

## The Rouging Effect in Pharmaceutical Water Systems: Causes and Strategies for Prevention

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#### INTRODUCTION

Rouging, which describes the presence of a surface layer of iron oxide, is a phenomenon that often affects pharmaceutical and hospital water systems constructed from stainless components (1). Rouging presents a particular risk to high-purity water systems, such as Water-for-Injections or Purified Water (produced by either distillation or reverse osmosis.) A similar effect can occur with clean steam systems. Experience suggests that rouging is most common with Water-for-Injection systems operating at 60°C and above. Such water is required to have a low conductivity (less than 1.25 µS/cm) in order to reduce the level of ions. Whilst this means that the corrosion properties of this grade of water are far lower than with any other type of water, rouging still occurs.

Rouge is the chemical development of ferric oxide and “rouging” is used to describe the build-up of red colored deposits on the inner surface of pipework or within holding tanks. Although rouge itself is the result of iron oxide, sites of “rouging” may also contain chromium, nickel, and molybdenum in oxidized forms. These oxides vary in composition, degree of oxidation, color, texture, and adherence.

While an assessment of rouging is not currently a parameter for assessment within any of the major pharmacopeias, it remains an important issue for pharmaceutical organizations. The risk that arises from rouging is that product contamination, through the presence of particulates, could occur. To add to this, there is an impact on water quality for rouge may be the source of contaminants that lead to the chemical deterioration of water quality. Furthermore, buildups of rouge byproducts can lead to operational problems including blockages in filters. If more severe localized corrosion (pitting) occurs, this can lead to more serious operational issues. In addition, pitted and damaged surfaces can promote bacterial attachment and such conditions could promote biofilm formation (2).

Rouging can, arguably, never be avoided. Rouge formation is a steady chemical process that is underway in all metallic piping systems in contact with water and all stainless steels corrode over time as minor ingredients are lost and electrochemical potentials rise. What varies is the pace of the reaction. The process is exacerbated by high temperature and particular metal compositions.

This paper discusses the chemical nature of rouging and discusses some of the steps that can be followed to remove rouging and the key points with system design that can prevent (or rather slow down) rouging.

#### ROUGING

Rouging can occur with high-purity hot water systems where the pipework or holding tank is constructed from stainless steel. This effect can extend to distillation units, storage tanks, distribution systems (piping, valves, pump housings, fittings, and so on) and process vessels. Rouging appears as a thin red or, sometime black, powdery deposit. On occasions the powdery composition appears slime-like. This should not be confused with a biofilm.

With a biofilm, this describes the phenomenon when irreversible bacterial adhesion occurs through interactions between extracellular microbial structures, and secretions and a surface. Bacterial cells secrete a polysaccharide known as glycocalyx (hydrated polymeric slimy matrices), which subsequently enables the bacterium to encapsulate itself on the surface and subsequent interactions lead to biofilm formation, a distinct microbial community (3).

Rouging is physicochemical rather than biological. Rouging is comprised of iron oxides and hydroxide corrosion products in differing oxidation states (4). The appearance of shades of red through to black relates to different combinations and states of ferric ion ( $\text{Fe}^{3+}$ ) oxide and hydroxide corrosion products.

Chemically the process of rouging involves the transformation of  $\text{Fe}^{2+}$  ions. These ions are readily soluble; however, when they become oxidized and transform into  $\text{Fe}^{3+}$  ions, these ions are insoluble and lead to the formation of oxides ( $\text{Fe}_2\text{O}_3$  and  $\text{Fe}_3\text{O}_4$ ) and hydroxides like ferric oxide ( $\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$ ) (what is sometimes called hematite.). This is an equivalent reaction to the rusting process of carbon steels (rust is iron oxide formed by the redox reaction of iron and oxygen in the presence of water or air moisture (5). In terms of physical effects, surface roughness and iron oxide layer thickness increase with increasing rouge severity.

Unlike full-blown rust, rouging can be wiped away with a cloth; however, rouging will reform if action is not taken in relation to the specific region of the pipework that is prone to rouging. Rouging layers have a thickness of 0.1 to 10  $\mu\text{m}$  whereby only the thinner films are to be considered rouge contamination. Larger and more stable films are classified as rust.

The mechanism that leads to rouging is not fully understood. Most research suggests that it is linked to destabilization of the passive layer on stainless steel (6). Before looking at de-passivation, it is necessary to consider the preparation of stainless steel.

Stainless steel is rendered "stainless" because the alloy forms a thin, protective, transparent chromium oxide film that functions to protect the metal against destructive corrosive species in aqueous solutions. The formation of the protective layer is termed passivation, and this protects the metal from staining and corrosion. Here, passivation is defined as the formation of a film of chromium oxide. This film blocks surface corrosion by preventing oxygen diffusion to the steel surface. Furthermore, it halts any corrosion from spreading into the internal structure of the metal. For passivation to occur the chromium must be at a sufficiently high proportion enough and oxygen must be present.

To be classed as "stainless" steel must be composed of a minimum of 10.5% chromium content by mass. Stainless steel is not fully stain-proof in low-oxygen, high-salinity, or poor air-circulation environments.

With the temporary loss of passivation, ions in the water passing through interact with the ions in the outer coating of pipework or the holding tank. These stainless steel constructs are commonly coated with chromium. The ionic pull of the water can sometimes be strong enough to strip the protective chromium oxide off the steel surface. This interaction will occasionally cause breaches within the coating, leading to corrosion of the underlying stainless steel before the passive layer seals. The major elements composing stainless steel are iron, chromium, and nickel. It is the iron that reacts with the water, and it is this subsequent chemical reaction that triggers rouging. Nonetheless, the de-passivation / re-passivation process needs to happen many times in order for visible rouging to be observed.

An alternative reason for rouging has been put forward by Frantzen *et al* (7). In an experiment, a research group exposed large areas of partly submerged stainless steel coupons in boiling water for 6 weeks. Through this process rouging was reproduced in the laboratory. The research concluded that the degree of rouging was affected by the applied gas atmosphere and the coupon surface quality (finish). Significantly, none of the exposed coupons showed visible signs of localized corrosion, which suggests that rouging is a result of passive film dissolution and re-precipitation of iron rich deposits.

Rouging has been reported to be associated with:

- Water oxygen content and pH. The relative water solubilities of ferrous ( $\text{Fe}^{2+}$ ) and Ferric ( $\text{Fe}^{3+}$ ) ions are influenced by pH and this also accounts for the range of rouge colors formed (in conditions where the pH is  $<7$ .)
- The presence of any iron contamination in systems.

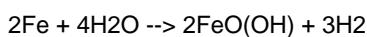
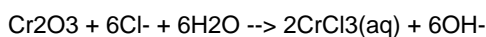
- Type of surface finish (degree of surface roughness).
- Non-metallic inclusion levels in the steel.
- Welding defects, debris, heat tint or improperly cleaned areas.
- Hot process water (>60°C). The reason that hot water has a greater effect than cold water is because local de-passivation is promoted by the considerably reduced amount of dissolved oxygen in hot waters as well as by a strongly increased capacity for ion dissolution due to the purity of pharmaceutical grade water. Moreover, elevated temperatures cause iron atoms to increasingly diffuse to the surface and to react with the oxygen present at the surface to form oxides and hydroxides.

Each of these is consistent with the interaction between water and exposed stainless steel.

Rouging occurs to different degrees. According Gatlin, rouging can be grouped into three categories (8):

- Class I Rouge is a deposited corrosion product. This consists of iron oxides and hydroxides originating elsewhere in the water system and deposited downstream. Sources include carbon steel in the system including tie rods, bolts, nuts, wrenches, staples etc. The underlying stainless-steel surface beneath such deposits usually remains unaltered. This rouge deposit can be wiped away, provided that this part of the system can be accessed.
- Class II Rouge is an adherent corrosion product originating *in-situ* on un-passivated or improperly passivated stainless-steel surfaces. Due to this reaction, the passive-protective film on the stainless-steel surface is altered.

Class II Rouge forms in a two stage reaction, the first is the dissolution of the chromium oxide passive layer, the second the oxidation of the iron in the substrate:



This reaction is self-perpetuating by the chloride reacting with the chromium to form hypochlorous acid as a byproduct, and the hypochlorous acid oxidizing the iron and forming more chloride.

- Class III Rouge is a blue or black. This is the result of an iron oxide corrosion product called magnetite. This product forms on surfaces in high-temperature steam systems. On electropolished surfaces, corrosion deposit may be glossy black, stable, and adherent. In contrast, on un-passivated mechanically polished surfaces, the corrosion deposit may be powdery black, and it may slough off.

## TREATING ROUGING

Rouging is difficult to detect in the initial stages. Visual inspection with the use of a handheld flashlight can be used for the evaluation of such rouging, although it is qualitative expression. It is not straightforward to examine the degree of rouging in these early stages discoloration quantitatively. Instruments can be used, either for interval sampling or on-line, to detect rouging at different stages. Some sensors function by measuring the reflectance or luster of the stainless steel surface using a light source (9).

Once rouging has been discovered then de-rouging can be undertaken. This requires production downtime. Mechanical cleaning processes, designed to remove visible particles adhering loosely to the surface, are usually limited to easily accessible areas. Beyond manual cleaning, the two most commonly used media for de-rouging are inorganic acids and chelating agents.

With acids, nitric acid is the most commonly used. Other acids used for re-passivation treatments include phosphoric, citric, or other oxidizing acid solutions. The use of these acids can, if correctly used, restore the corrosion resistance of stainless steel systems by removing or fully re-oxidizing the affected layer of stainless steel. Care must be taken when using acids not to damage the surface. Organic acids tend to be avoided because such acids do not possess the same solubilizing capacity as highly concentrated mineral acids.

Chelants, chemical compounds composed of a metal ion and a chelating agent, are known for their ability to remove particular cations such as iron. An example is ethylenediaminetetraacetic acid (EDTA). The main concern with chelates is that the

reaction that removes oxidized metal is not self-terminating. The chelant will continue to dissolve the surface metal even after the corroded oxide coating is removed. This means that it needs to be removed after a certain period of time has elapsed.

An alternative to acids and chelates are neutral cleaning solutions containing dithionite and/or disulfite. All chemicals used for de-rouging present an environmental concern.

Once rouging has been treated, there are different steps that can be taken to lower the risk of rouging occurring. These include:

- Improving corrosion resistance.
- Using electropolishing to passivate and smooth of surface finishes.

Although such measures can be implemented, the risk of rouging occurring over the longer-term remains and a system inspection at periodic intervals should be undertaken.

## **LIMITING THE RATE OF ROUGING**

Water systems can be designed to lower the possibility of rouging occurring. Such measures include:

### **a) Type of stainless steel used**

Selecting an appropriate grade of stainless steel is important. Low grades of stainless steel are not suitable for pharmaceutical systems due to their tendency to corrode (10). The minimum specification for a hot, high purity water system is SAE (Society of Automotive Engineers) 304 type stainless steel. A higher specification 316 type confers greater protection (and very rarely the higher specified high-Ni-Cr-Mo alloy C-276 variant.) This is because the additional nickel confers greater passive layer stability. Furthermore, the additional molybdenum improves micro-pitting resistance as well as strengthening the material from chlorine attack. Both of these factors have been associated with rouging protection.

With the use of stainless steel, carbon steel must never be connected to stainless steel. This can lead to rust formation. Stainless steel differs from carbon steel by the amount of chromium present. This difference is apparent since unprotected carbon steel rusts readily when exposed to air and moisture.

### **b) Surface finish**

Smooth surface finishes are not only necessary to prevent the formation of a microbial biofilm; smooth surfaces also assist with avoidance of rouging. This is because the amount of rouge that appears in a system may be affected by the roughness of the metal surfaces (11). Smoothness is created through electropolishing, which additionally improves the stability of the passive layer. Electropolishing removes these microscopic crevices and produces a passive layer with a higher chromium: iron ratio (12).

Surface finishing can be verified by examining sections of stainless steel through different methods, including X-Ray Photoelectron Spectroscopy (XPS), Energy Dispersive Spectroscopy (EDS) and Scanning Electron Microscopy (SEM). Here, SEM allows for the detailed visual examination of the surface; EDS enables spot analyses of surface anomalies to be performed; and XPS permits layer-by-layer analyses of the rouge deposits and identification of the molecular species.

### **c) Surface imperfections**

Surface imperfections from non-metallic inclusions can also be sites where the passive layer can become disrupted and become corrosion initiation sites. Given that non-metallic inclusions, such as sulphides and oxides are an inherent result of alloy production, then a review should be conducted to ensure that the stainless steel used for the water system is of the appropriate quality.

Other manufacturing issues of importance include localized corrosion in vulnerable areas of the passive film; poor welding including heat tint; various surface contaminants, such as mild steel particles; and grinding dust and residues from emery wheels.

#### d) Iron contamination

Iron contamination or carry-over of a corrosion product from other non-stainless steel parts of a system will lead to rouge formation. This is due to iron corroding (as rust) relatively easily in water. This corrosion provides a source of ions ( $\text{Fe}^{3+}$ ) that can, as discussed above, form the rouge products.

#### e) System operation

Rouge-formation rate can occur due to system operation, relating to water flow and pressure, points of use, oscillations in water temperatures, and supply or make-up issues. Excessive velocities and pump inefficiencies in hot water systems results in pump cavitation and this can also lead to rouging.

#### f) The avoidance of stainless steel

In place of stainless steel, thermoplastic plastics can be used, although these will not suit every applicable. Plastics are not subject to rouging and do not require passivation. Suitable materials include Polyvinylidene Fluoride (PVDF) and Polypropylene (PP). Plastics require careful evaluation in relation to the operating temperature and pressure.

#### g) Operating atmosphere.

Rouge can be prevented by using a controlled atmosphere which does not contain carbon dioxide. For example, this could be controlled atmosphere is a mixture of about 80% nitrogen and about 20% oxygen. Such atmospheres can be created for small-scale and specific applications.

#### h) Water temperature

Reduced distribution loop temperatures can theoretically reduce corrosion and rouging. Care must be taken, however, that temperature reductions do not lead to a loss of microbial control.

## CONCLUSION

This paper has discussed the issue of rouging and the impact upon pharmaceutical and healthcare operations. Rouging is an important subject because it can affect product quality and it can lead to system inefficiencies. For these reasons, the managers of water systems and quality personnel must measure and assess rouge formation at periodic intervals and take action where rouging develops through de-rouging or re-passivation exercises. Commercial devices are available to assess the rouging rate in microns/month and rouge accumulation in microns (0.001 - 10  $\mu\text{m}$ ).

The frequency of such reviews varies. As Collentro points out, one particular WFI storage and distribution system maintaining a water temperature of 80-85°C may show extensive rouging and will, therefore, need de-rouging and re-passivation annually; whereas in contrast, a similar system at another facility may operate for two to four years before rouging is noted (13). The important point here is in understanding the water system and setting an appropriate inspection frequency accordingly.

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