CORROSION DYNAMICS OF COBALT-CHROMIUM ALLOY F-75 POWDER

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ABSTRACT

Corrosion Dynamics of Cobalt-Chromium Alloy F-75 Powder

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The increasing usage of metal-on-metal joint replacements consisting of a cobalt-chromium-molybdenum alloy requires increasing concern regarding the inevitable generation of metallic wear debris. Patients with these joint replacements exhibit elevated concentrations of cobalt and chromium ions within their serum, blood and urine. The presence of these metal ions suggests the potential for bodily damage and indicates corrosive processes are acting upon wear debris.

To understand the behavior of these corrosive processes, powders of cobalt-chromium-molybdenum alloy F-75 were studied. Four powder sizes (44, 74, 105, and 420 μm diameter) were subjected to Hank's Balanced Salt Solution (HBSS) for a 42 day immersion test within an incubating shaker set at 37°C. Samples were removed periodically and analyzed for cobalt and chromium content using Inductive Coupled Plasma – Optical Emission Spectroscopy (ICP-OES). The resulting data gathered allowed for an evaluation of the corrosion rate as a function of particle diameter and exposure duration.

Two observations were noted from the results. First, cobalt concentration (no chromium was detected) increased as a logarithmic function of time. For the 44, 105, and 420 μm diameter powders, cobalt concentration increased rapidly within four days of exposure but corrosion reached a plateau afterwards. The development of an oxide layer that inhibited further corrosion was the cause for this behavior. Second, the cobalt concentration reached a different upper limit depending on the particle diameter. For the 44, 105, and 420 μm diameter powders, samples reached average limits of 0.0611, 0.0314, and 0.0291 ppm Co, respectively. This observation can be related to the increase in particle surface area as diameter decreases within a given volume of particles.

Modeling of this data resulted in empirical relationships for cobalt concentration and corrosion rate as a function of time, and particle diameter or surface area. However, these relationships were not reliably accurate in predicting the results of external corrosion studies on submicron cobalt-chromium particles. Consequently, this model of particle corrosion does not predict what may occur with nano-scale particles.

Keywords: Cobalt-chromium alloy, Powder, Wear debris, Corrosion rate, Metallic ions

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1. INTRODUCTION

Orthopaedic devices used to remedy end-stage arthritis in joint replacements include total hip and knee replacements (THR/TKR). These treatments have been successful in restoring mobility to patients with arthritic hips or knees. The Center for Disease Control and Prevention reported that 235,000 total hip replacements and 534,000 total knee replacements were performed in the U.S. in 2005 (Center for Disease Control and Prevention, 2007). Many patients depend on these procedures to rejuvenate their quality of life and, considering the invasive nature of revision surgeries, will need the device to function for the rest of their lives.

1.1 ARTIFICIAL HIP REPLACEMENT CONCERNS

There are two main material combinations used in hip joint replacements. One combination utilizes a cobalt-chromium-molybdenum alloy (hereafter cobalt-chromium) articulating component and an ultra-high molecular weight polyethylene (UHMWPE) bearing component (**Figure 1**). The second combination is referred to as a metal-on-metal device since both articulating and bearing components are made of a cobalt-chromium alloy. This metal-on-metal combination has been increasingly utilized in hip replacements due to concerns over failed implants employing the metal-on-polyethylene combination. Polyethylene wear debris has been implicated as the root cause for these failures (Campbell, Clarke, & Kossovsky, 1991). This debris triggers a process called osteolysis, where bone around the implant becomes resorbed and eventually leads to aseptic loosening, failure of the implant, and revision surgery.

Although the metal-on-metal combination does not generate the osteolytic polyethylene wear debris, metal particulates are produced, which have their own set of concerns. Once liberated from the implant, the metal debris corrodes within the bodily environment, which releases metal ions and other corrosion products (Cobb & Schmalzreid, 2006). Further compounding this problem is the dissemination of metal ions and particulates not only in the local synovial fluid and periprosthetic tissue, but throughout the lymphatic and vascular system (Keegan, Learmonth, & Case, 2007). This means that the debris could potentially accumulate in a patient's organs. The presence of metallic ions within the body is troubling because they are toxic metals that have been suspected of carcinogenicity and genotoxicity, among other health concerns (Campbell, Clarke, & Kossovsky, 1991).

FIGURE 1: Visual comparison of metal-on-metal (left) and metal-on-polyethylene (right) hip replacements. The absence of a polyethylene liner in the metal-on-metal prosthesis allows for a

larger diameter femoral head. Both types of hip replacements utilize textured surfaces at the acetabular shell and femoral stem to improve implant fixation. Image source: healthbase.com and direct-healthcare.com.

1.1.1 METALLIC DEBRIS PREVALENCE

The production of metallic wear debris and subsequent ion release will result in accumulation of metal ions not only in local tissues and fluids, but also throughout the body (Keegan, Learmonth, & Case, 2007). In tissues surrounding the implant, debris accumulation is inevitable. Examinations of tissues adjacent to explanted or revised prostheses reveal the presence of metal particulates (Korovessis, Petsinis, Repanti, & Repantis, 2006). Metallic accumulation has also been found in the liver, spleen, and lymph nodes since white blood cells that have consumed the wear particles can move through the lymphatic system (Keegan, Learmonth, & Case, 2007). These observations elicit obvious health concerns as this implies metal ions may be transported to any organ via the lymphatic system (**Figure 2**).

FIGURE 2: Diagram of the human lymphatic system. Exposure to the lymphatic system would allow particles to potentially travel anywhere in the body. Source: nevdp.org.au.

The detection of metallic ions within bodily fluids, such as synovial fluid, blood, serum, and urine, confirms the existence of corrosive events acting upon the implant and generated wear debris (Hallab, Anderson, Caicedo, Skipor, Campbell, & Jacobs, 2004). One study found that two years after a metal-on-metal implantation, an average of 1.10 parts per billion (ppb) of Co and 2.5 ppb of Cr were found in blood, while 14.73 ppb of Co and 4.53 ppb of Cr were found in urine samples (Cobb & Schmalzreid, 2006). In another study, ion concentrations in patients with metal resurfacing implants, which are a type of metal-on-metal implant, were found to have increased steadily from 0.14 ppb Co and 0.16 ppb Cr pre-operatively to an average of 2.45 ppb Co and 2.70 ppb Cr postoperatively as measured in blood after 12 months (Heisel, Streich, Krachler, Jakubowitz, & Kretzer, 2008). Though evidence of corrosion can be associated with

metallic wear debris and a rate of corrosion may be implied from bodily fluid measurements, a better understanding of how these wear particles corrode is needed.

1.1.2 BODILY RESPONSE TO METALLIC DEBRIS

Several studies have been carried out to characterize and explain the bodily reactions to foreign metallic debris and ions. Damage to tissues may include metallosis, osteolysis, metal hypersensitivity, cytotoxicity, and genotoxicity. When the presence of wear particles is detected by the body, macrophages will consume particles larger than 150 nm and set off a chain of destructive events (Abu-Amer, Darweh, & Clohisy, 2007). There may be a release of factors that cause inflammation, cell necrosis and osteolysis (Thomas & Summer, 2005). Particles that are smaller than 150 nm may be consumed by other phagocytes through “receptor-mediated endocytosis and pinocytosis” (Keegan, Learmonth, & Case, 2007). When the body recognizes foreign matter, it tries to isolate the foreign bodies and decompose or dispose of them (**Figure 3**). However, the ingestion of the particles can cause “cytotoxicity, chromosomal damage, and oxidative stress” to the phagocyte (Keegan, Learmonth, & Case, 2007). These cytotoxic effects may then hinder local bone formation and regeneration (Thomas & Summer, 2005).

FIGURE 3: Optical micrograph of histologic section of extracted tissue from a hip afflicted by aseptic loosening (400x). Foreign-body giant cells (red arrow) appear as large gray masses while histiocytes, or tissue macrophages, appear as smaller blue-violet cells. Metallic wear debris is shown to be consumed by these cells (black arrow) as part of the body's immune response. Source: (Korovessis, Petsinis, Repanti, & Repantis, 2006).

Hypersensitivity to certain metal elements may develop for some patients. The inflammatory factors created by the macrophages induce the presence of antigen presenting cells (APCs), where the antigens are metal ions in this case (Thomas & Summer, 2005). The interaction between the APC and the metal ions then triggers the activation of T-cells, which are a type of lymphocyte (Thomas & Summer, 2005). The activation of the T-cells to the metal ions then leads to sensitization (Hallab, Anderson, Caicedo, Skipor, Campbell, & Jacobs, 2004). Thus, the continued detection of metal ions by T-cells will induce an inflammatory response from the body. Furthermore, this

mechanism can result in pain and subsequent osteolytic implant loosening (Milosev, Trebse, Kovac, Cor, & Pisot, 2006).

The carcinogenicity of metallic ions remains an unresolved issue. While ions may cause chromosomal damage and inhibit DNA repair and expression, they have not been definitively implicated in causing tumors (Keegan, Learmonth, & Case, 2007). There is evidence to suggest that metal ions may cause the genesis of tumors, but the mechanism remains unclear (Campbell, Clarke, & Kossovsky, 1991). Work has been done to show that DNA damage in T-cells does not necessarily occur before cell necrosis or apoptosis can occur (Caicedo, Jacobs, Reddy, & Hallab, 2007). This suggests that tumor proliferation may not develop before the cell dies.

1.1.3 METALLIC DEBRIS GENERATION

The source of the problematic metallic debris is the wearing of the articulating component against the bearing component in a joint replacement device. There are four modes of wear that a joint replacement may experience. Mode 1 is wear due to intended function of the device and is expected to occur. Mode 2 is defined as “micro-separation wear,” which is when the articulating component temporarily loses Mode 1 contact and other areas of the component are in contact with the bearing component (Clarke, Donaldson, Bowsher, Nasser, & Takahashi, 2005). Mode 3 wear can be referred to as third-body wear. In this wear mode, the debris and particulates that are generated (third bodies) become lodged in the interface between the articulating and bearing components. This leads to increased wear of the two surfaces, especially if particles

harder than the alloy are present, such as cement, bone, or metal oxide particles (Campbell, Clarke, & Kossovsky, 1991). These third bodies may scratch or gouge the surfaces at the interface, and produce more debris. Furthermore, the base metal may become exposed to bodily fluids if the scratches penetrate the metal oxide layer, which would make the alloy susceptible to corrosion. In Mode 4 wear, the two surfaces undergoing wear are secondary surfaces that are not intended to wear (Schmalzried & Callaghan, 1999). For example, the acetabular cup rim may wear against the femoral neck of the implant (Schmalzried & Callaghan, 1999). This may occur if the acetabular cup impinges on the stem during walking. Another example of Mode 4 wear is micromotion between the femoral stem and the bone cement used to fixate the stem within the femur (Zhang, Blunt, Jiang, Brown, Barrans, & Zhao, 2008). Relative motion between the stem and cement would generate both metallic and cement particles. These four modes are graphically summarized in **Figure 4**.

FIGURE 4: Summary schematic of applicable wear modes in total hip replacements. Mode 1 indicates expected wear from proper motion between femoral head and acetabular cup. Mode 2 shows wear of the head against rim during separation from cup. Mode 3 demonstrates wear due to the presence of third bodies. Mode 4 illustrates unintended wear between femoral neck and cup rim. Each mode produces unique wear tracks and patterns at different areas. Adapted from (McKellop, et al., 1995).

In a metal-on-metal implant, the main wear mechanism in each of these modes is abrasive wear. In this mechanism, the asperities from each surface, which are peaks of material protruding from the bulk material, contact each other under an applied load and this causes some asperities to break off. In the case of cobalt-chromium alloys, these broken asperities may be cobalt and chromium oxide particles. Once these asperities are liberated from the bulk surfaces, they may contribute to third body wear between the two surfaces.

Adhesive wear is a secondary wear mechanism that may occur to a lesser extent. In tribological theory, if the lubrication between two identical metal surfaces is insufficient, asperities from both surfaces could potentially bond. The asperity may then shear along a path around the asperity and through the bulk surface rather than through the bonding interface. The removed chunk could then shear again at the bonding interface, resulting in the creation of a wear particle. Though this process does not occur when proper lubrication is present, adhesive wear is a potential wear mechanism in metal-on-metal implants since both surfaces are identical.

1.1.4 IMPLANT WEAR RATES

The wear rate of metal-on-metal implants has been widely studied. Many authors cite the higher wear rate of metal-on-UHMWPE implants as a main factor for using metal-on-metal implants (Heisel, Streich, Krachler, Jakubowitz, & Kretzer, 2008). In metal-on-metal implants, it has been shown that the wear rate varies as a function of implantation time. Wear rates are generally higher immediately after implantation and

stabilize to a lower rate after a “running-in” period (Hallab, Anderson, Caicedo, Skipor, Campbell, & Jacobs, 2004). One study found the mean cumulative steady-state wear rate of both head and cup components to be 5 $\mu\text{m}/\text{year}$ in linear dimension and 0.3 mm^3/year in volume after a mean implantation time of 22 months (Milosev, Trebse, Kovac, Cor, & Pisot, 2006). Another study found a similar linear wear rate of 6.3 $\mu\text{m}/\text{year}$ and volumetric wear rate of 0.43 mm^3/year after a mean implantation time of 85 months (McKellop, et al., 1995). In terms of the bulk number of particles, one paper estimates 2×10^{14} cobalt-chromium particles per year are released, which translates to 2×10^8 particles per footstep (Clarke, Donaldson, Bowsher, Nasser, & Takahashi, 2005). During the running-in period, the femoral and acetabular surfaces are being further polished through the elimination of larger asperities. Once the surfaces have been smoothed of these larger asperities, less debris is generated and thus, steady-state wear is achieved (Figure 5).

FIGURE 5: Comparison of mean volumetric wear (y-axis, units: mm³) over a number of loading cycles (x-axis, units: 10⁶ cycles) and two different femoral head diameters (size 39 and 55 mm). Production of wear by volume decreases after an initial “running-in” period. This trend is reflected at both femoral head diameters. The smaller head exhibits more wear due to higher contact stresses. Source: (Leslie, et al., 2008).

Many factors may influence the wear rates of these implants. Patient factors are a significant consideration on how fast the implant will wear. These variables include “age, weight, and activity” (Schmalzried & Callaghan, 1999). Age and activity are somewhat related in that age can determine how active a patient will be afterwards. An increase in activity would lead to increased wear rates. Likewise, weight affects the loads placed on the prosthesis and a higher load would translate to higher wear rates.

Another possible factor influencing implant wear rate is the geometric matching of the cup and ball surfaces. The femoral head will have a slightly smaller radius of curvature than the acetabular cup and this difference in curvature is referred to as radial mismatch. If the radial mismatch is too small, lubrication may not be pulled into the gap between the two surfaces via capillary forces and “higher frictional torques” may result (Clarke, Donaldson, Bowsher, Nasser, & Takahashi, 2005). This situation would lead to more wear. If the radial mismatch is too large, the “contact stresses may become too high” (Clarke, Donaldson, Bowsher, Nasser, & Takahashi, 2005). This situation would also lead to more wear. However, the proper “radial mismatch” is still unclear as studies have produced conflicting conclusions (Clarke, Donaldson, Bowsher, Nasser, & Takahashi, 2005).

1.1.5 DEBRIS MORPHOLOGY

Characterizing the morphology of generated wear debris requires high resolution imaging techniques. One study has obtained particles generated from a hip simulator and utilized Transmission Electron Microscopy (TEM) to visualize them (Bowsher, Hussain, Williams, & Shelton, 2006). The particles that were analyzed showed diameters ranging from 10 nm to 3000 nm (Bowsher, Hussain, Williams, & Shelton, 2006). Mean diameter of the particles was 99 nm for normal walking simulations to 132 nm for fast jogging simulations (Bowsher, Hussain, Williams, & Shelton, 2006). The particles produced from hip simulators were usually round or oval in shape, although some particles were shown to be needle shaped (Bowsher, Hussain, Williams, & Shelton, 2006). Another study examined particles extracted from patients with hip replacements using a transmission electron microscope (TEM) (**Figure 6**). Out of 11 patients' particle samples, they found the average median particle size to be 42 nm with a round or oval shape (Doorn, Campbell, Worrall, Benya, McKellop, & Amstutz, 1998). Given that a majority of the particles are on the nano-scale and that estimates of particles generated yearly exceed hundreds of trillions, the total particle surface area exposed to the body is enormous, even if particles agglomerate (Clarke, Donaldson, Bowsher, Nasser, & Takahashi, 2005). With such a large area of exposed particle surface, there would be a large amount of debris reactivity within the human body.

FIGURE 6: Bright Field Transmission Electron Microscope (TEM) micrograph of a single metallic wear particle. These particles may also appear in clusters in tissues. The authors reported that most of the particles found were globular in shape and had irregular boundaries. Source: (Doorn, Campbell, Worrall, Benya, McKellop, & Amstutz, 1998).

1.1.6 CORROSION INDUCED ION RELEASE

Metallic wear particles undergo corrosive processes once introduced to the body (Shahgladi, Heatley, Dewar, & Corrin, 1995). For corrosion to occur, there must be four components: oxidation reactions, flow of electrons, metal atoms and ions, and reduction reactions (**Figure 7**). Oxidation reactions occur at an anodic location, which releases electrons and ions. The electrons and ions must then travel towards a cathodic location, where a reduction reaction occurs to recombine free electrons with the ions. The result is a gain of mass at the cathode, which may be an oxide layer. An alternative reduction reaction in an aqueous environment may occur so that metallic ions remain in solution. A reaction between water, oxygen, and free electrons can form hydroxide (Eq. 1).

One specific corrosion mechanism that may affect wear particles is uniform corrosion. In this mechanism, local anodes and cathodes can form on the same continuous metal

due to slight differences within the material. The anodes and cathodes may shift as corrosion changes the material. The result is a uniformly corroded metal.

FIGURE 7: Schematic of a corrosion cell in an aqueous environment. The oxidation reaction occurs at the anode and results in a loss of material. The metal ions (iron, in this case) dissociate into solution while the electrons travel to the cathodic location. There, reduction reactions occur so that an oxide layer may form (rust, in this case) or hydroxide ions may form and dissolve into solution. Source: gordonengland.co.uk.

There are two factors that govern the thermodynamics of corrosion. First, the free energy of the oxidation and reduction reactions determines whether or not the reactions occur (Eq. 2)(Jacobs, Gilbert, & Urban, 1998).

$$\Delta G_{red} = \Delta G^{\circ} + RT \ln \left[\frac{[M]}{[M^{n+}]^m [e^{-}]^n} \right] \quad (\text{Eq. 2})$$

In the equation for a reduction reaction of a pure metal, " ΔG_{red} " is the free energy of the reduction reaction, " ΔG° " is the free energy of the reaction in a defined standard state, R is the gas constant, T is the temperature, and the bracketed values are the concentrations

(or activities) of the species involved in the reaction” (Jacobs, Gilbert, & Urban, 1998). If this energy is negative, then the reaction will occur spontaneously. Second, there is a driving force in the form of an electric potential once the electrons and metallic ions have become liberated from the oxidation reaction (Jacobs, Gilbert, & Urban, 1998). When the positive metallic ions dissolve into the local aqueous environment and the negative electrons remain with the bulk metal, the presence of an electric double layer at the metal-liquid interface results in a separation of charge, which is an electrical potential (Eq. 3)(Jacobs, Gilbert, & Urban, 1998).

$$\Delta G = -nF\Delta E \quad (\text{Eq. 3})$$

In this equation for the electric potential, “ n is the number of electrons lost or gained in the reaction, F is the Faraday constant, and ΔE is the voltage or potential across the interface between the metal and the solution. The strength of this electric potential dictates the reactivity of the metal within the liquid. When the chemical and electrical driving forces are balanced, the Nernst equation can be derived (Eq. 4)(Jacobs, Gilbert, & Urban, 1998). This equation is a combination of Eq. 2 and 3 with the addition of ΔE° , which is the electrode potential under standard state conditions. The Nernst equation can be used to determine the thermodynamic potential for corrosion of a particular metal. Based on thermodynamics, most metals will readily corrode in an aqueous environment.

$$\Delta E = \Delta E^\circ + \frac{RT}{nF} \ln \left[\frac{[M^{n+}]}{[M]} \right] \quad (\text{Eq. 4})$$

Although a reaction may be thermodynamically spontaneous, kinetics govern how fast that reaction proceeds. The main defense a metal has against corrosion is its oxide layer, which is a layer comprised of corrosion products. This layer blocks the transport of ions to the cathode and act as a “kinetic barrier” to any further corrosion depending on its structure(Jacobs, Gilbert, & Urban, 1998).

However, the oxide layer may be mechanically damaged, especially under the cyclic stresses experienced by the hip replacement, which may lead to further corrosion as the base metal becomes exposed. The extent of any further corrosion is dependent upon the ability of the metal to repassivate, or reform the oxide layer, and the frequency of mechanical damage. Therefore, the integrity of the oxide layer to itself and onto the base metal is crucial to inhibiting corrosion reactions.

Proteins may also have an effect on the corrosion rate of the implant and wear debris. Once an implant enters the body, proteins immediately bind to its surface as part of the foreign body response. In one study, the authors found that proteins and amino acids reduce the corrosion resistance of a low-carbon cobalt-chromium-molybdenum alloy (Yan, Neville, & Dowson, 2006). Others have shown that corrosion is mitigated due to a reduction in charge transfer (Yan, Neville, & Dowson, 2006). However, there are conflicting studies as some researchers find that proteins increase the corrosion rate.

If afflicted by corrosion processes, the physical dimensions and chemical composition of the particles are subject to change (Hanawa, 2004). Given the large

particle surface area exposed to bodily fluids by a small mass of wear particles, the corrosion produced can be greatly exacerbated. For cobalt-chromium wear particles, cobalt is likely to be leached out because it is more soluble in the body (Yan, Neville, & Dowson, 2006). However, there is no consensus in the literature on which metal species is most soluble within the body.

1.2 CORROSION BEHAVIOR OF COBALT-CHROMIUM WEAR PARTICLES

The nature of the corrosive events occurring on wear particles within the body has not been extensively studied. Methods have been developed to isolate and corrode metal wear particles generated *in vitro*. Rogers, Percy, Hay, Haynes, Bramley, and Howie (1993) describe how particles may be generated from the shaking of metal blocks encapsulated within a shell containing a solution simulating biological fluids. Isolation of particles within a specific range of diameters was accomplished with an iterative process of differential centrifugation.

The subsequent study of these isolated particles (0.2- 0.5 μm and 0.5-3.0 μm) found that corrosion increased with decreasing particle size and pH, and the corrosion rate was initially high but decreased to a lower rate after a short exposure duration (Haynes, Crotti, & Haywood, 2000). This research has established a consistent method by which to study the corrosion behavior of specific particle size ranges. However, the study of particles closer to 50 nm as well as those extracted from periprosthetic tissues has yet to be performed.

1.3 RESEARCH GOALS

Metallic wear debris from orthopaedic prostheses is a primary source of limited implant longevity. Thus, understanding the origins and consequences of wear debris is paramount to improving implant life and long term patient outcomes. The tribological origin of wear debris has been extensively studied. The method of wear generation from different wear modes and the rates at which it occurs is fairly well understood. The techniques necessary to characterize the wear debris in terms of morphology and distribution of various morphologies have been developed and more work is needed to apply these techniques to completely characterize the debris. Much research has taken place regarding the biological responses to foreign debris and some mechanisms involving the immune system are understood. However, more complex mechanisms may be at the root of bodily reactions. In particular, long term studies of the carcinogenic potential of wear debris are needed to fully assess this risk. More work is also needed to determine the corrosion mechanisms and rates of the metal particulates. Studies involving the generation, isolation, and corrosion of simulated wear particles are key to accomplishing this.

This thesis focuses on determining the corrosion dynamics of cobalt-chromium powder (44 – 420 μm) which leads toward understanding the corrosion dynamics of cobalt-chromium wear particles. The corrosion method developed by Midander, Pan, & Leygraf (2006) as well as current elemental analysis techniques were used. The following three goals encompass the intent of this thesis:

1. Adapt a method to repeatably corrode cobalt-chromium powders of differing particle sizes (44, 74, 105, and 420 μm).
2. Determine the solution concentrations of cobalt and chromium after powder exposure to media that simulate human bodily fluids.
3. Explain and model *in vitro* corrosion rate as a function of particle diameter and exposure duration.

2. MATERIALS AND METHODS

2.1 TEST PLAN

To determine the dissolution rate of wear particles, a method was first adapted to produce detectable and repeatable chromium and cobalt ion measurements. A comparison of the ion levels in solution between two sizes of cobalt-chromium powder was explored. The hypothesis for this set of experiments is a smaller cobalt-chromium sphere would corrode faster than a larger sphere, holding all other factors constant. After it was illustrated that the experimental method supported this theory, the corrosion rate of four different sizes of cobalt-chromium powder was then determined.

A description of the corrosion and elemental analysis methodology will be described first. Then the contributions to the current methodology of the six preliminary experiments will be summarized. Finally, the parameters governing the corrosion rate experiment will be discussed.

2.2 CORROSION TESTING

The following methodology used to induce corrosion of cobalt-chromium powders was adapted from Midander, Pan, & Leygraf (2006). It was utilized for a series of seven experiments, in which the first six were aimed at validation of the methodology and the seventh was used to determine the corrosion rate of the powders.

2.2.1 TESTING MATERIALS AND EXPERIMENTAL SETUP

Experiments 1 through 6 utilized powders composed of cobalt-chromium alloy F-75 (composition shown in **Table 1**), which were provided by UCLA -Orthopaedic Hospital. Each successive experiment involved different test variables such as powder mass, medium, and particle diameter to refine and obtain a valid methodology. These experiments tested two sphere sizes, which had minimum diameters of 420 μm (420-500 μm) and 44 μm (44-105 μm). Experiment 7 tested both these particle sizes and two additional particle sizes manufactured by Advanced Specialty Metals Inc. The supplementary powder consisted of cobalt-chromium alloy F-75, which came in minimum sizes of 74 μm (74-149 μm) and 105 μm (105-149 μm). No sieve analysis was provided with the 420 μm and 44 μm powders but the sieve analysis provided with the 74 μm and 105 μm powders by Advanced Specialty Metals Inc. is shown in **Table 2**.

TABLE 1: Elemental Composition of Cobalt-Chromium Powder

	Element (Wt. %)			
	Co	Cr	Mo	C
ASTM F75 Standard	66.1	27.5	6.00	0.35
As Received 420 μm Sphere	64.2	27.79	4.97	1.43

TABLE 2: Sieve Analysis of Advanced Specialty Materials Powder

74 μm Powder							
Sieve Opening (um)	62	74	88	105	125	149	177
% Retained on screen	14.3	31.7	29.2	15.3	7.7	1.8	0
105 μm Powder							
Sieve Opening (um)	< 74	74	88	105	125	149	177
% Retained on screen	0	0	1.1	35	52.4	11.5	0

Each particle sample was weighed with an analytical balance (XS205, Mettler-Toledo), placed in containers, and filled with a testing medium (**Figure 8**). Each container was filled until the meniscus of the liquid at the container opening was convex. This was done to minimize any air trapped in the container when the cap was screwed on. Every sample had a powder mass within 1 mg of the respective target mass (**Table 3**). The containers utilized included 40 mL high-density polyethylene (HDPE) and 22 mL glass vials. After Experiment 5, glass vials were used as containers because of their inert and optically clear nature. All containers and glassware were cleaned with dish soap, rinsed with deionized water, and dried on a hotplate to minimize any contamination.

FIGURE 8: Collection of samples from Experiment 6. Glass vials were introduced in Experiment 6 to eliminate any reactions from the medium. The clear glass allowed for examination and dissipation of particle clumps. Though the caps contained a polymer pad to seal the vial, some were not tightened enough, which led to leakage, as evidenced by the three clear vials in the lower right corner.

TABLE 3: Mass Levels and Equivalent Concentrations per Experiment

Experiment	Mass Levels	Mass Concentration (mass per volume solution)	Replications
1	5, 10, 15 & 20 mg	0.125, 0.25, 0.375, & 0.5 g/L	2
2	5, 10, 15 & 20 mg	0.125, 0.25, 0.375, & 0.5 g/L	2
3	100 mg	2.5 g/L	6
4	20, 50 & 100 mg	0.5, 1.0, & 2.5 g/L	1
5	100 mg	2.5 g/L	15
6	22, 44, 66 mg	1.0, 2.0, & 3.0 g/L	3
7	66 mg	3.0 g/L	3

The testing medium used in the first two experiments was phosphate buffered saline (PBS, Hyclone), the third used 35% concentrated hydrochloric acid (HCl, Fisher Scientific), and the fourth through seventh employed Hank's Balanced Salt Solution (HBSS, Hyclone). Samples requiring lower pH solutions were adjusted with 35% HCl. Verification of pH levels was performed with a digital pH meter (pH 11 Hand-Held Meter, Oakton Instruments). Control containers of deionized water and medium were also prepared for each experiment. **Table 4** describes the testing conditions for each experiment.

TABLE 4: Conditions Utilized for Experimentation

Experiment	Particle Size (μm)	Medium	Duration (days)	pH
1	420	PBS	28	pH 7.4
2	44	PBS	28	pH 7.4
3	420	HCL	1	pH 2
4	420 & 44	HBSS	42	pH 7.2, 4, & 3
5	420 & 44	HBSS	42	pH 4
6	420 & 44	HBSS	42	pH 7.2 & 4
7	420, 105, 74, & 44	HBSS	42	pH 7.2

2.2.2 TESTING ENVIRONMENT

The prepared samples were placed in a gyrating water bath shaker (G76D, New Brunswick Sci. Co.) maintained at $37 \pm 1^\circ\text{C}$ and were agitated at 140 RPM for the duration of each experiment. Fixation of the bottles to the shaker plate was initially accomplished by tying the bottles down to the base shaker plate. However, the need for more capacity in Experiment 5 led to fixation via a stacked arrangement of aluminum plates. The bottles were placed between layers of cushioned plates. These plates were then linked to the base shaker plate with four threaded vertical rods and fastened with nuts (**Figure 9**). By locking down the position of each plate with the nuts, the compressive force exerted on the bottles prevented their movement (**Figure 10**).

FIGURE 9: Images of incubating shaker and shaker plate loaded with samples from Experiment 7. The layers of bubble wrap also provided traction for the glass vials and further prevented movement. The four outer arms of plate apparatus were affixed to the four drive arms, which provided rotational agitation.

FIGURE 10: Image of shaker plate loaded with samples from Experiment 7 between plates and cushioning.

2.2.3 SOLUTION EXTRACTION AND FILTRATION

After each test period, the solutions were extracted from the containers and isolated from the metal particles by vacuum filtration. These particles were analyzed in another study (Grandfield, 2009). The vacuum filtration system (**Figure 11**) was comprised of a vacuum rotary-vane pump (Hitachi) that drew air out of a vacuum flask and pulled the solutions through a filtration apparatus (Millipore) equipped with 2.5 μm particle retention paper filter (No. 42, Whatman). The upper part of the filtration apparatus served as the solution funnel and the lower part was fabricated of porous sintered glass, which provided mechanical support to the filter paper and allowed the filtered solution to pass through. Filter paper was placed in between these two parts and an aluminum clamp fixated the components to each other. The lower component of the filtration unit also had a rubber stopper to seal the unit to the vacuum flask.

After the solution was drawn through the filter, it was then poured into a 50 mL centrifuge tube for storage at room temperature (FisherScientific). Solution losses were due to residual fluid in the containers and filtration unit, and suction through the vacuum port of the flask. The filtration unit was rinsed with deionized water and dried with KimWipes (Kimberly-Clark) to eliminate cross-contamination between samples. Used vacuum flasks were cleaned with soap, rinsed with deionized water, and dried with KimWipes and a hotplate.

FIGURE 11: Image of vacuum filtration system. Much of each container's solution was extracted. Losses were due to residual fluid in the containers and filtration unit, and suction through the vacuum port of the flask.

2.3 ELEMENTAL ANALYSIS

The determination of Cr and Co ions after dissolution testing was accomplished with two techniques: flame atomic absorption spectrometry (AAS) and inductively coupled plasma – optical emission spectroscopy (ICP-OES). These techniques can be

sensitive to trace elemental concentrations in the sub-parts per million (ppm). Though the ICP-OES is slightly more sensitive, the AAS was employed for Experiments 1-5 because it was readily available. The ICP-OES (University of California, Santa Barbara) was available for Experiments 6 and 7.

2.3.1 CALIBRATION SOLUTIONS

The calibration standards made for the AAS were confined to certain ranges since it may only measure absorbance from one wavelength at a time. For chromium at 425.4 nm, the range of quantitation is 0.4 to 40 ppm and for cobalt at 240.7 nm, the range of quantitation is from 0.05 to 15 ppm. Since the ICP-OES may measure multiple wavelengths simultaneously and detect lower concentrations, its calibration standards were more dilute and ranged from 0.001 to 1 ppm for both cobalt and chromium.

The calibration solutions were created by dispensing the appropriate volume of stock solution into 50 mL volumetric flasks (Kimex) with a micropipetter (Eppendorf) and filled to volume with Type I water. The solution was then transferred to a centrifuge tube for storage.

Initially, stock solutions were made in the laboratory by dissolving potassium chromate (FisherScientific) in Type I water for chromium solutions and cobalt (II) chloride hexahydrate (FisherScientific) for cobalt solutions in accordance with ASTM D1687 and D3558. However, after Experiment 1, premade chromium and cobalt stock solutions (1000 ppm) were purchased (Ricca Chemical) to eliminate any errors from making solutions in-house.

There are several ways to ensure the calibration standards are accurate. First, the closer the matrix of the standards matches the unknown, the more accurate the reading. For this reason, calibration standards made after Experiment 4 were filled to volume with the medium used in the experiment, which was HBSS. Second, the standards should be prepared as close to analysis time as possible. Because the standards are usually lower than 1000 ppm, they cannot be stored for long periods of time as adsorption of the ions onto the container walls will significantly reduce the solution concentrations.

2.3.2 ANALYTICAL INSTRUMENTATION

Following sample filtration, cobalt and chromium ion concentrations were determined using either a flame AAS (AA240, Varian, **Figure 12**) or ICP-OES (iCAP6300, Thermo Scientific, **Figure 13**). The calibrations standards were first measured and after the instrument was calibrated, the samples were then measured. Calibration checks were performed every hour and if the measurement differed by more than 2% from the true concentration, then the instrument was recalibrated.

FIGURE 12: Schematic of an AAS. The sample uptake aspirates solution into the flame. The lamps are continuously emitting light of a characteristic wavelength through the flame to a detector. Any decrease in the intensity of this light due to the sample will be attributed to absorbance by the atoms that have this characteristic absorption wavelength. Image source: varian.com.

FIGURE 13: Schematic of an ICP-OES. The sample is drawn from the uptake into the nebulizer where it is converted into an aerosol with the argon gas. The aerosol is then pumped into the plasma housing where inductor coils will energize the aerosol mixture.

The AAS measures the absorbance of light emitted from a lamp after it passes through the sample. This light has a wavelength matching the absorption wavelength of the analyte. The sample is atomized by the energy in the flame and any atoms of the

element of interest will absorb the characteristic light. The relationship between light absorbance and ion concentration is established in the Beer-Lambert law, where A is the absorbance, ϵ is the molar absorptivity ($\text{dm}^3 \text{mol}^{-1} \text{cm}^{-1}$), c is the concentration of the analyte (mol dm^{-3}), and l is the length over which absorption takes place (cm) (Eq. 5) (McNaught & Wilkinson, 1997).

$$A = \epsilon cl \quad (\text{Eq. 5})$$

From this law, concentration should be linearly proportional to absorbance. However, at higher concentrations, this law becomes nonlinear. As the concentration of solute increases, the probability of solute-solute interactions increases. These interactions alter the electronic band structure of the solute, which results in a different absorption wavelength and thus, less absorbance (Seely, 2000). A calibration curve produced using cobalt standards exemplifies this deviation from linearity (**Figure 14**).

FIGURE 14: Example of an AAS calibration curve (y-axis: absorbance, x-axis: concentration (ppm)). Because absorbances of unknown samples are compared against the absorbances of the standards to determine the concentrations, it is vital that the standards are properly made so that the calculated concentrations are accurate. Several standards are used as data points for a curve fit.

In contrast, the ICP-OES employs high temperature argon plasma to atomize the sample and excite an atom's electrons into higher orbitals. When the electrons relax back to the ground state from this excited state, they will emit light at characteristic wavelengths, the intensity of which is measured by a charge-coupled device (CCD) detector.

Each instrument had different capabilities. The iCAP 6300 was found to have lower detection limits for cobalt and chromium than the AA240. The empirically established detection limit is defined as three times the standard deviation for ten concentration measurements of a blank sample (Doyle, 2008). Any sample that has a concentration below the detection limit is considered not statistically different from a blank. The iCAP 6300 has a detection limit of 0.023 ppm for Cr and 0.0024 ppm for Co. The AA240 has a detection limit of 0.11 ppm for Cr and 0.022 ppm for Co. Thus, the iCAP 6300 is about ten times more sensitive than the AA240.

Another difference between the AA240 and iCAP 6300 was the use of interference correction. Interference correction was not employed with the AA240 but was utilized with the iCAP6300. Because the iCAP 6300 measures emitted photons from multiple wavelengths on the same CCD, photons from nearby wavelengths may be detected along with photons from the target wavelength on the same pixel. These conflicting photons must then be isolated to obtain the true photon count of the target wavelength by using background correction (**Figure 15**). The "subarray plot" depicts a row of 12 pixels, where each pixel will pick up slightly different wavelengths of light.

The target wavelengths will be focused on the “center” pixels (“C”) and display the signal intensity. However, if photons from nearby wavelengths contact the center pixels, the target wavelength will show higher photon intensity than what is actually representative of the sample. Therefore, if it is assumed that the same amount of stray photons that strike the center pixels are detected by adjacent pixels, the “background signal” can then be subtracted from the target signal.

FIGURE 15: Example of using a subarray plot to apply background correction. The target wavelength photons are detected on the center pixels (denoted “C”). In this case, the adjacent pixels (denoted “L” and “R”) do not detect any other photons so there is no need to subtract out any background signal.

2.4 METHODOLOGY REFINEMENT

The experiment methodology was refined through Experiments 1-6. This section describes the rationale behind these experiments and how their results advanced the methodology.

2.4.1 EXPERIMENT 1: FIRST ATTEMPT AT CORROSION RATE

Experiment 1 was designed as a first attempt to determine the corrosion rate. Initially, the amount of metal in each sample was determined by particle counts so that surface areas may be estimated. While this was possible with the 420 μm powder, individual particles of the 44 μm powder were not discernible. Thus, only the 420 μm powder was tested in Experiment 1. Powder amounts were subsequently determined using an analytical balance and surface areas were estimated from the mass of particles, average particle diameter, and metal density. Low mass loadings (0.125, 0.25, 0.375, & 0.5 g/L) were chosen because higher mass loadings could potentially coalesce and reduced the effective surface area exposed to medium (Midander, Pan, & Leygraf, 2006). Four different mass loadings were chosen based on the hypothesis that increasing mass would increase the amount of corrosion. Each loading had two replicate samples. Phosphate buffered saline (PBS) was chosen as the medium because it replicates the ionic strength and pH of human blood (Midander, Pan, & Leygraf, 2006).

To obtain concentration data over time, 10 mL of each sample was extracted with a pipette for elemental analysis every three days. 10 mL of fresh medium would then refill the container. The concentration of this diluted sample could then be calculated as

a dilution of the extracted solution. The difference between this calculated concentration and the measured concentration of the next extracted sample divided by the exposure time would be the corrosion rate. The duration of the test eventually lasted 28 days despite the observation that “metal release rates reach steady state by one week” (Midander, Pan, & Leygraf, 2006) to allow the ions to accumulate to detectable levels. The absorbance values of the samples were near zero and not different from control measurements. It was clear that no ions were present in the samples.

2.4.2 EXPERIMENT 2: INTRODUCING SMALLER PARTICLES

In Experiment 2, the goal was to produce detectable levels of corrosion. In an attempt to induce more corrosion, the smaller 44 μm powder was used because the particles would have a higher surface area to volume ratio, which would lead to more reactive particles. To retain some degree of qualitative comparison to the 420 μm powder, the medium, mass loadings, and duration of Experiment 2 was the same as Experiment 1. However, because no ions were detected in Experiment 1, the samples were not sampled periodically but only once after 28 days. To ensure the calibration standards were accurate, purchased stock solutions were used. However, the concentrations of chromium and cobalt in the samples were still below the detection limit.

2.4.3 EXPERIMENT 3: DEMONSTRATING DETECTABLE CONCENTRATIONS

In Experiment 3, the goal was to demonstrate that chromium and cobalt ions could be detected if corrosion had occurred. The mass loading was increased to 2.5 g/L to induce more corrosion. To definitively corrode the powder, the medium was changed to an aggressive 35% HCl. Additionally, only six samples of 420 μm powder were created to limit the use of HCl. To alleviate concerns about container degradation in the incubating shaker, a bottle was filled with the medium and allowed to sit in secondary containment under a fume hood for one day. The sample containers were then filled with HCl and placed in the incubating shaker for only one day to minimize the risk of an HCl release. Because the HCl solutions could not be directly filtered or analyzed as is, they were placed in beakers and the HCl was allowed to evaporate under a fume hood. Once evaporated, the ions and particles were reconstituted with 40 mL of deionized water, tested for safety with pH strips, and subjected to filtration. Initial elemental analysis of these samples oversaturated the detector, which meant the concentrations were above the working ranges for each element. The samples were then volumetrically diluted by a factor of 50 and reanalyzed. After accounting for the dilution, the samples were found to have an average of 58.67 ppm Cr and 142.55 ppm Co (**Figure 16**). These results showed that the AAS was capable of detecting corrosion products and the testing parameters only needed to be optimized to produce detectable levels of ions.

FIGURE 16: Graph of chromium and cobalt concentrations found in Experiment 3. The differences in chromium and cobalt content may be explained by a preferential corrosion of cobalt (Grandfield, 2009).

2.4.4 EXPERIMENT 4: IDENTIFYING MOST CORROSIVE ENVIRONMENT

The goal of Experiment 4 was to identify the combination of mass and pH that would provide the highest ion content while still using a clinically relevant media. It was determined from Experiment 3 that reducing pH would accelerate corrosion but testing in HCl is not relevant to bodily conditions. The most acidic environment the body experiences around an implant may be pH 3.0 when osteoclasts are present to resorb bone, which may occur as part of aseptic loosening (Silver, Murrills, & Etherington, 1988). Thus, the three pH conditions chosen were pH 3.0, pH 4.0, and the neutral pH 7.2 of Hank's Balanced Salt Solution (HBSS). The medium was switched from PBS to HBSS because PBS was not available at the time. However, HBSS is another type of saline solution used in biological research and is comparable to PBS. Because mass loading may have been a factor in the increase of metal ions detected, several

loadings were explored (0.5, 1.0, and 2.5 g/L). Only one replicate of each condition was created due to limited capacity in the incubating shaker. The duration of this experiment was increased to 42 days to allow higher concentrations of metal ions in the solution.

The 420 μm powder samples had detectable concentrations of both chromium and cobalt whereas the ion concentrations of the 44 μm samples were below the detection limit. This indicated experimental error. In each of the pH conditions, the highest mass loading generated the highest ion concentrations for both elements. By comparing different pH values at the same mass loading, it was found that a pH 4 medium produced the most corrosion. Because one sample was prepared for each condition, the comparisons and trends were only qualitative.

2.4.5 EXPERIMENT 5: INCREASING STATISTICAL POWER

The goal of Experiment 5 was to evaluate the relationship between powder size and corrosion with more samples to increase statistical power. Because the mass loading and pH combination that lead to highest ion concentrations produced was 2.5 g/L and pH 4, this was the only condition studied. 15 samples of this condition were duplicated for each powder size. This required an expansion of the incubating shaker's capacity, which was accomplished with multiple plate layers. AAS analysis again revealed that the 420 μm samples had, on average, significantly higher levels of chromium and cobalt ions than the 44 μm samples (p-value < 0.05), which indicated an error with the method (**Figure 17**). After glass vials replaced the HDPE containers in

Experiment 6, it was clear why this was occurring. Although most of the air was purged from the container upon closure, tiny bubbles apparently remained. These bubbles attracted the smaller 44 μm particles but not the 420 μm powder. With particles coalescing on the bubble, the actual surface area exposed to the medium was reduced. Since it was not possible to diagnose and resolve this problem in the opaque HDPE bottles, it may explain the lower ion concentrations detected in the 44 μm samples compared to the 420 μm samples. However, the concentrations of chromium were below the detection limit (0.1139 ppm) for both powder sizes, which was contrary to the findings of Experiment 4. This could be due to the use of only one sample in Experiment 4 with these mass and pH conditions.

FIGURE 17: Graph of chromium and cobalt concentrations found in Experiment 5. Detection limits for each element are shown in red (Cr: 0.1139, Co: 0.0217).

2.5 EXPERIMENT 6: CONFIRMATION OF METHOD VALIDITY

Given the results of Experiment 5, Experiment 6 was needed to isolate the conditions that would generate the most corrosion, which was the intention of Experiment 4. However, more samples would be prepared per condition to allow for a statistical analysis of the results. The sample size was established with a power analysis of the results from Experiment 5. The power analysis is based on an estimate of the difference between average ion concentrations of the two sample populations (420 μm and 44 μm) but the difference found in Experiment 5 was not expected and was potentially an incorrect estimate of the true difference. Despite this, a power analysis based on these results was the best option to estimate sample size. Each element's concentrations were analyzed separately to achieve 80% power at a 5% significance criterion. Chromium was found to require three samples per condition and cobalt was found to require four samples per condition. Ultimately, it was decided that a sample size of three per condition was adequate.

The treatment variables tested were mass loading (1.0, 2.0, and 3.0 g/L), pH (pH 7.2 and 4), and powder size (420 μm and 44 μm), which resulted in 12 unique conditions. These conditions were tested in smaller glass vials rather than HDPE bottles. This reduced the powder and medium needed per container, increased capacity in the incubating shaker, and most importantly, permitted a visual inspection of the container contents. When capping the vials, it was observed that some of the 44 μm particles were adhering to tiny air bubbles trapped inside the vial. However, this was easily remedied by vigorously shaking the vial until the particles were knocked off the bubble. Because

the powder would settle to the bottom of the vial and the bubbles would float to the top, further interaction in the incubating shaker was not a concern. Examination of the vial contents after the experiment revealed no interaction took place during agitation.

Experiment 6 data was analyzed by element and pH. All hypothesized trends were validated by cobalt analysis of the pH 7.2 samples (**Figure 18**). The data show a concentration increase with increasing mass loading, and with a decrease in powder size. A t-test was performed at each mass loading to find any statistically significant differences in cobalt concentration between powder sizes. Such a difference was only found at the 3.0 g/L loading ($p < 0.05$). However, chromium analysis of the pH 7.2 samples revealed no detectable levels of corrosion (**Figure 19**). Cobalt analysis of the pH4 sample measurements revealed unexpected trends. Although the pH 4 solutions contained more cobalt ions in each treatment condition, increasing mass loadings of the 44 μm samples did not correlate with increasing cobalt content (**Figure 20**). Furthermore, at 2.0 g/L and 3.0 g/L loadings, the 420 μm samples had higher cobalt concentrations than the 44 μm samples, which was reminiscent of Experiment 5. For chromium in the pH 4 samples, only one (420 μm at 3.0g/L) was recorded above the detection limit (**Figure 21**). All control solutions were below detection limits for both elements.

FIGURE 18: Comparison of cobalt concentrations versus mass loading and powder size at pH 7.2. Detection limit for cobalt (0.0024 ppm) is shown in red. Ion concentration increased as mass loading increased and particle diameter decreased.

FIGURE 19: Comparison of chromium concentrations by mass loading and particle size in pH 7.2 medium. All measurements were below the chromium detection limit (0.0228 ppm) shown in red.

FIGURE 20: Comparison of cobalt concentrations for three mass loadings and two powder sizes in pH 4 medium. All sample concentrations were found to be above the detection limit (red) but did not follow hypothesized trends. One replicate from the 44 μm samples at 1.0 g/L was rejected as an outlier with Dixon's Q-test at 99% confidence. The outlier had a concentration of 0.09980 ppm whereas the other two were measured as 0.02380 and 0.02386 ppm.

FIGURE 21: Comparison of chromium concentrations across different mass loadings and particles diameters in pH 4 medium. Only the 3.0 g/L mass loading resulted in chromium content above the detection limit (red).

Although the hypothesized trends were not observed in the pH 4 samples, the method was sufficiently validated with the pH 7.2 data set. Some of the pH 4 solutions exhibited higher concentrations with the 420 μm particles compared to the 44 μm but particle aggregation was ruled out with visual inspection. Thus, the cause for this behavior remains unclear. More research would be needed to deduce the cause because an acidic environment is relevant to localized situations within the body. However, because a neutral environment is more clinically relevant to what wear particles experience, and the hypotheses regarding corrosion behavior were proven to be correct in this environment, the method was considered valid.

2.6 SUMMARY OF KEY METHOD IMPROVEMENTS

The successful validation of this method was dependent upon several essential issues. First, the accurate preparation of calibration standards will dictate the accuracy of elemental measurements. Minimizing the introduction of errors may be accomplished by properly cleaning all glassware, using purchased standards, and matching standard and test solution matrices as closely as possible. Second, any particles agglomerated on bubbles could be found when optically clear glass vials were used. The aggregation of particles reduced the effective surface area exposed to medium, which resulted in lower amounts of corrosion. However, the vials could be shaken to break the aggregates. Finally, the use of an ICP-OES granted more sensitivity than an AAS. This was critical for Experiment 6 because several of the lower mass

samples registered concentrations below the cobalt detection limit of the AAS. These improvements contributed greatly to the current method.

2.7 EXPERIMENT 7: ASCERTAINING POWDER CORROSION RATE

With the method validated, an experiment to determine the corrosion rate was undertaken. This required periodic extraction of solution and since the rate was believed to be initially higher and taper off over the 42 day period, more sampling was performed over the first seven days. A schedule of the 11 extraction time points is shown in **Table 5**.

TABLE 5: Experiment 7 Exposure Durations

Time (days)	0.25	0.5	1.08	2.08	4.0	7.04	14.17	21.96	28.0	35.7	42.0
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To remain relevant to implant conditions, only medium at pH 7.2 was used. At this pH, a mass loading of 3.0 g/L was chosen as it produced the most corrosion in Experiment 6. Using this data, the number of replicates was calculated with a power analysis of the cobalt ion concentrations for both sizes. Though the power analysis only called for two replicates to yield 96.6% statistical power, three replicates were employed per exposure duration in case a sample became compromised. The last major change made was the inclusion of two additional powder sizes: 105 μm and 74 μm . These sizes provided additional data for trend comparisons. Thus, each time point contained three replicates of each powder size.

It should be noted that chromium ions have not been detected in any previous experiments with a pH 7.2 environment and were not expected to be detected in Experiment 7. The absence of chromium ions within the samples is surprising because both cobalt and chromium ions are detected in patients with artificial hip replacements (Heisel, Streich, Krachler, Jakubowitz, & Kretzer, 2008). However, in a study performed by Haynes, Crotti, and Haywood (2000), chromium was not detected in significant amounts. The authors suggested this occurs because chromium “is associated with forming the passivating layer” (Haynes, Crotti, & Haywood, 2000). Chromium is a common alloying element because of its ability to provide an adherent oxide layer and the oxide layer is most likely damaged in third body wearing between the articulating components, which could generate chromium-containing oxide particles. The particles’ oxide layers were not subject to any mechanical damage in previous experiments, which potentially explains why chromium is found within patients but is not found in these pH neutral *in vitro* experiments.

3. RESULTS

3.1 OVERVIEW OF OBJECTIVES

In order to understand the corrosion dynamics of cobalt-chromium alloy F-75 powder, the following objectives were stipulated for this thesis:

1. Adapt a method to repeatably corrode cobalt-chromium powders of differing particle sizes (44, 74, 105, and 420 μm).
2. Determine the solution concentrations of cobalt and chromium after powder exposure to media that simulate human bodily fluids.
3. Explain and model *in vitro* corrosion rate as a function of particle diameter and exposure duration.

3.2 METHOD REPEATABILITY AND REPRODUCIBILITY

The repeatability and reproducibility of the method used in Experiment 7 was assessed. Repeatability was defined as the precision of the ion concentration measurements between the three replicates for each of the 44 combinations of powder size and exposure duration. Because each replicate vial was independently prepared, the similarity between replicate vials was a measure of the procedure's consistency. The percent relative standard deviation (%RSD) may be used as a metric for precision. Lower %RSD indicates procedural consistency. It should be noted that the %RSDs were calculated using cobalt measurements because chromium was not detected in either this or any previous experiments. For each exposure duration and powder size, the %RSDs between replicates ranged from 0.28% to 27.85% (**Figure 22**). Generally, the 74 μm

samples had the highest %RSDs while the 44 μm and 105 μm samples had the lowest %RSDs.

FIGURE 22: Comparison of repeatability (%RSD) in cobalt measurements between triplicate samples for each powder size in Experiment 7. Average values computed from all time points for each size. In general, the 105 μm and 44 μm samples had the lowest deviations between replicate samples, while the 74 μm samples had the most variability between replicates.

Method reproducibility was evaluated between independent experiments. The conditions in common between Experiment 6 and 7 were 420 μm and 44 μm powders loaded at 3.0 g/L in pH 7.2 medium for 42 days. A comparison of each particle size exposed to these conditions in Experiments 6 and 7 revealed no significant difference (p-value = 0.4167 for 420 μm and 0.2692 for 44 μm) in cobalt concentrations (**Figure 23**).

FIGURE 23: Comparison of samples under identical conditions in two independent experiments. Left columns are data from Experiment 6 and right columns are data from Experiment 7. Two powder sizes were used in both experiments and subjected to HBSS for 42 days. Both experiments produced similar amounts of corrosion for each powder size (p-value > 0.05).

3.3 ACCURACY AND PRECISION OF ELEMENTAL ANALYSIS

The validity of the elemental analysis can be evaluated through its accuracy and precision. The accuracy was determined through calibration checks to verify that the instrument was correctly measuring elemental concentrations. In Experiment 7, the degree of error ranged from 0.64% to 1.98% (**Table 6**). The average error can thus be quantified as 1.25% with a standard deviation of 0.55%. Based on ICP-OES measurements of these checks throughout Experiment 7, the instrument had moderate accuracy.

TABLE 6: Comparison of Known Standards to Measured Concentrations in Experiment 7

Calibration Standard	Mean Cobalt (ppm)	Mean Chromium (ppm)	% Error
0.0999 ppm Co (0 ppm Cr)	0.0986	-0.0011	-1.26
	0.0981	0.0000	-1.80
	0.0988	0.0008	-1.10

	0.0979	0.0003	-1.98
	0.0993	-0.0014	-0.64
0.1000 ppm Cr (0 ppm Co)	0.0001	0.1007	0.72

The precision of measurements was again assessed using %RSD. In this case, the %RSD reflected the precision of the instrument's three replicate measurements for each sample. Only the %RSD of cobalt measurements was used to gauge instrument precision because chromium was not detected in either Experiment 6 or 7. The average %RSD in Experiment 6 and 7 was almost identical. In Experiment 6, an average sample had a %RSD of 1.67% with a standard deviation of 1.18%, whereas the measurements in Experiment 7 averaged a %RSD of 1.66% with a standard deviation of 1.20% (**Figure 24**). This indicated that measurement precision in both experiments was moderate.

FIGURE 24: Comparison of average measurement precision for each sample in Experiments 6 and 7. Each sample was measured three times in sequence. Average %RSD and standard deviation in both experiments are similar.

3.4 CORROSION RATE AS A FUNCTION OF PARTICLE SIZE AND TIME

The periodic extractions in Experiment 7 were designed to capture sample concentrations at different durations of powder exposure to medium. However, it was found that chromium concentrations were below the detection limit, which was also the case for pH 7.2 samples in Experiment 6. A discussion regarding the lack of chromium present was presented in Section 2.7. Thus, only cobalt measurements were plotted for each powder size and exposure duration (**Figure 25**). A data point was added at 10^{-7} days and 0.0024 ppm Co to represent the initial conditions, at which the concentration would correspond to the detection limit of the ICP-OES.

FIGURE 25: Comparison of cobalt concentrations over exposure time for each powder size. A data point corresponding to initial conditions was added at 10^{-7} days and 0.0024 ppm Co. The 44 μm and 105 μm samples produced the two highest amounts of corrosion.

Three observations can be made regarding the data gathered from Experiment 7.

First, the 74 μm particles exhibited a pattern of corrosion inconsistent with the other

three particles sizes. In the 420 μm , 105 μm , and 44 μm samples, the corrosion appeared to slow down after four days of exposure and level out. In the 74 μm samples, the cobalt concentrations increased erratically over time without any clear trend. The 74 μm samples also had poor repeatability as shown in Section 3.2. Based on the sieve analysis provided by the manufacturer of the 74 and 105 μm powders, a majority of the 74 μm powder was comprised of particles smaller in diameter than the particles from the 105 μm powder (**Figure 26**). Given this, it was expected that the 74 μm powder would produce slightly more corrosion than the 105 μm powder. Additionally, the preparation of the 74 μm samples was identical to the preparation of the other powder samples. No irregularities were observed at any procedure during the experiment. However, the large deviations throughout the 74 μm samples compared to the other powder sizes indicate that further procedural refinement is possible. Consequently, more refined experimentation with the 74 μm powder would be needed to confirm the behavior of this powder in Experiment 7. These facts resulted in the justified removal of the 74 μm data set. The data for the remaining three powder sizes was fitted with logarithmic curves (**Figure 27**).

FIGURE 26: Size distribution of particles from “74” and “105” μm powders. The majority of particles from the 74 μm powder were smaller than the 105 μm powder particles.

The second observation was that the amount of corrosion was dependent on the exposure time. Initially, the amount of corrosion increased rapidly and then, after about four days, the amount of corrosion reached an asymptotic limit over the remaining exposure durations. Finally, the third observation was that the amount of corrosion varied between particle sizes. When considering the concentration at which the asymptotic behavior occurs, cobalt content increased as particle size decreased.

FIGURE 27: Logarithmic curve fit of 44, 105, and 420 μm powder corrosion data at sampled intervals from Experiment 7. All three powder sizes exhibit similar corrosion behavior with respect to time; cobalt concentrations increase rapidly and reach an upper limit after the initial corrosion. This limit increases as particle size decreases.

Each of the logarithmic fit equations was differentiated with respect to time to obtain an equation for the corrosion rate of each powder size. This equation was then used to determine the instantaneous corrosion rate over the exposure duration (**Figure 28**). The instantaneous rate decreased within four days to low levels for the remainder of Experiment 7.

FIGURE 28: Corrosion rates calculated from derivative of logarithmic regression equations. The rates decreased over the first four days of exposure and remained at low levels for the remainder of the experiment.

4. DISCUSSION

4.1 REVIEW OF OBJECTIVES

The aim of this project was to examine the corrosion dynamics of cobalt-chromium alloy F-75 powder. The specific objectives were to:

1. Adapt a method to repeatably corrode cobalt-chromium powders of differing particle sizes (44, 74, 105, and 420 μm).
2. Determine the solution concentrations of cobalt and chromium after powder exposure to media that simulate human bodily fluids.
3. Explain and model *in vitro* corrosion rate as a function of particle diameter and exposure duration.

4.2 METHOD REPEATABILITY AND REPRODUCIBILITY

Method repeatability was assessed through a comparison of measurements from each condition's three independent vial replicates and reproducibility was assessed by comparing identical conditions between independent experiments. Each condition was evaluated by the percent relative standard deviation (%RSD) of cobalt measurements between its three replicates to determine how closely each replicate resembled each other. Ideally, this value should be low, which would indicate a high degree of precision in sample preparation. By comparing differences in identical conditions between experiments, the ability of the method to duplicate results can be gauged. Establishing the repeatability and reproducibility of this method is necessary for validating the collected data.

It was found in Experiment 7 that the %RSD varied substantially between particle size and exposure durations. The %RSD ranged from 0.28% to 27.85% across all samples. However, all six deviations over 16% originated from the 74 μm exposure durations. The 420 μm samples ranked as the second least repeatable powder size. Five of the 420 μm exposure times had double digit %RSDs whereas the 44 μm and 105 μm each only had one such time point. It was also found that identical conditions in Experiments 6 and 7 yielded cobalt measurements that were not statistically different. This implied that the method was executed consistently enough to reproduce similar results in replicate vials and separate tests.

There are three factors that contributed to deviations between the triplicate samples prepared for each condition. First, the mass loading for each vial was specified as 66 mg $\pm$ 1 mg. This means that any two vials could have a mass difference up to 2 mg, which would lead to differences in cobalt levels. Second, there is a range of particle diameters and each powder size label was the nominal particle diameter for that powder. According to Midander, Pan, and Leygraf (2005), a “relatively non-representative particle size distribution within the sample relative to the bulk powder” may result in “increased deviations from the normal release rates.” In other words, no two vials would have the same proportions of the various particle sizes when the powders were distributed. Theoretically, particles of differing diameters would generate different amounts of corrosion under the same conditions. Therefore, the varying proportions of particle sizes in each vial would lead to differing amounts of

corrosion between each of the three “identical” replicate samples. This could potentially explain the large variations in the 74 μm powder samples because it had a larger range of particle sizes than the 105 μm samples (62 – 149 μm compared to 88 – 149 μm). Furthermore, this problem may have been exacerbated by the weighing procedure. Powders were poured into weighing trays and the tray was held at an angle over a vial that was zeroed on the scale. The trays were gently tapped to induce small amounts of the powder to fall into the vial until the desired mass was reached. Though providing consistent sample masses, this procedure likely resulted in particle segregation, which “takes place as fine particles settle down through the spaces formed between larger particles”(Nushart, 2002). Since the 74 μm powder had a wider range of particle sizes compared to the 105 μm powder, this effect would be more pronounced, which would introduce more error.

Third, some vials had incomplete or failed seals, which led to contamination of the medium with the surrounding incubating water. These vials would then have diluted metal concentrations in the medium. However, after elemental analysis, only one vial had a significantly lower concentration from the other two replicates. Thus, the vials with failed seals were included in the data set to increase statistical power. In the future, a tighter tolerance to the target mass loading, a narrower range of particle sizes within a powder, and better containment would be needed to ensure better repeatability between replicate samples. Despite these shortcomings, the reproducibility between replicate samples was acceptable. Additionally, similar results were produced from two

independent experiments. This demonstrated that a reliable method was achieved and can be used to corrode powders containing particles ranging from 44 μm to 420 μm .

4.3 ACCURACY AND PRECISION OF ELEMENTAL ANALYSIS

The accuracy and precision of the elemental analysis performed in Experiment 7 can be quantified to gauge the capabilities of the ICP-OES. The accuracy of this instrument was evaluated by its ability to correctly detect a solution with a known concentration of cobalt ions. It was quantified as an average percent error of 1.25%. The precision of the ICP-OES was assessed by the amount of deviation (%RSD) between the three repeated measurements it performs for each sample. This was quantified as an average %RSD of 1.66%. This means that the measurements made by the ICP-OES were within 1.25% of the true concentration and could be repeated to within 1.66%.

The degree of accuracy attained by the ICP-OES is predicated upon proper configuration of the instrument's settings, sample content, and calibration. According to Olesik (1991) and Doyle (2008), factors that influence accuracy include "Relative Intensity of the line (target wavelength), accuracy of the element map, interferences from nearby lines, the sample matrix, and background elements." In regards to instrument configuration, this means that selectively detecting the highest Relative Intensity (brightest) wavelengths, correctly defining the background correction with the element map (**Figure 15**), and excluding the detection of nearby wavelengths to avoid spectral interferences (Gaines) will allow for more accurate measurements. The software for this ICP-OES made this simple and straightforward. With respect to sample preparation,

care should be taken to avoid the introduction of elements that may emit photons of similar wavelengths to the target element. Since only a few milliliters of the sample are needed to make measurements, it must be homogenous so that results are representative of the sample. Because the uptake system of the ICP-OES is easily clogged by particulates, which would alter the homogeneity of future measurements, samples must be filtered. Another factor affecting measurement accuracy is the use of calibration solutions. Assuming they are prepared correctly, accuracy can be improved if the concentration range of the calibration solutions is slightly wider than that of the samples (Doyle, 2008). By analyzing several unknown samples, a rough range of expected concentrations can be obtained and the instrument can then be calibrated with standards that cover this range so that the most accurate measurements can be made. After accounting for all of these factors, the ICP-OES should produce measurements that deviate no more than 2% from the true concentration every hour (Doyle, 2008). The calibration checks concurred with this claim and measurements were accurate to within 2%.

The precision afforded by the ICP-OES may be attributed to the refined state of the entire system. According to Doyle (2008), the Thermo Scientific ICP-OES system has improved to the point that the largest contribution of inconsistency stems from the initial sample uptake system. Deviations are introduced as the peristaltic pump pulsates the sample along the uptake tube, which results in an inconsistent flow (Gaines). Even with this variation, the three measurements per sample can be expected to deviate from

each other no more than 2% (Doyle, 2008). According to Olesik (1991), the ICP-OES is capable of precision between 0.5% and 5%. Another study states an acceptable %RSD for ICP-OES ranges from 0.5% to 2.5% (McKinstry, Indyk, & Kim, 1999). This was demonstrated in Experiment 7 as the RSD between measurements was found to be 1.66%. Thus, the accuracy and precision of the measurements performed in Experiment 7 were within the range of values expected from the ICP-OES.

4.4 CORROSION RATE AS A FUNCTION OF EXPOSURE DURATION AND PARTICLE DIAMETER

The periodic extractions from Experiment 7 were used to estimate the corrosion rates for four powder sizes at different exposure durations. There were three qualitative observations from this data (**Figure 25**). First, the 74 μm samples corroded in a manner unlike the three other powder sizes. The corrosion detected from this powder increased erratically without any signs of leveling out whereas the other three powders increased rapidly after exposure and released fewer cobalt ions after an initial period. After the 74 μm data was considered invalid, it was removed and the remaining data was fitted with logarithmic regression curves (**Figure 27**). Second, the corrosion produced was found to vary non-linearly over time. More specifically, corrosion increased quickly over the initial four days of exposure but began to reach an asymptotic limit as exposure time increased. Third, the amount of corrosion produced was also dependent on particle diameter. Based on the limit at which the 44, 105, and 420 μm powders displayed asymptotic behavior, the 44 μm samples produced the highest corrosion, followed by the 105 and 420 μm samples.

Instantaneous corrosion rates were derived from the logarithmic regression of the data (**Figure 28**). It was shown that the 44 μm samples had the highest rate and was followed by the 105 and 420 μm samples. For all sizes, most of the corrosion occurred within the first four days of exposure.

4.4.1 CORROSION AS A FUNCTION OF EXPOSURE DURATION

The corrosion behavior of the powders was modeled using logarithmic regressions of the data. The equations for the curve fits in **Figure 27** and their derivatives in **Figure 28** can be generalized into the following forms for cobalt concentration (Eq. 6) and corrosion rate (Eq. 7), where t is in units of days. The constants A and B will be discussed in section 4.4.2. These equations describe the corrosion behavior of the powders as initially rapid but reaching an asymptotic limit with increasing exposure time.

$$C_{Co} = A \ln(t) + B \quad (\text{Eq. 6})$$

$$\frac{dC_{Co}}{dt} = \frac{A}{t} \quad (\text{Eq. 7})$$

This corrosion behavior exhibited in Experiment 7 was similarly observed in an external study. Haynes, Crotti, and Haywood (2000) found that the cobalt release rate from cobalt-chromium particles varying from 0.5 -3.0 μm (0.95 μm mode) also slowed after an initial period of relatively high corrosion (**Figure 29**). However, when particles ranging from 0.2 -0.5 μm (0.275 μm mode) were tested, the release of cobalt continually increased over time, which suggests that the corrosion behavior may accelerate as

particle size decreases rather than reach an asymptotic limit (**Figure 30**). Consequently, this observation may reduce the application of these equations.

FIGURE 29: Comparison of cobalt and chromium metal corrosion concentrations as a function of exposure duration from an external study of 0.5 -3.0 μm (0.95 μm mode) cobalt-chromium particles. This graph shows how the cobalt concentration in pH 7.2 medium decreases after the first hour of exposure regardless of the metal concentration in the medium. Source: (Haynes, Crotti, & Haywood, 2000).

FIGURE 30: Comparison of cobalt and chromium metal corrosion concentrations as a function of exposure duration from an external study of 0.2 -0.5 μm (0.275 μm mode) cobalt-chromium particles. This graph shows how, unlike the 0.5-3.0 μm particles, the cobalt concentration in the pH 7.2 medium continually increases over the entire exposure duration. Source: (Haynes, Crotti, & Haywood, 2000).

The dependence of corrosion on exposure duration may be explained by activation polarization, where corrosion becomes limited by the reaction rate. The decrease in corrosion after the initial four days of exposure may occur because the corrosion process has become activation polarized. According to Haynes, Crotti, and Haywood (2000), the particles generated *in vivo* will passivate when exposed to the new aqueous environment and results in a high metal release rate during this process. Once the particles have developed this layer, the corrosion rate becomes activation controlled, which means that further corrosion is limited by either the oxidation or reduction reaction. This occurs because the oxide layer prevents the diffusion of reactants to the base metal.

This explanation suggests that within a generally neutral environment such as the body, the particles generated from an implant will immediately corrode. Since the corrosion rate decreases as the particle passivates, the presence of passivated particles in the body may be less disconcerting. However, passivated particles may become agents for further third body wear with the articulating components, which would lead to the generation of fresh particles as well as mechanical damage to the passivated particles' oxide layer. Furthermore, when phagocytes attempt to consume these foreign bodies, the particles within the cell may be subjected to a pH 4.5 environment, which could induce enough corrosion to poison and kill the cell (Haynes, Crotti, & Haywood, 2000). Passivated particles that are consumed by phagocytes may also trigger an increase in bone resorbing cytokines such as IL-6 and prostaglandin E₂ (Haynes, Crotti, & Haywood, 2000). Consequently, the corrosion behavior of wear particles within the body remains a serious design consideration in future orthopaedic hip replacements.

4.4.2 CORROSION RATE AS A FUNCTION OF PARTICLE DIAMETER

As introduced earlier, the equations for the curve fits in **Figure 27** and their derivatives in **Figure 28** can be generalized for cobalt concentration (Eq. 6) and corrosion rate (Eq. 7), where t is in units of days. The constants A and B change with particle diameter and because particle diameter was the only parameter altered in Experiment 7, it can be reasoned that these constants are dependent on particle diameter or a function of particle diameter, such as surface area.

Mathematically, the constant A affects the “curvature” of the regression curve in Eq. 8 and B affects the displacement of the regression curve along the y-axis. As A increases, the steady state region of curve described by Eq. 6 changes from a negligible asymptotic corrosion rate to a more positive corrosion rate. Furthermore, the instantaneous corrosion rate described by Eq. 7 increases as A increases. As B increases, the curve defined by $A \ln(t)$ term shifts along the y-axis in the positive direction.

To empirically determine if any correlation between these constants and particle diameter exists, the values of these constants were plotted against their corresponding particle diameters and surface areas. The total powder surface area in a sample was estimated by calculating the product of the number of particles and the surface area per particle (Eq. 8, **Table 7**). The number of particles in a 66 mg sample was estimated by dividing the volume of metal by the volume per particle. The surface area of a particle was estimated by modeling the particle as smooth and round sphere with a diameter equal to the nominal particle size.

$$\text{Total Surface Area} = \frac{\text{Sample Mass (g)}}{\text{Metal Density} \left(\frac{\text{g}}{\text{m}^3} \right)} \times \frac{1 \text{ Particle}}{\text{Vol. (m}^3\text{)}} \times \frac{S.A. \left(\frac{4}{3} \pi r^2 \right)}{1 \text{ Particle}} \quad (\text{Eq. 8})$$

TABLE 7: Estimated Total Surface Area for 66 mg of Cobalt-Chromium Powder

Powder Size (μm)	Total Surface Area (cm^2)
420	1.14
105	4.55
44	10.09

While these estimates assume that all particles are of nominal size, this is not correct since there was a distribution of various sizes in each powder. There were

particles larger than the nominal diameter, which means the total surface area would actually be less. Furthermore, this calculation does not account for the reduction in exposed surface area due to contact with the vial and other particles. Since the particles were too large to remain suspended in solution, they settled onto the vial wall and upon neighboring particles. The agitation provided by the shaker plate should allow a given particle's surface to be intermittently exposed to solution for most of test duration but there will still be contact area losses. Although these values overestimate the true exposed area, they are the best estimate available.

Both A and B showed a strong negative linear correlation with particle diameter (**Figure 31** and **Figure 32**). Both A and B also showed a strong positive logarithmic correlation with total exposed surface area (**Figure 33** and **Figure 34**). This implies that as particle size decreases or as surface area increases, both A and B will increase, which increases the corrosion rate and positively shifts the curve up the cobalt concentration axis.

FIGURE 31: Plot of modeled constant A against particle diameter. A strong negative linear correlation is observed between A and particle diameter.

FIGURE 32: Plot of modeled constant B against particle diameter. A strong negative linear correlation is observed between B and particle diameter.

FIGURE 33: Plot of modeled constant A against total sample surface area. A strong logarithmic correlation is observed between A and total sample surface area.

FIGURE 34: Plot of modeled constant B against total sample surface area. A strong logarithmic correlation is observed between B and total sample surface area.

The empirical relationships for cobalt concentration and corrosion rate may then be expressed in terms of particle diameter (Eq. 9 and 10) or total surface area (Eq. 11 and 12), where D is in μm and SA is in cm^2 . These relationships provide a means of

modeling cobalt concentration and corrosion rate given particle diameters or sample surface areas.

$$C_{Co} = [\ln(t)][-4 \times 10^{-6}D + 0.0031] - 8 \times 10^{-5}D + 0.0566 \quad (Eq. 9)$$

$$\frac{dC_{Co}}{dt} = \frac{-4 \times 10^{-6}D + .0031}{t} \quad (Eq. 10)$$

$$C_{Co} = [\ln(t)][0.0007 \ln(SA) + .0015] + .0144 \ln(SA) + 0.0224 \quad (Eq. 11)$$

$$\frac{dC_{Co}}{dt} = \frac{0.0007 \ln(SA) + 0.0015}{t} \quad (Eq. 12)$$

The increase in corrosion rate as particle diameter decreased appears to be linked to an increase in surface area. The rate of any reaction between reactants in different phases is dependent on the interfacial area between the reactants. According to collision theory, the larger this interfacial area, the more likely reactants would collide with each other and execute the reaction. Therefore, a sample with more cobalt-chromium powder surface exposed to the medium will result in a higher corrosion rate. Each vial had similar masses of powder, which means that samples of smaller particles had a total surface area larger than samples with larger diameter particles (**Table 7**). This implies that samples of the smaller powders would corrode more than the larger powders. As predicted, the levels of cobalt ions measured increased as the particle diameter decreased.

Haynes, Crotti, and Haywood's (2000) study of cobalt-chromium particles found higher levels of cobalt release with samples containing 0.2 – 0.5 μm (0.275 μm mode)

diameter particles when compared to samples of 0.5 – 3.0 μm (0.95 μm mode) diameter particles, which they attributed to the increase in surface area. Comparison of the results from Experiment 7 to the study performed by Haynes, Crotti, and Haywood (2000) clearly demonstrates the effect of particle diameter on corrosion behavior. A direct comparison of the cobalt ion concentrations after 28 days is difficult because both the 0.95 μm and 0.275 μm samples continually corroded even after a high initial rate. However, if compared after one day of exposure, where the corrosion behavior has not yet become steady-state, it can be observed that compared to the 44 μm samples, the 0.95 μm samples had at least four times more cobalt ions and the 0.275 μm samples produced at least 10 times more cobalt ions (Figure 35). Because of the differences in steady-state behavior between the 44-420 μm and 0.275-0.95 μm particles, this only qualitatively illustrates how decreasing particle diameters results in higher corrosion rates.

FIGURE 35: Comparison of 420 and 44 μm powder to an external study (Haynes, Crotti, & Haywood, 2000), where 0.95 and 0.275 μm particle results are included. External values were estimated from charts in the authors' paper. As particle size decreases, there is a dramatic

increase in corrosion. The 0.275 μm particles released over 10 times more cobalt ions than the 44 μm samples. This comparison does not account for the difference in particle mass concentration between the two studies.

Another important factor to consider when making this comparison is the mass loading utilized. Recall for Experiment 7 that the mass loading was 3.0 mg/mL, whereas Haynes, Crotti, and Haywood (2000) used a loading of 26.9 $\mu\text{g/mL}$, which is approximately 112 times less mass per unit volume. If the cobalt concentrations are normalized by mass loading to allow for a direct comparison of data, the 0.95 μm samples could actually produce at least 448 times more corrosion than the 44 μm samples and the 0.275 μm samples could produce at least 1120 times more. This further highlights the effect that decreasing particle diameter has on corrosion rate and the significance of understanding the corrosion behavior of smaller wear particles.

The empirical equations found (Eq. 9-12) may be validated if they can predict the results from the study by Haynes, Crotti, and Haywood (2000). From their 0.275 μm data, the cobalt concentration measured after 28 days was 7.5 ppm Co. After scaling the mass loading up from 26.9 $\mu\text{g/mL}$ to 3000 $\mu\text{g/mL}$, the concentration is 836 ppm Co. However, using Eq. 11, the predicted cobalt concentration for 0.275 μm particles after 28 days of exposure is only 0.067 ppm Co. This means that the equations significantly underestimate the corrosion produced at particle diameters below 44 μm .

This underestimation results from the difference in steady-state behavior between the 44-420 μm and 0.275-0.95 μm particles. As observed earlier, the 0.275-0.95 μm particles had a more positive steady-state corrosion rate whereas the particles from this study had a nearly negligible steady-state corrosion rate. Thus, the equations based

on the 44-420 μm particles would not reflect the behavior observed in the smaller particles. This limits the applicability of the empirical relationships for cobalt concentration and corrosion rate to particle diameters between 44-420 μm and total surface areas between 1.14 and 10.09 cm^2 .

5. CONCLUSIONS

Growing concerns regarding the potential health issues posed by the production of metallic wear debris from articulating joint replacements has prompted questions about this debris. Issues include the debris' impact on implant longevity, immunological response, and toxicity of corrosion products. The root cause of corrosion is a critical component of this last issue. The purpose of this research was to understand the corrosion behavior of cobalt-chromium alloy F-75 powder with respect to particle diameter and exposure time as a precursor to understanding the corrosion behavior of wear debris generated from metal-on-metal hip joint replacements. To achieve this, three goals were set:

1. Adapt a method to repeatably corrode cobalt-chromium powders of differing particle sizes (44, 74, 105, and 420 μm).
2. Determine the solution concentrations of cobalt and chromium after powder exposure to media that simulate human bodily fluids.
3. Explain and model *in vitro* corrosion rate as a function of particle diameter and exposure duration.

The first two goals were accomplished through an iterative process of experimentation and refinement. The methodology included weighing samples of cobalt-chromium powders (44, 74, 105, and 420 μm), immersing the powders in Hank's buffered saline solution at 37°C, filtering the particles from the solution, and measuring the cobalt and chromium ion concentrations with ICP-OES. Method repeatability was gauged by comparing the %RSD between the three sample replicates of each condition.

After eliminating the 74 μm data set, the remaining three powder sizes had average %RSDs below 10%. Though improvements to increase repeatability, such as utilizing better sample containment and more precise sample weighing, are still possible, the data gathered were acceptable. Moderately accurate and precise measurements were attained with the use of the ICP-OES, which allowed sample cobalt concentrations to be measured within 1.25% of the true value and with 1.66% precision between repeated measurements. With the method validated, results for the third objective could be obtained confidently.

From the results gathered, equations were developed to model cobalt concentration and corrosion rate as a function of time, and particle diameter or surface area (Eq. 9-12).

$$C_{Co} = [\ln(t)][-4 \times 10^{-6}D + 0.0031] - 8 \times 10^{-5}D + 0.0566 \quad (\text{Eq. 9})$$

$$\frac{dC_{Co}}{dt} = \frac{-4 \times 10^{-6}D + .0031}{t} \quad (\text{Eq. 10})$$

$$C_{Co} = [\ln(t)][0.0007 \ln(SA) + .0015] + .0144 \ln(SA) + 0.0224 \quad (\text{Eq. 11})$$

$$\frac{dC_{Co}}{dt} = \frac{0.0007 \ln(SA) + 0.0015}{t} \quad (\text{Eq. 12})$$

Two trends were observed from the data and these models. First, the particles studied initially corroded at relatively high rates until a passivation layer developed on the surface. The initial period of high corrosion occurred during the first day, after which the rate diminished until it reached an asymptotic limit at approximately four

days. The growth of an oxide layer over this initial period progressively slowed any corrosion processes and eventually leads to a less reactive particle surface. Second, corrosion rates are related to particle diameter. By comparing the total amount of corrosion generated, the cobalt ion concentration of the 44 μm powder was twice the concentration from the 420 μm samples. The disparity in corrosion between powder sizes was attributed to the increase in exposed surface area with decreasing particle diameter. However, when these equations were used to predict the outcome of an external study (Haynes, Crotti, & Haywood, 2000), the predictions underestimated the results found in this study.

These findings have significant implications for predicting the implications of wear particles within the body. First, although a majority of any wear particle corrosion takes place shortly after formation of the particle, damage to the body may continue in other forms, such as third body generation of fresh wear particles and a bone-resorbing immune response. Second, when the diameter approaches that of a wear particle, the surface area becomes very large and could result in large concentrations of metal ions within the body. Furthermore, the predictive capability of the aforementioned equations is not applicable towards the smaller wear particles. Consequently, the potential harm resulting from the corrosion of wear particles merits future research of wear particles and implant design consideration.

RECOMMENDATIONS

From the results of this study, there are two areas of research that may further the current understanding of how particles corrode within the body. First, a testing environment more representative bodily conditions could be utilized. Second, the testing of recovered or simulated wear debris from hip prostheses should be carried out to determine their corrosion behavior.

A more accurate recreation of the bodily processes that would influence corrosion behavior of the wear particles would provide more realistic data. The medium used for corrosion testing of the powders was a basic replication of bodily fluids. Fetal bovine serum has been used extensively to simulate synovial fluid and could be used to determine the effect of proteins on corrosion behavior. One concern for the use of fetal bovine serum is that it may foul over longer duration experiments. Another potential representation of the body could be the inclusion of cell cultures in the corrosion experiment to simulate the effect cell processes on debris corrosion.

Given the significant corrosion potential of nano-scale wear debris, studying the corrosion of such debris is another logical path. Handling this type of debris would require significant changes to sample preparation and extraction procedures. Obtaining particles of specific diameters involves the differential centrifugal separation of generated wear debris (Rogers, Percy, Hay, Haynes, Bramley, & Howie, 1993). Additional complexity arises when dealing with particles from periprosthetic tissues. Extra care must be taken to remove the attached proteins without damaging the

particles. To extract the media from the samples for elemental analysis also requires the use of an ultracentrifuge. This line of research is highly recommended because it is directly applicable to understanding wear debris corrosion.

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