die and are replaced as shown in Fig. 4 a-b. Normal arteries have laminar flow except at bifurcations.



(a)

(b)

Figure 4. (a) Normal carotid artery on top with laminar flow. Diseased carotid on bottom; (b) Diseased coronary artery beyond a stenosis at a branch.

Pipes, tubes, surfaces and organic contamination

Structures that carry and store fluids, except in a totally sterile environment, have a cellular component just like arteries. Organic contamination contains many different microorganisms that create a living tissue that covers every surface as shown in Fig. 5.

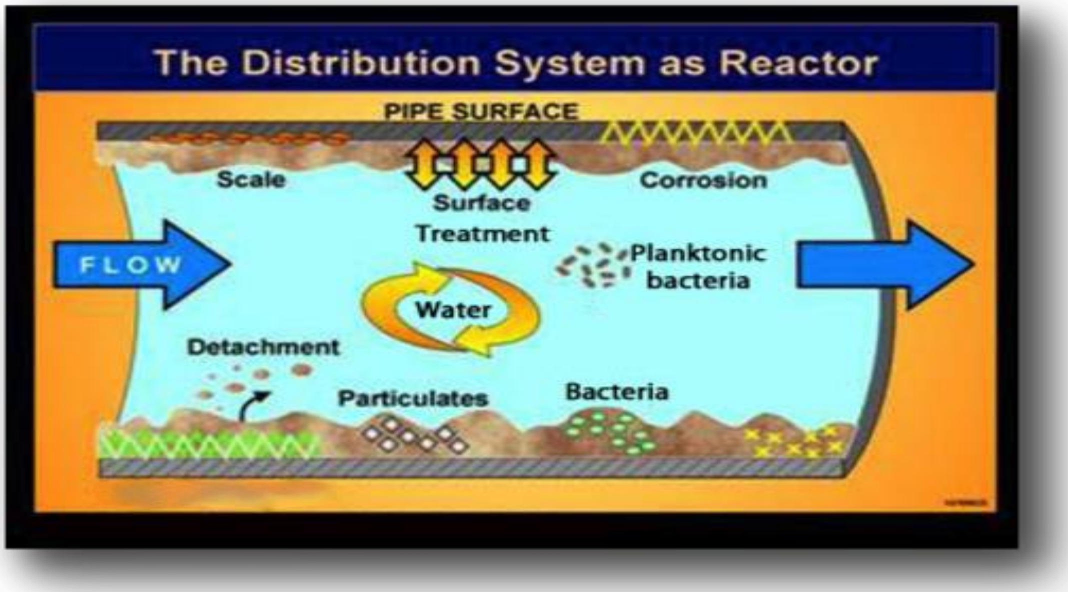


Figure 5. Organic contamination on a conduit.

The microorganisms in the organic contamination live, die, reproduce, and create a structure just like the cells that line an artery as shown in Fig. 6.

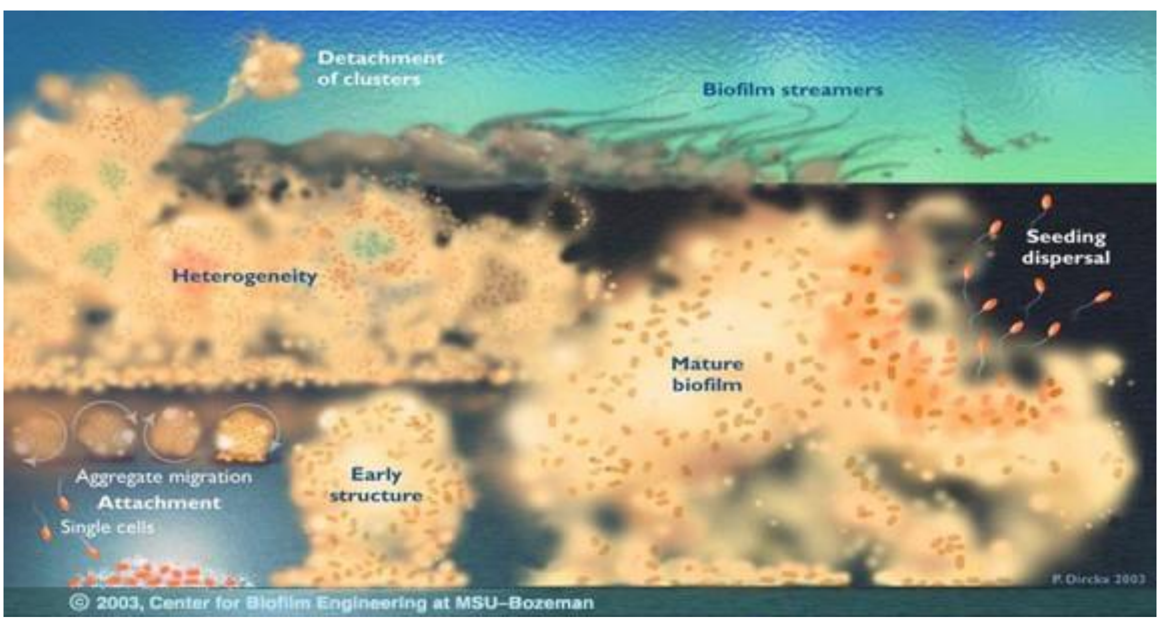


Figure 6. Organic contamination structure on the surface of a conduit.

Oxygen diffusion and consumption

Single cells or bacteria floating in a fluid can extract oxygen and nutrients from the fluid and release metabolites that can be toxic to the cell or bacteria as shown in Fig. 7.

Figure 7. Individual endothelial cells from a wound grown in a collagen gel.

When multiple cells or bacteria stick together and grow on a culture plate they obtain enough nutrients to remain alive and grow as long as the growth media is changed as shown in Fig. 8.

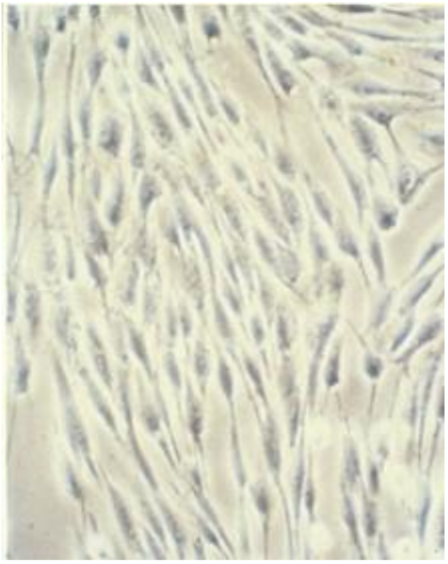


Figure 8. Endothelial cells grown on a culture dish.

When cells grow into a tissue or organic contamination without nutrient circulation from capillaries or flow channels, oxygen and metabolites can only diffuse into the outer layer of cells. The inner core of cells often dies and bacteria switch from aerobic (with oxygen) to anaerobic (without oxygen) metabolism as shown in Fig. 9.

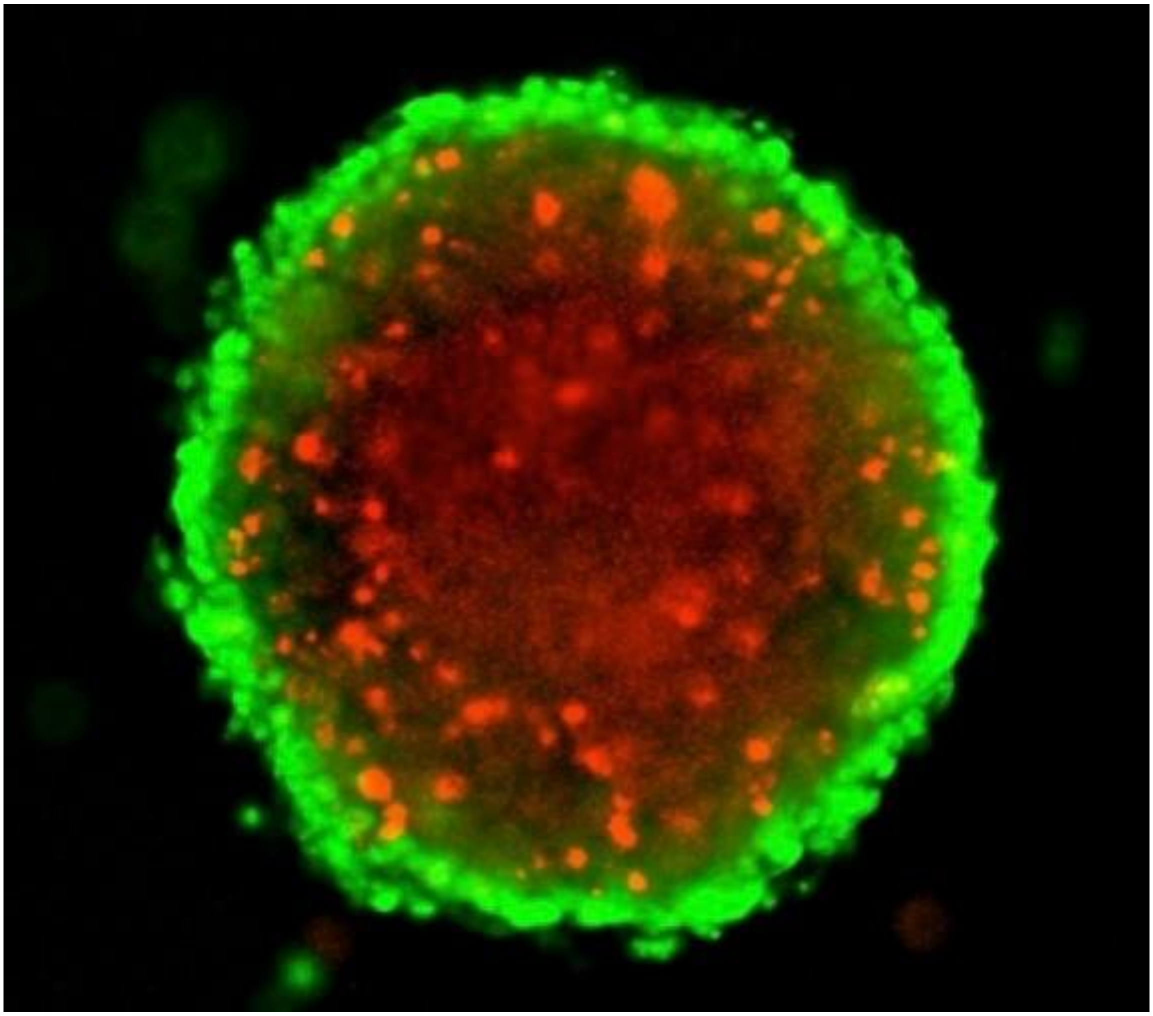


Figure 9. Cellular spheroid. Cells on the outer edge are living, cells in the center are dead.

For cells to make a tissue, blood vessels need to grow to supply oxygen and remove metabolites as shown in Fig. 10.

The channels that form within organic contamination serve the same purpose as shown in Fig 11.

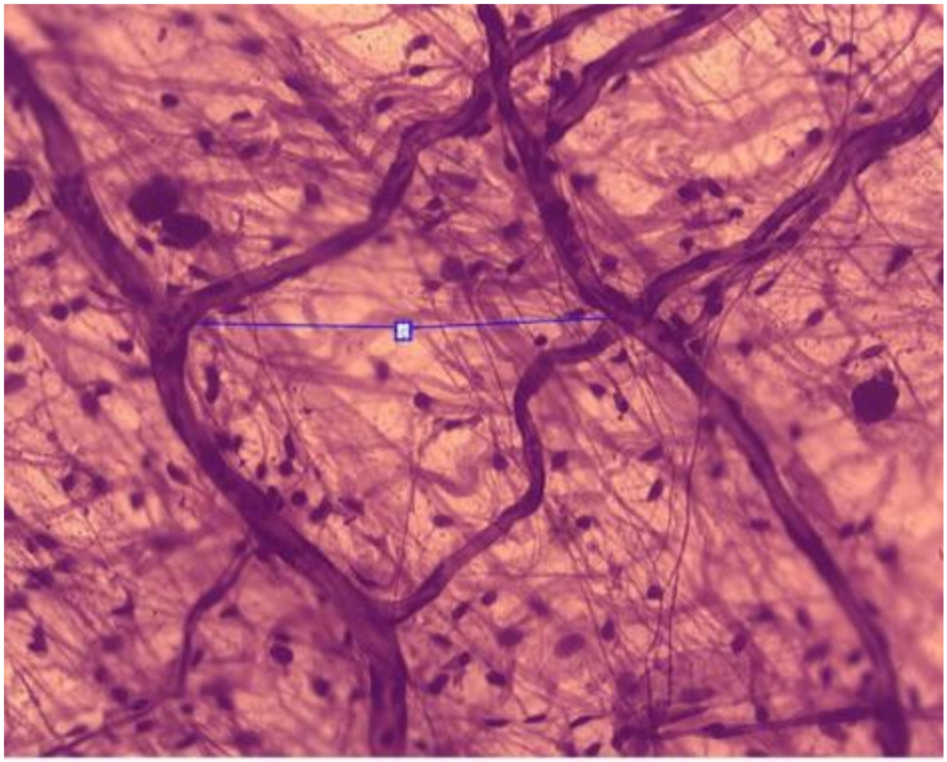


Figure 10. Capillaries in a tissue.

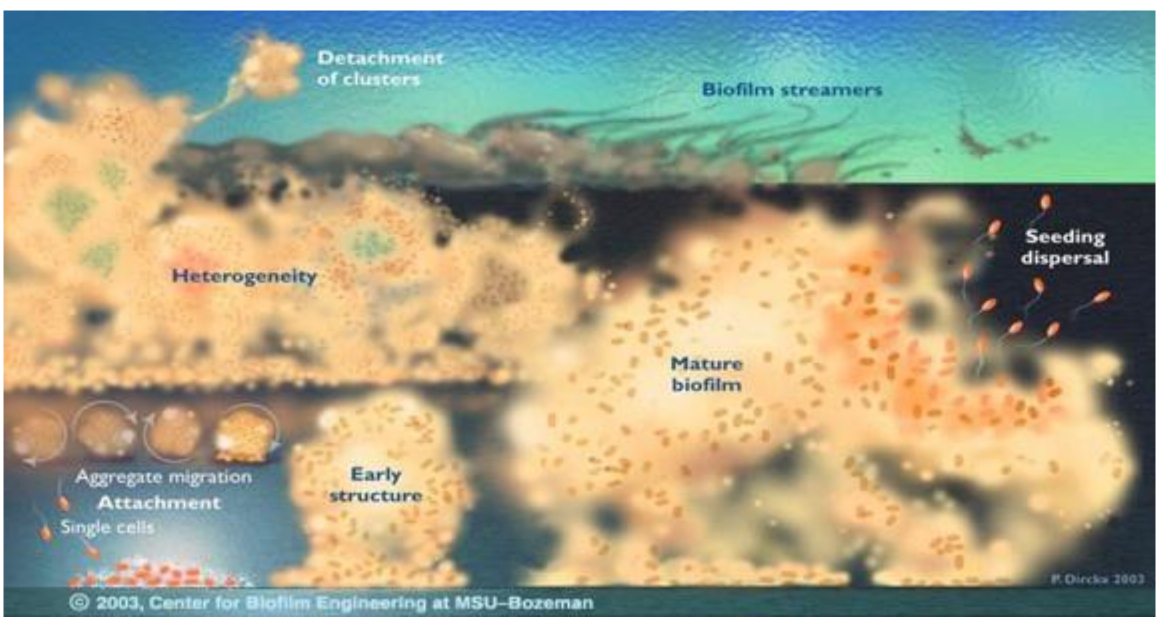
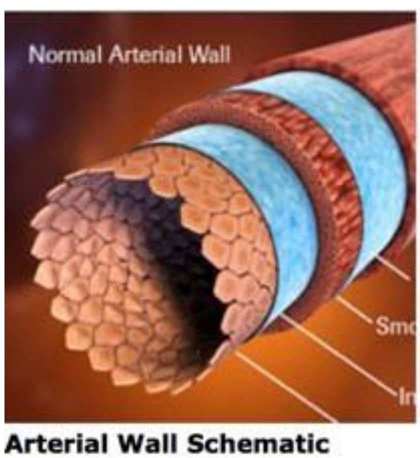


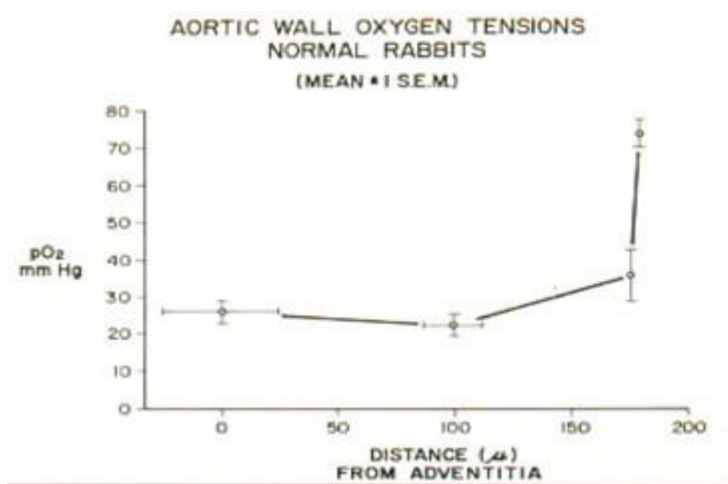
Figure 11. Nutrient flow around organic contamination.

Oxygen doesn't diffuse well across tissue or organic contamination. Depending on the oxygen concentration in the fluid, the oxygen level deeper in the tissues or at the bottom of the organic contamination approaches zero. The distance cells or microorganisms can grow from the nearest blood vessel in the artery wall, or channel in the organic contamination depends on the diffusion of nutrients, metabolism of the cell, and removal of wastes.

Unique microenvironments are created on the surface, in the middle and at the bottom of tissues and organic contamination. For example, we measured the oxygen tension, using a microelectrode across a normal artery as shown in Fig. 12 a. At the time, most physicians thought that the artery wall had uniform oxygen delivery from the lumen of the artery to the outer wall. In fact there is a portion of the artery wall that has very little oxygen. The outer wall receives its blood supply from capillaries on the surface of the artery. They penetrate to the middle of the artery wall. The endothelium that line the artery are in the boundary layer and since there is little flow and high viscosity, they live in a moderately hypoxic environment. Below the endothelial cells, in the media of the artery the oxygen tension goes very low. This is called a vascular watershed as shown in Fig. 12 b. Atherosclerosis occurs in this portion of the artery wall.



(a)



(b)

Figure 12 (a) Structure of a normal artery wall; (b) Micro-oxygen tension across an artery wall.

Organic contamination microenvironments follow a similar profile as shown in Fig. 13.

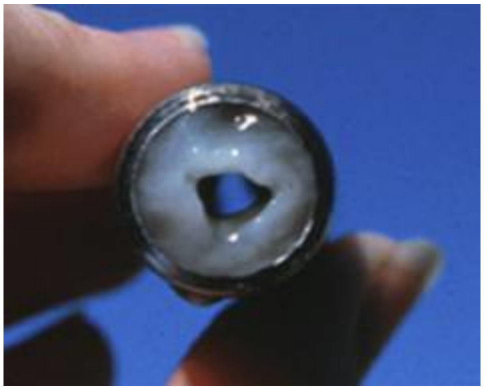


Figure 13. Plastic pipe filled with organic contamination.

Researchers have measured the pH and oxygen concentration across organic contamination from the fluid border to the conduit wall as shown in Fig. 14.

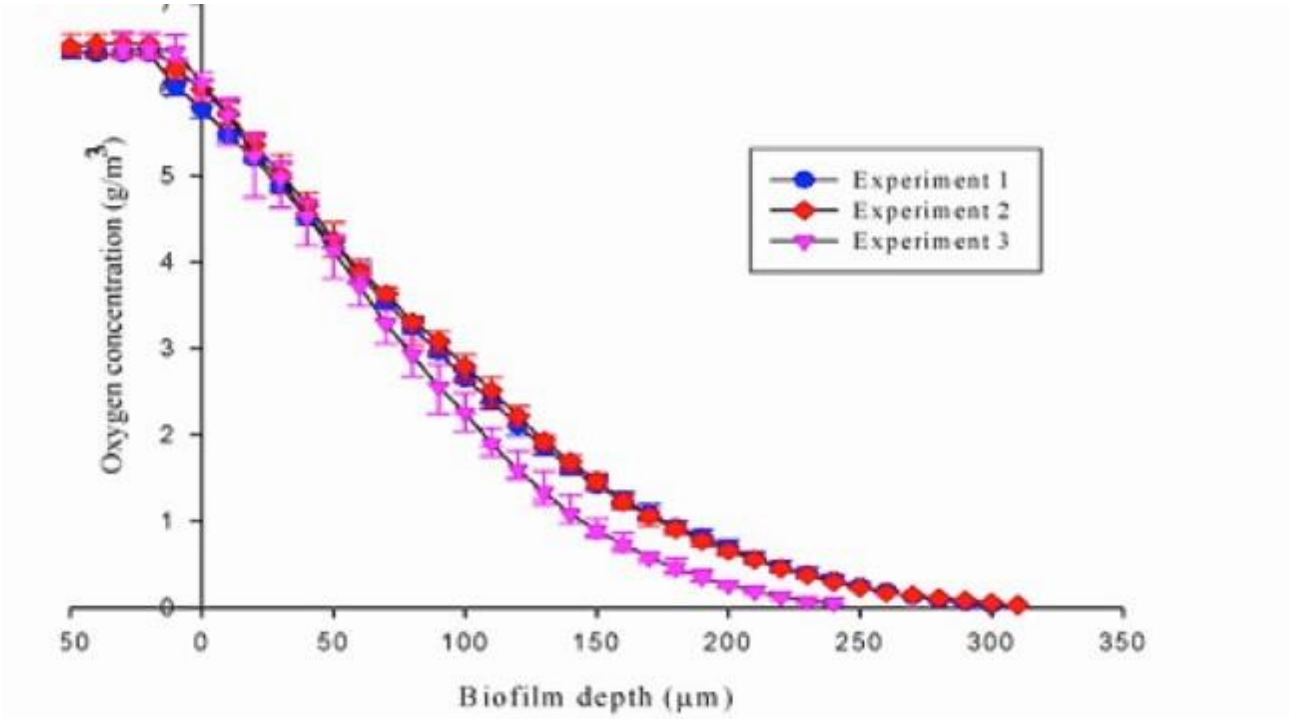


Figure 14. Oxygen consumption across organic contamination.

The microorganisms in organic contamination have high metabolic activity so they consume a lot of oxygen, nutrients and give off waste. Some microorganisms metabolize oxygen and others don't need oxygen. Those that use oxygen create carbon dioxide and those that don't, create lactic acid. When scientists look at organic contamination they find the microorganisms that use oxygen near the surface and close to the channels that carry fluid, and those that don't deep in the organic contamination near the conduit wall. pH measurements near the bottom of the organic contamination can be as low as 3.0, with no oxygen present.

Atherosclerosis, scale and corrosion

Atherosclerosis

When arteries become diseased, plaques form in the wall of the artery. Atherosclerotic plaques are made from cells that behave like a healing wound. In fact, the microenvironment in a healing wound is identical to the microenvironment in the wall of the artery where the plaque forms. There are five major reasons that plaques form: age, hypertension, diabetes, smoking and abnormal lipid profiles. We recreated all these in experiments and measured the oxygen tension across the arteries. All these risk factors decreased the oxygen tension in the media where plaques start. As the plaque grows, it disrupts laminar flow and causes turbulence. This cycle becomes a feedback loop that will eventually destroy the artery and the tissue it feeds. The area can calcify and make a hard plaque much like scale as shown in Fig. 15.

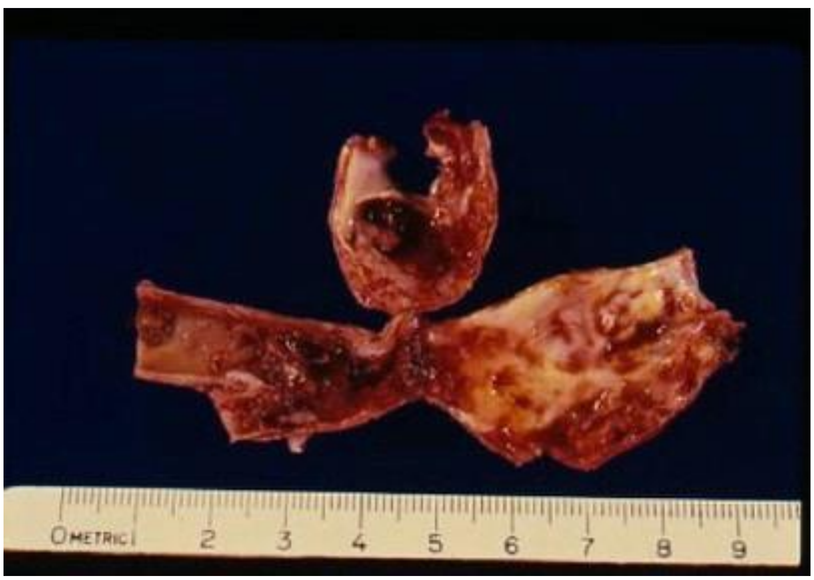
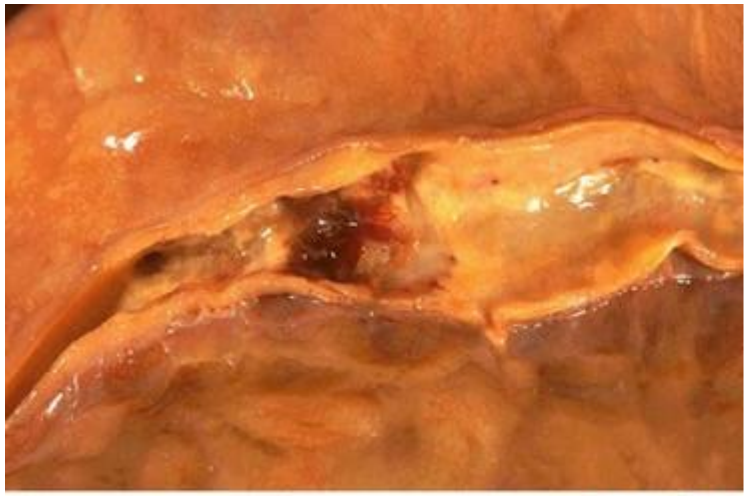


Figure 15. Atherosclerotic plaque removed from an artery.

Cells in the plaque cause inflammation that destroys the artery much like corrosion. Arterial plaque and aneurysm formation, much like scale and corrosion can be seen in the same section of a diseased artery as shown in Fig. 4b.



Coronary atherosclerosis is shown here complicated by hemorrhage into the atheromatous plaque. Such hemorrhage acutely may narrow the arterial lumen.

(b)

Figure 4. (b) Diseased coronary artery beyond a stenosis at a branch.

Organic contamination, Sphagnum moss, scale and corrosion

Here is where we switch careers and start treating pools and spas with Sphagnum moss 14 years ago as shown in Fig. 16.

Figure 16. Sphagnum Moss

To make a very long story short, we noticed that scale gradually was removed from pool surfaces, that backwashing of media filters was needed less and less, that the organic contamination covering surge tanks and pipes gradually disappeared, scale on heat exchangers gradually disappeared, and corrosion of spa heaters stopped as shown in Fig. 17 a-b.

(a)

(b)

Figure 17. (a) Scale accumulation on a heat exchanger from a pool without Sphagum moss; **(b)** Heat exchanger from a pool on Sphagum moss for 4 years.

We knew that the Sphagnum moss absorbed 20X its weight in water, 10X its weight in oil, removed positively charged ions from the water, and slightly acidified the water. In our laboratory and during years of field-testing, we determined that it also removes and inhibits the formation of organic contamination and scale, and inhibits corrosion.

Combining the laboratory data and treating water in pools, spas, cooling towers, boilers, chiller loops and waste water, we came to the following conclusions: that organic contamination plays an integral role in scale formation and microbiological induced corrosion, and that all surfaces in contact with water are covered with organic contamination. The correct species of Sphagnum moss directly inhibits and accelerates removal of organic contamination. Over time, we have shown that the accumulation of organic contamination significantly decreases.

Treatments such as chemicals delivered to the water very rarely come in contact with the surface of the conduit, they come in contact with the organic contamination covering the conduit. The organic contamination absorbs chemicals, ions, and molecules from the water.

Microorganisms in the organic contamination can be killed where contact occurs, but those at the bottom of the organic contamination don't see the chemicals and can go into a completely dormant state and survive until the environment becomes favorable for their growth and repopulation of the system.

Sphagnum moss, organic contamination and scale formation

It is known that certain species of Sphagnum moss absorb positively charged ions into the structure of the leaf. As a result, levels of ionized iron, calcium, manganese and zinc in the water decrease. We tested this in the laboratory by creating scale on acid washed beakers by boiling off tap water. We then added water to one beaker and water with Sphagnum moss to the other. After seven days we measured the concentration of calcium left in the scale and in the water. In the control experiment (without moss) most of the calcium stayed in the scale. In the moss treated water, the scale was remove from the beaker and the calcium increased in the water as shown in Fig. 18.

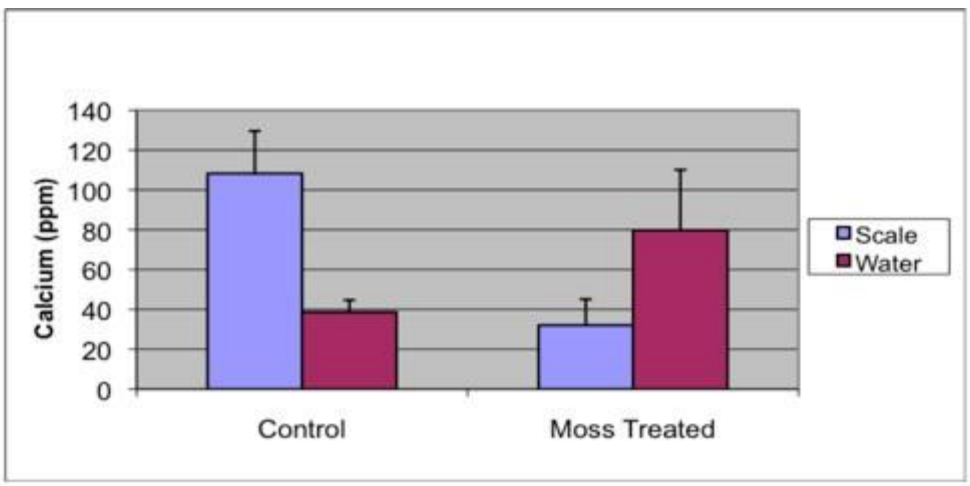
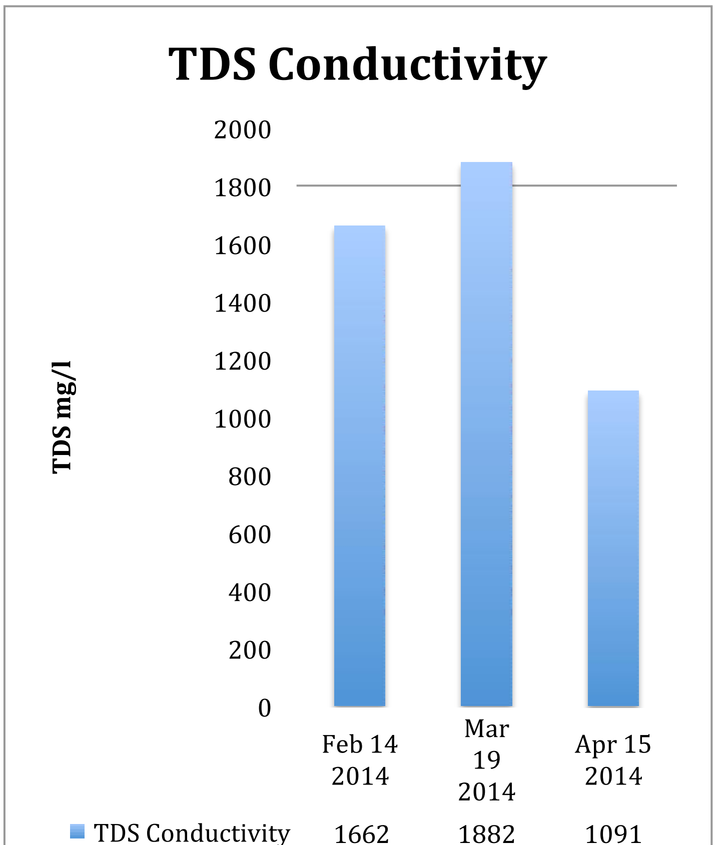


Figure 2. Effect of Sphagnum moss on scale removal. Blue bars represent the amount of scale remaining (as calcium, after solubilisation with HCL in 500mls distilled water) in beakers after 7 days of treatment. Control vs Moss Treated, $p<0.001$. Red bars represent the amount of calcium in the water portion of the system prior to the addition of distilled water and solubilisation of the scale portion. Control vs Moss Treated, $p<0.05$. The pH of the water in both control and moss treated beakers was periodically monitored during the course of the studies and remained within 0.1-0.2 units of each other.

Figure 18. Results of laboratory experiments with scale.

To test this in cooling towers, we obtained baseline pH, alkalinity, calcium and iron ion levels, turbidity, and TDS in three cooling towers with a single basin. Without changing the chemical water treatment, we then added Sphagnum moss to the system. After two months, we found that levels of iron and calcium decreased, TDS elevated and then decreased, and turbidity decreased from 6 to 1 NTU. Visual inspection showed that scale started to come off the media in contact with the water and on the basin floor. Foaming was present before starting the Sphagnum moss, and completely resolved after the first month as shown in Fig. 19 a-d.



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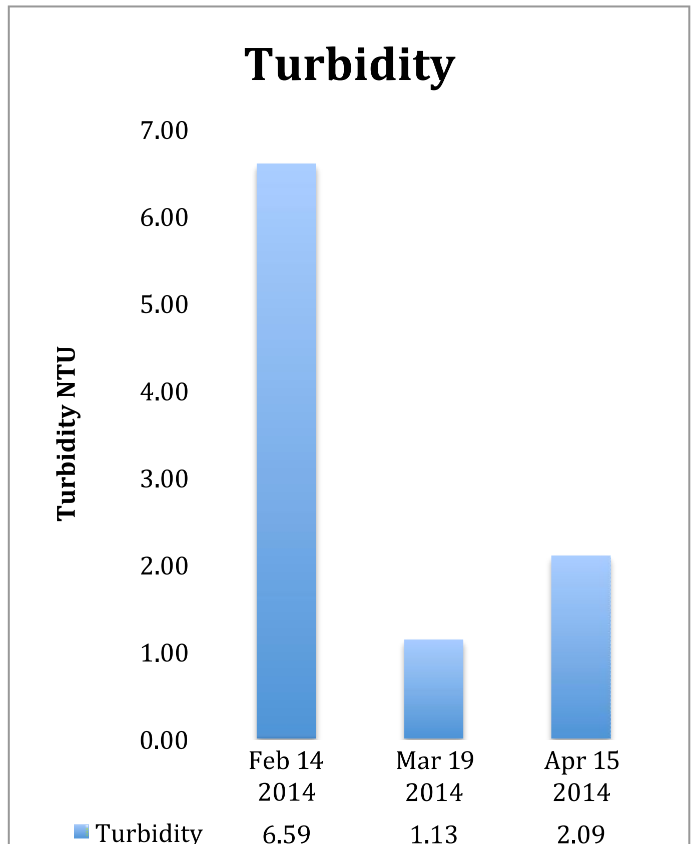

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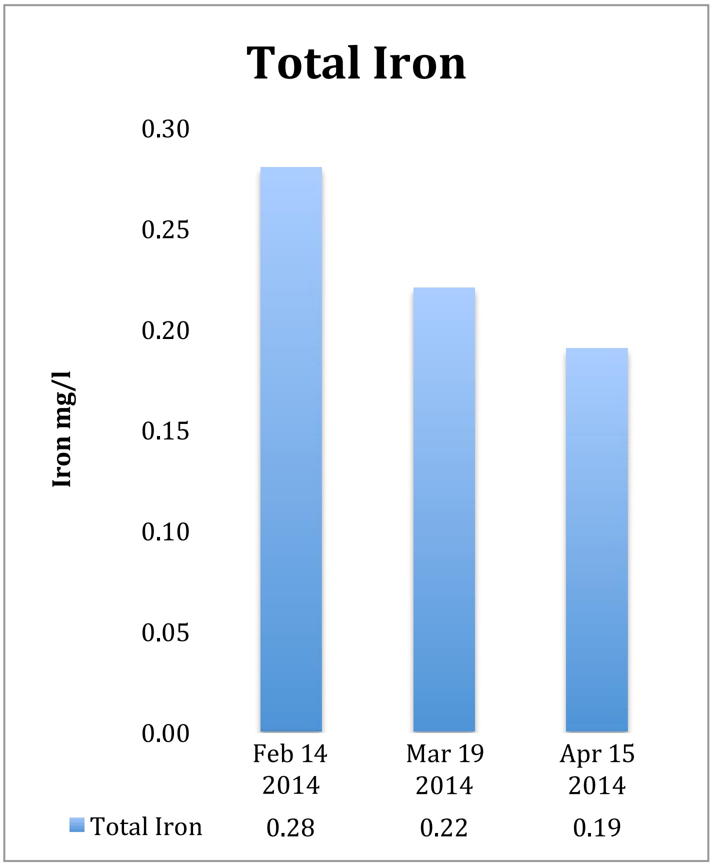

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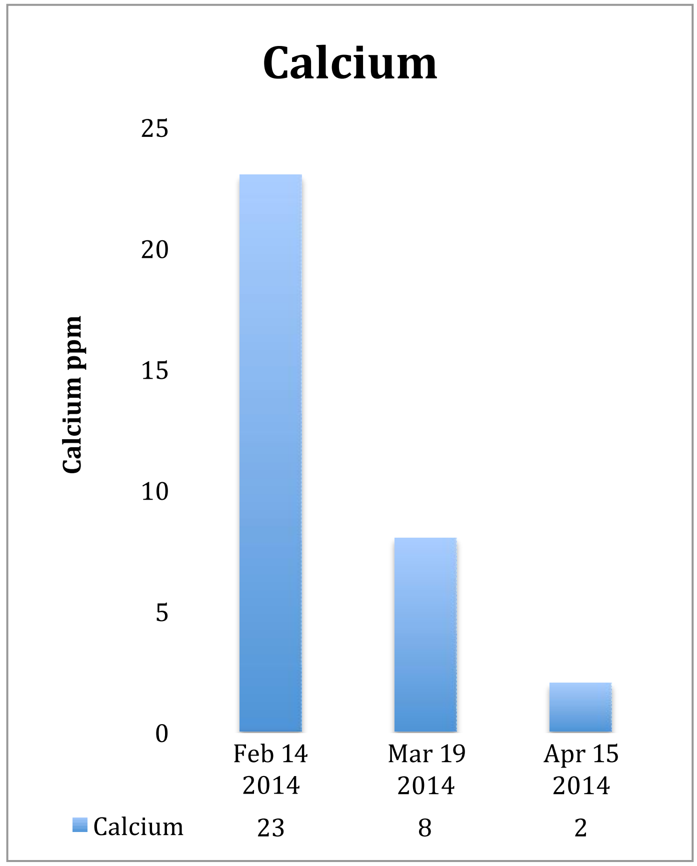
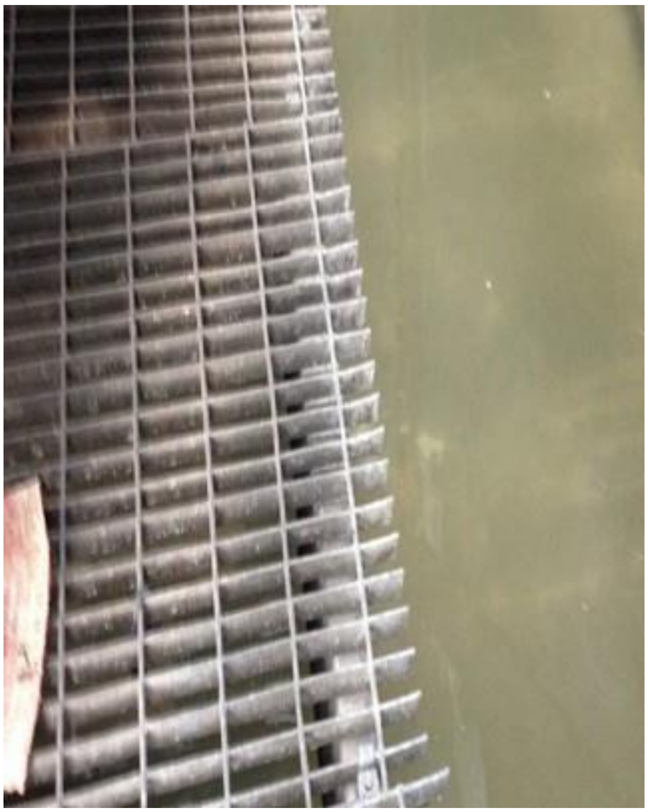


(d)

Figure 19. (a) TDS in a cooling tower before Sphagnum moss Feb and 2 months after addition of Sphagnum Moss; (b) Turbidity in a cooling tower before Sphagnum moss Feb and 2 months after addition of Sphagnum Moss; (c) Iron levels in a cooling tower before Sphagnum moss Feb and 2 months after addition of Sphagnum Moss; (d) Calcium levels in a cooling tower before Sphagnum moss Feb and 2 months after addition of Sphagnum Moss.

Scale formation is a crystallization process that requires a nucleation site. We think that organic contamination is the major nucleation site for scale formation. Observing cooling towers with significant scaling of the basin and media, we measured significant decreases in iron and calcium in the water after two months of treatment, and visible removal of scale from the surfaces with an increase of “sand” particles on the tower floor.

After 6 months of treatment the scale was gone from the media where the water flowed but remained at the top where aerosolized water droplets evaporated. We think that the Sphagnum moss is removing the organic contamination that sticks the scale to the surface as shown in Fig. 20 a-c, and that the solubility product in the fluid is decreasing due to the absorption of positively charged ions.



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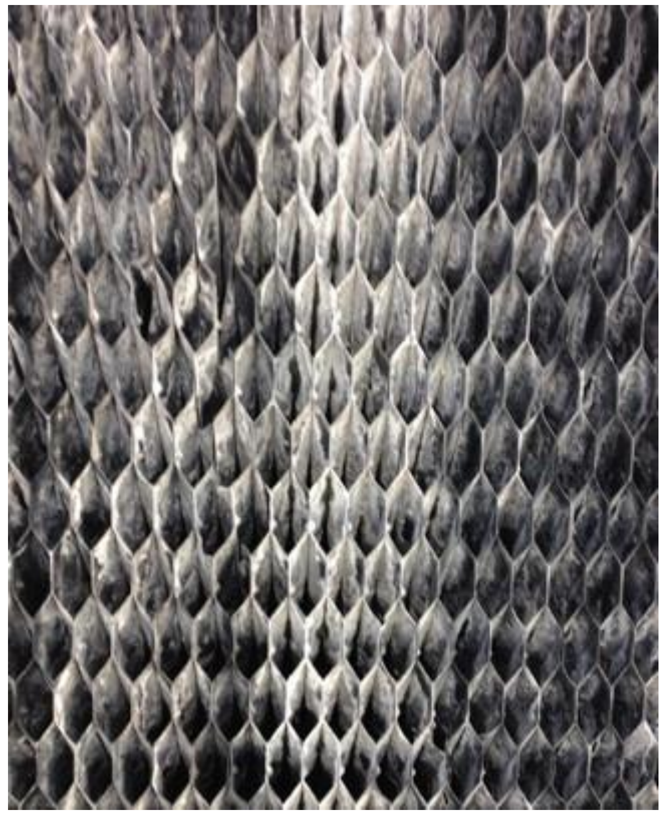

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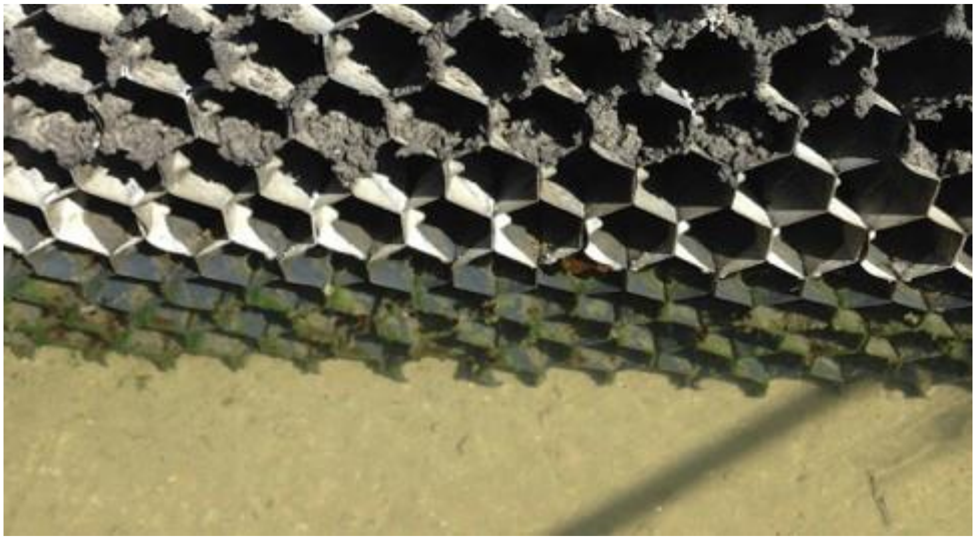


(c)

Figure 20. (a) Scale and water in a cooling tower one month before starting Sphagnum Moss. Water is cloudy, Turbidity is 6 NTU; (b) Scaling of cooling media of a cooling tower one month before starting Sphagnum moss; (c) Cooling tower and media 2 months after starting Sphagnum moss. Water is clear with low turbidity and the scale is coming off the media in contact with the water.

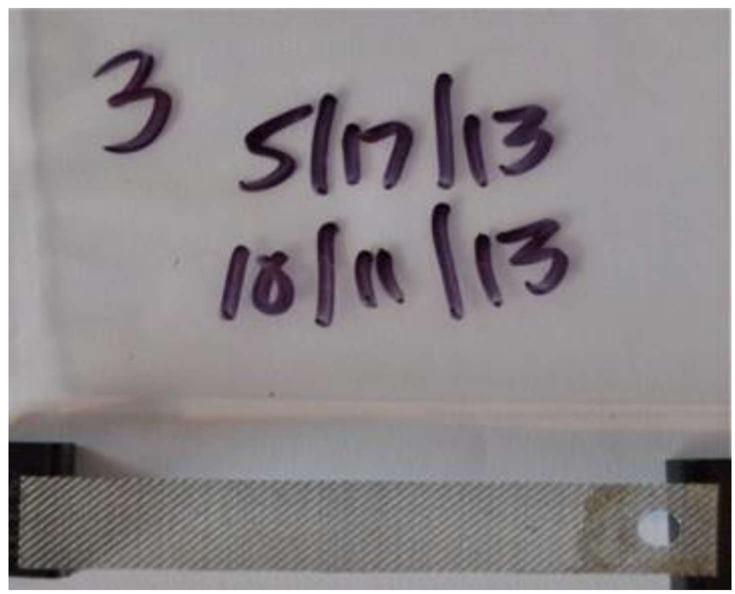
Sphagnum moss, organic contamination and microbiological induced corrosion (MIC)

The first time I appreciated the destructive capacity of corrosion was when the maintenance supervisor at a local recreational facility that started using Sphagnum moss in their pools and spas showed me a destroyed heat exchanger from his spa. I was impressed with the extent of the destruction and the surface pitting and channels that ate the metal. To me it resembled an infection in a wound or bone. He later reported that after a year treating his pool and spa water with moss, that his pump seals stopped leaking.

Since we knew that the moss inhibited organic contamination in the lab, we hypothesized that the low pH, current, and redox at the bottom of the organic contamination, along with the enzymes produced by bacteria to ionize metal for their metabolism, was the cause of MIC.

We tested this hypothesis in cooling towers that were treated with biocide, dispersant and corrosion inhibitors. We treated one tower with Sphagnum moss and used the second tower as a control. We measured organic contamination accumulation with special coupons, and corrosion for copper with coupons and linear polarization probes. The test period was five months during the summer cooling season in Minnesota. We found that there was no organic contamination accumulation on the coupons in the moss treated tower and a 90% decrease in corrosivity for copper as shown in Fig. 21 a-d.

(a)



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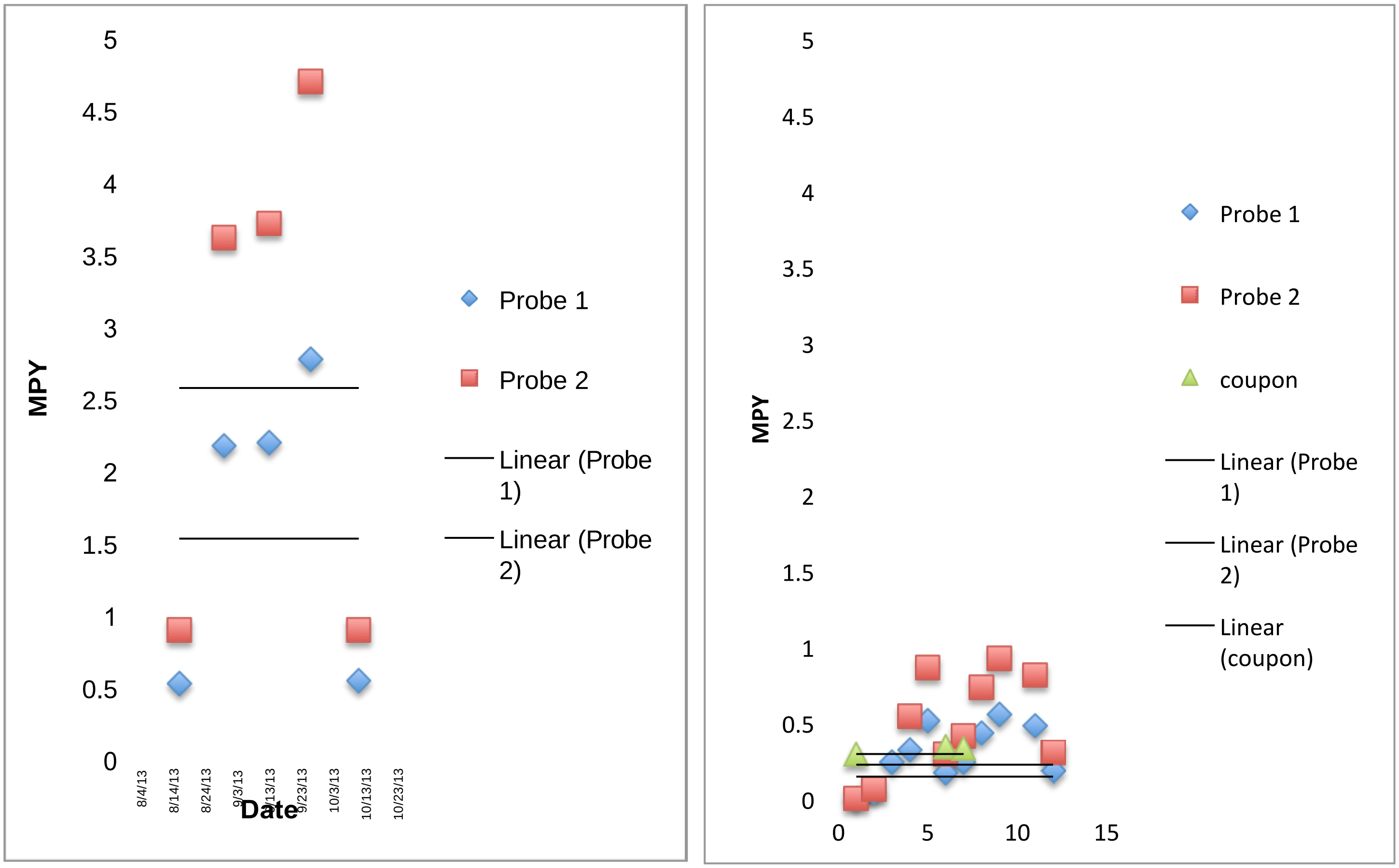

(c) **(d)**

Figure 21. (a) Organic contamination on a coupon from a cooling tower treated with biocide and dispersant and without Sphagnum moss; (b) Organic contamination coupon on a cooling tower with biocide, dispersant and Sphagnum moss. No organic contamination accumulated over 5 months; (c) Corrosion for copper in a cooling tower with biocide, dispersant and corrosion inhibitor without Sphagnum moss. Average is 2.5 MPY; (d) Corrosivity on a cooling tower with biocide, dispersant and corrosion inhibitor with Sphagnum moss. Average corrosivity for copper is .25 mpy, a 90% decrease compared to the tower without Sphagnum moss.

Conclusions

1. Laminar flow, turbulence and boundary dynamics contribute to plaque in arteries and organic contamination in conduits.

2. The microenvironment and organic contamination create conditions that result in atherosclerosis in arteries and scale and corrosion in conduits.

3. Sphagnum moss water treatment inhibits accumulation and promotes removal of organic contamination.

4. Laboratory studies demonstrate that Sphagnum moss inhibits scale formation.

5. Cooling tower studies demonstrate that Sphagnum moss improves water clarity, reduces iron, calcium and TDS levels and reduces corrosivity and scale.

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