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CORROSION BETWEEN ORTHODONTIC ARCHWIRES AND BRACKET COUPLES

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ABSTRACT

CORROSION BETWEEN ORTHODONTIC ARCHWIRES AND BRACKET COUPLES

Brian C. O'Leary, D.M.D.

Nickel-containing orthodontic wires have been reported to cause allergic reactions in sensitive individuals. However, stainless steel brackets also contain nickel and could potentially elicit a reaction. The ability of these metals to cause an allergic reaction is related to corrosion of the alloys and subsequent leaching of nickel ions into the oral cavity. The purpose of this study was to determine if there is a significant difference in the corrosive potential of stainless steel, NiTi and TMA wires either alone or when coupled with a stainless steel bracket.

At least two wires and bracket/wire combinations of each type were tested using potentiostatic anodic polarization. The samples were tested in 0.9% NaCl solution at room temperature with neutral pH. Using a Wenking MP 95 potentiostat, the breakdown potential for each sample was determined from constructed polarization curves. The potentiostat was connected to an electrochemical corrosion cell and data was collected using a computer and data acquisition program. The samples were visually analyzed for surface changes and photographs were taken.

The breakdown potentials of stainless steel ("A" Co.), NiTi (Ormco), TMA (Ormco), and the stainless steel bracket (Ormco) were 600 mv, 1600 mv, >2000 mv, and 200 mv respectively. When coupled with a stainless steel bracket, the breakdown potential for all three of the wire types was 200 mv. The breakdown potential of the stainless steel bracket overrode the potential for the wires themselves and the samples all broke down at the point where the bracket would have corroded by itself. The stainless steel brackets proved to be the weak ling in the galvanic couple with the three wire types and the brackets have a significantly higher corrosive potential than any of the wires themselves.

If a patient has a nickel allergy, the orthodontist would be wise to avoid the use of stainless steel brackets in addition to nickel containing archwires. TMA wires do not contain nickel and they have a very high resistance to corrosion. TMA wires would be an acceptable substitute for NiTi while ceramic brackets should be considered instead of stainless steel.

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CHAPTER I

INTRODUCTION

BACKGROUND

Orthodontic wires containing nickel have been implicated in allergic reactions. Nickel has been shown to be an allergen in certain individuals.[1] Sources that may provide nickel exposure include jewelry, food, environmental, occupational, and dental alloys.[2-14] With increased exposure to nickel comes a greater likelihood of developing an allergy. Individuals may become sensitized to nickel, which may lead to a subsequent allergic reaction.[2-14] In the field of dentistry, nickel containing alloys are commonly used. Recently, in orthodontics, with the advent of nickel-titanium wires, nickel-containing alloys are utilized much more frequently.[15] Introduced as Nitinol in the late 1970's and popularized as NiTi in the late 1980's, these "superelastic" archwires have become almost a standard element of the orthodontist's armamentarium. Stainless steel brackets and wires have been used for over a century in orthodontics and contain approximately 8% nickel. Case studies report hypersensitivity reactions to nickel, stimulated by the exposure to stainless steel orthodontic brackets.[12]

All metals will corrode in the proper environment. Nickel can be made available from alloys through leaching and corrosion.[9] The corroding of the metal is evidenced by surface changes such as discoloration and pitting.[16,17] After corrosion testing, the solution can be analyzed for the presence of ions.[18-20] The most common form of corrosion testing is called potentiostatic anodic polarization. This technique has been used for years to study the corrosive behavior of metals.[21-34] The test is electrochemical in nature and can determine when a sample has passed from a passive to an active state. This correlates with the breakdown of the passive layer and when corrosion of the sample begins.

Corrosion of biomaterials may release nickel to be absorbed by the body. The prolonged exposure to nickel alloys may lead to a sensitization to nickel. The ability of orthodontic brackets and wires to cause an allergic reaction is related to the pattern and mode of corrosion with subsequent release of nickel into the oral cavity. When unlike metals are placed in the same environment, a galvanic couple is created. Coupled corrosion may differ greatly from corrosion of an individual metal. When two dissimilar metals are in contact with each other, the more noble metal will behave in a cathodic manner.[35] The less noble metal in a coupled system will become the anode and corrode at an accelerated rate. Orthodontic treatment commonly employs the use of dissimilar metallic components in the same appliance. The corrosion resistance of stainless steel and other orthodontic metals is relatively good. However, these metal alloys are challenged by the hostile environment in the mouth, and are susceptible to localized corrosion in a low pH environment containing chloride ions.[35] Archwires and brackets used in orthodontics are commonly made of many different alloys. The corrosive potential that exists between archwires and brackets of various metal compositions has not been thoroughly investigated.

STATEMENT OF THE PROBLEM

Do nickel titanium (NiTi) archwires have a higher corrosive potential than stainless steel or titanium molybdenum alloy (TMA) wires when coupled with a stainless steel orthodontic bracket?

SIGNIFICANCE OF THE STUDY

Wires and appliances that contain nickel are used routinely in the practice of orthodontics. Nickel-titanium archwires and expansion appliances have an especially high content of nickel. Corrosion of these alloys releases nickel into the oral cavity and may contribute to the development of a nickel allergy or elicit an allergic response in certain predisposed individuals. The combination of archwires and stainless steel brackets produces a galvanic couple, which may enhance the corrosive potential of the dissimilar metals and could have very different corrosive characteristics than the single metal. By determining the corrosive potentials of commonly coupled orthodontic alloys, the clinician may be better prepared to select which brackets and archwires to use to avoid potential nickel allergy problems in particular patients.

HYPOTHESIS 1

There is a significant difference in the corrosive potential of stainless steel, NiTi, and TMA orthodontic archwires when tested using potentiostatic anodic polarization testing.

HYPOTHESIS 2

There is a significant difference in the corrosive potential of stainless steel, NiTi, and TMA orthodontic archwires when galvanically coupled with a stainless steel bracket using potentiostatic anodic polarization testing.

HYPOTHESIS 3

There is a significant difference in the corrosive potential of stainless steel, NiTi, and TMA orthodontic archwires when galvanically coupled with a stainless steel bracket versus the corrosive potential of the wire or bracket alone using potentiostatic anodic polarization testing.

SPECIFIC AIMS

The specific aims of this study are to:

1. Compare the breakdown potentials of stainless steel, NiTi, and TMA orthodontic archwires.
2. Compare the corrosive breakdown potential of stainless steel, NiTi, and TMA orthodontic archwires when galvanically coupled with a 0.22” slotted stainless steel bracket.

DEFINITION OF TERMS

Anode--the electrode of an electrolytic cell where oxidation occurs. Electrons flow away from the anode in an electric circuit.

Anodic dissolution--the transfer of metal ions into solution from the anode of an electrochemical cell when a potential is applied.

Anodic polarization--the change of the electrode potential in the positive or noble direction due to current flow.

Auxiliary or counter electrode--the electrode in an electrochemical cell that is used to transfer current to or from a test electrode. (Usually platinum)

Breakdown potential--the least noble potential where pitting, crevice corrosion, or both will initiate and propagate releasing metal ions. Characterized by a significant increase in current.

Cathode--the electrode of an electrochemical cell where reduction occurs.

Corrosion--the chemical or electrochemical reaction between a material, usually a metal, and its environment that produces a deterioration of the material and its properties.

Crevice corrosion--localized corrosion of a metal surface, at or immediately adjacent to, an area that is shielded from full exposure to environment because of close proximity between the metal and the surface of another material.

Current density--the electric current to or from a unit area of an electrode surface – units are typically mA/mm^2.

Electrochemical cell--an electrochemical system consisting of an anode and a cathode in metallic contact and immersed in an electrolyte.

External circuit--the wires, connectors, measuring devices, current sources, etc. that are used to bring about or measure the desired electrochemical conditions within the test cell.

Galvanic couple--a pair of dissimilar conductors, commonly metals in electric contact.

Internal Circuit--the working, counter, and reference electrodes immersed in the electrolyte.

Pitting--corrosion of a metal surface, confined to a point or small area, that takes the form of cavities.

Potentiostat--an instrument for automatically maintaining an electrode in an electrolyte at a constant potential or controlled potentials with respect to a suitable reference electrode.

Reference electrode--usually a saturated calomel electrode used as the reference potential of an electrochemical cell.

Working electrode--the test or specimen electrode in an electrochemical cell.

ASSUMPTIONS

Three assumptions form the basis of this study. The first is that the breakdown potential for the bracket, wires and combinations can be reached using potentiostatic anodic polarization testing. The second is that the wire and bracket combinations are consistent in their imperfections from one combination to another. Finally, the results of anodic polarization provide data relevant to corrosion of biomaterials.

LIMITATIONS

1. The environment of the oral cavity cannot be accurately duplicated in an in vitro study of this nature.

2. The corrosive potentials may fluctuate with changes in pH, temperature, percentage oxygen (pO_2), and percentage carbon dioxide (pCO_2).

DELIMITATIONS

1. A limited number of bracket and archwire combinations will be studied.
2. The testing solution will not be oxygenated.
3. The testing conditions will be maintained at neutral pH and room temperature.

CHAPTER II

REVIEW OF LITERATURE

Nickel can be found in all parts of the world and is the 24th most abundant element in the earth's crust. [2] Allergies to nickel are commonly seen and are more prevalent in women, causing allergic contact dermatitis.[1] Female predilection can be explained by the use of jewelry and in particular inexpensive costume jewelry. In the United States, the reported prevalence of nickel sensitivity ranges from 9.5% - 31.9% in females and 2% - 20.7% in males.[3-5,14,19] However in countries such as Nigeria, the prevalence of nickel allergies is equal between the sexes as a result of equal wearing of jewelry.[7]

The contact dermititis that results from a nickel allergy was originally associated with workers in the nickel industry and was referred to as "nickel itch". Clinical presentation was characterized by an itching or burning papular erythema. Another presentation is a papular or papulovesicular dermatitis with a propensity for lichenification.[8]

Allergies have appeared in dentistry and related fields with the use of nickel containing alloys and are sometimes associated with the oral lesions of lichen planus.[10] An allergic reaction to nickel-titanium orthodontic wire was reported in the late 1980's.[12] The patient reported a history of allergic reactions to jewelry and responded to the alloy after only a few days. The patient complained of a burning sensation of the oral mucosa and developed painful lesions within one month. Large erythematous macular lesions were seen throughout the mouth. After removal of the NiTi wire, complete healing occurred within four days.

It has been shown that the ability of a metal to cause an allergic reaction is related to the process of corrosion. Corrosion is seen in all base metals and is relatively high in nickel alloys.[9] When a nickel containing alloy corrodes it leaches nickel and may cause an allergic reaction in certain individuals.[8]

Corrosion is a very complex process that results in the deterioration of a metal by its reaction with the environment. The oral cavity is conducive to electrochemical or electrolytic corrosion due to its moisture content.[35] When a metal is placed in an aqueous solution it will be thermodynamically unstable if the tendency to pass from a solid state to an ionic form is associated with a decrease in energy. This direction of energy change can be influenced by many factors. They include: the metal, the surface morphology of the metal, composition of the solution, pH, temperature and other metals in the environment. As with all things in nature, equilibrium will attempt to be reached, by decreasing the energy of the system. The process will continue until this equilibrium is reached or the release of ions is prevented. A passivating film that coats a metal surface will prevent the metal from contacting the solution.[36-41] When ions are not released, then corrosion does not occur.

Corrosion testing can be performed in several ways. Simple observation of surface characteristics, such as pitting may be done using various forms of microscopy.[16-17] Another method to evaluate corrosion is to analyze the material and solution in which a corrosive potential has been created.[18-20] The standard testing technique uses a potentiostatic anodic polarization (PAP) device. P.A.P. has become the benchmark for measuring the corrosive behavior of metals.[21-34] P.A.P. techniques are the most commonly used electrochemical methods for quantifying corrosive characteristics of a metal. P.A.P. applies a potential to produce corrosion of a test sample. Polarization measurement using potentiostatic techniques have been shown to be valuable in characterizing, and quantifying active-passive systems. P.A.P techniques are able to detect the transition of a system from a passive state to an active state, or in other words, when corrosion begins.[31] The potentiostat is notable in that it maintains a constant potential of a specimen at a desired level by automatically altering the current flowing between the working electrode and a counter electrode to maintain the desired potential or voltage.[33] Initially, when the applied potential is low, the current is low. The current and voltage are recorded. The voltage is increased over time until the potential is sufficiently high to break down the passive layer and significantly increase the current. This is referred to as the “critical” or “breakdown” potential, and is typically accompanied by a release of oxygen from the surface film. With the data obtained, a potentiostatic polarization curve can be plotted and the breakdown potential can be determined.

Rostoker et al.[16] attempted to quantify surface irregularities by observing the surface of the metals using optical microscopy before and after testing. The samples were submerged in 1% saline solution at 37 degrees centigrade for up to 100 days without the use of applied potential. The samples were designed to simulate galvanic coupling and crevice conditions. The results of the study showed that no corrosion was visible on the Ti-6A1-4V when uncoupled, coupled with itself, or coupled with

316L stainless steel, cast Co-Cr-Mo, or graphite. In contrast, 316L stainless steel exhibited multiple areas of pitting in all tests. These results imply that the principles of galvanic corrosion apply and the lesser noble metal will have an increased corrosion potential.

A comparison study was performed by Edie et al.[17] to demonstrate the surface corrosion characteristics of nitinol and stainless steel orthodontic archwires after intraoral use and subsequent exposure to anodic dissolution. In this study, only the nitinol wires were subjected to anodic dissolution. The sample consisted of eleven nitinol and eleven stainless steel wires after being in clinical use from one to eight months. The used wires, unused portions of nitinol and stainless steel wires, and nitinol wires which had been subjected to anodic dissolution for two minutes, were mounted for SEM observation. The results of the study demonstrated that unused nitinol wire showed large variations in surface texture when compared to stainless steel. SEM studies showed no discernible differences in surface morphology between nitinol wires before and after anodic dissolution. No pits were observed on either nitinol or stainless steel wires after clinical use. The conclusion was drawn that there was no evidence to support that nitinol wires have a higher corrosive potential than stainless steel wires.   Other authors state that nitinol is more prone to corrosion than stainless steel.[22]

To test the effects of corrosion on mechanical properties, Harris et al.[43] attempted to simulate the oral environment by submerging nitinol wires in buffered solutions of 1% NaCl at pH 3, pH 5, and pH 7. Straight sections of 0.016” nitinol wire were used in templates that deflected the wires 0,1,2, and 4 mm. Twelve samples were tested initially with four lengths of wire placed on each template. The templates were incubated in the solutions for 1,2, and 4 months at 37 degrees C and tested at these intervals. The nickel content of the test solutions was not reported. Wires were placed in an Instron unit and tested for ultimate stress, ultimate strain, modulus of elasticity, and 0.3% yield strength. The results of the study showed that for the wires incubated in solution, there was a 10% reduction in 0.2% yield strength and a significant reduction in ultimate stress and modulus of elasticity. The magnitude of decrease was comparable to other studies which exposed wires to solutions of differing pH or amount of deflection.[42-43] It has been shown that the pH in plaque can be as low as 4 and salivary pH can be as high as 9.

Grimsdottir et al. measured the amount of nickel and chromium released from individual orthodontic appliances when submerged in a .9% NaCl solution for 14 days. The testing sample consisted of five sections of common face-bows along with five molar bands, brackets and archwires. The section of the face-bow was taken from the portion where the outer bow and inner bow were soldered together. The face-bow and wire samples were then cut to approximate the area ratio of a molar band. The samples were separately placed in 1 ml of 0.9% NaCl solution and incubated for 7 days at 23 degrees C. At this point, the samples were then placed into a fresh solution and the process was completed at 14 days. The solutions were then analyzed for Ni and Cr content using flameless atomic absorption spectrophotometry. Negligible amounts of nickel and chromium were released from the archwires while the largest amounts were released from the face-bows, particularly GAC's (10.4micrograms Ni and 13.9 micrograms Cr). The increased amount from the face-bows was explained by the inclusion of the solder joint. The silver solder and stainless steel wire created a galvanic couple, reducing corrosion resistance.[19]

Corrosion can theoretically have a large impact on the mechanical properties of a metal. Schwaninger et al. and Harris et al. attempted to study the effects of corrosion on the physical properties of a nitinol archwire.[42,43] Schwaninger used 1% NaCl solution to recreate the recommended conditions of Sarkar's report that Ringer's solution adequately represents the corrosive nature of saliva in conjunction with potentiostatic anodic polarization.[20] The sample consisted of sixty 0.016" nitinol wires. The samples were divided into six groups of ten wires each. The control group consisted of one-inch spans removed from each wire. The remaining wires were then incubated at 37 degrees C. The wire samples were removed every two months after the first month for a total period of 11 months. After completion, five wires were tested for flexural yield and modulus of stiffness. Five wires were subjected to 90-degree bend cycles to fatigue the wire. The control samples were also tested. SEM observation was then used to analyze the fractured surfaces of the fatigued wires to determine the mode of failure. The results showed no significant difference in physical properties of nitinol wire after in vitro corrosion of eleven months. The conclusion was drawn that the early failure of the wire was due to the presence of surface defects generated during the manufacturing process and not due to corrosion effects. The nickel content of the solutions was not reported in the study.

Kerosuo et al.[20] studied Ni and Cr release from orthodontic appliances using static and dynamic conditions. The orthodontic appliances used were a face-bow, a quad-helix and fixed appliances. A simulated dental quadrant was constructed from central incisor to first molar. Fixed appliances were placed using a first molar band and brackets on the second premolar to the central incisor. A 0.014” NiTi wire was tied to the brackets using stainless steel ligatures. The inside surface of the band and the bracket bases were covered with cold cure acrylic. The quad-helix was constructed of 0.036” stainless steel wire soldered to a molar band and the wire was cut to use only half of the appliance. Once again, only half of the face-bow was used and it consisted of half of the inner bow and a molar band. Five samples of each appliance were tested under static conditions and each appliance was placed in 15 ml of 0.9% NaCl solution and incubated at room temperature for 2 hours, 24 hours and 7 days. After each time interval, the samples were removed and placed in a fresh NaCl solution. The testing solution was then analyzed for Ni and Cr content using flameless atomic absorption spectrophotometry. For the fixed appliances placed on the dental quadrant, an “oral functioning simulator” was constructed to study the effects of movement on corrosion. The sample quadrant was alternated between movement and rest every other hour. The results of the static test showed that only the quad helix had significant amounts of Ni release during the first two hours. At 24 hours and 7 days, significantly less Ni was released from the quad-helix than from the fixed appliances or the face-bow. The amount of Ni released in 7 days from the fixed appliances under dynamic conditions was significantly higher than those in the static state. The amount of Cr released in 7 days was significantly lower and there was no significant difference in the Cr release between static and dynamic conditions.[20]

Sarkar et al. performed a study to compare the corrosion byproducts of amalgam subjected to potentiostatic anodic polarization and corrosion byproducts of forty year-old amalgam which had been in service intraorally. The fresh amalgam sample was tested in Ringer's solution using potentiostatic anodic polarization. The experiment demonstrated that the corrosion byproducts of the two amalgam samples were very closely matched.[21]

Park et al.[18] studied the corrosion effect of a simulated intraoral environment on orthodontic appliances and the release of nickel and chromium. A solution of 0.05% NaCl was used. Incubated bands and brackets that would be used on a quadrant of the mandibular arch were tested. Ten simulated orthodontic appliances were constructed using brackets for the canine and incisors, first and second premolar bands, and first and second molar bands. The bracket bases and internal surfaces of the bands were covered with cold cure acrylic resin. The bands and brackets were attached to an 0.019" x 0.025" x 2.8" stainless steel wire with elastomeric ties. Each of the samples was placed in its own poplyethelene bottle filled with the NaCl solution and incubated at 37 degrees Celsius. Samples of 4 ml were taken from each solution bottle on days 3,6,9, and 12 and the same amount of fresh solution was replaced. Using flameless atomic absorption spectrophotometry, the solution was tested for nickel and chromium content. At the completion of the 12 days, the precipitate from each bottle was collected by centrifugation and washed three times with 0.5% NaCl solution. The precipitate was dried overnight at 85 degrees Celsius and solubilized in nitric acid to enable testing. The results showed that three times more nickel than chromium was solubilized. After 12 days of testing the total amounts of soluble nickel and chromium were 121 micrograms and 40 micrograms respectively. The resulting average daily release was 40 micrograms of nickel and 36 micrograms of chromium. No NiTi wires were used in this experiment.[18]

Products have been manufactured which minimize the corrosive potentials of alloys commonly employed by the orthodontist. Nickel-titanium wires have been manufactured with nitride and epoxy coatings. Nitride coatings are used in orthodontics to increase the hardness of the archwire, while epoxy coatings provide an esthetic alternative to the standard orthodontic wires. The addition of these coatings may provide some form of corrosion resistance as an added benefit. Kim and Johnson[44] used potentiostatic anodic polarization to test the corrosive potential of various archwires. Corrosion occurred readily in stainless steel and in some nickel-titanium wires. The breakdown potential of nickel-titanium wires seemed to vary between manufacturers. Nitride coating did not affect the corrosion of the metal while epoxy coating decreased corrosion. TMA and epoxy coated nickel-titanium wires had the least corrosive potential. The breakdown potential of TMA wire could not be reached. TMA remained passive throughout the entire range of 2000 mV. The breakdown potential for nickel-titanium and stainless steel ranged from 300-750 mV.

Upon microscopic examination, Kim and Johnson found extensive pitting and localized corrosion on stainless steel, nickel-titanium, and nitride coated wires subjected to potentiostatic anodic polarization. All three types of wire showed significant changes in surface morphology following anodic dissolution. Using SEM photographs, epoxy coated nickel-titanium wires and TMA wires showed no detectable difference in surface morphology between wires exposed to potentiostatic anodic polarization and those that were not.

Potentiostatic anodic polarization technique is a commonly accepted method of performing corrosion testing. Several basic concepts must be understood and applied when performing this testing procedure. These concepts include corrosion, passivity, oxidation, kinetics and the oral environment. A metal can be described as being either active or passive with relation to its environment depending on the observed rate of corrosion. The use of potentiostatic anodic polarization will enable one to quantify active and passive systems and determine when a system changes from a passive to an active state. The transition correlates with the onset of the corrosive process of the metal.[31] Natural corrosion can be accurately duplicated using potentiostatic anodic polarization if the normal environment of the metal can be reproduced. The natural conditions should be duplicated as closely as possible when using this process. The physical state of the metal, and the solution environment, including aerated conditions are important factors.[30,32]

The American Society for Testing and Materials (ASTM) has a standard reference test for potentiostatic anodic polarization measurements. There are several elements required for making the measurements. These include an electrochemical corrosion sell, a data acquisition device, and a potentiostat. The corrosion cell is made up of a polarization cell and a reference cell connected by a salt bridge. The polarization cell contains the working electrode, the auxilliary or counter electrode, and a Luggin capillary probe for the salt bridge connection. The working electrode is the test specimen and the auxiliary electrode can be platinum or graphite. The reference cell holds the reference electrode, such as a saturated calomel electrode, and the tubing connection of the salt bridge. Wires connect the corrosion cell and the potentiostat.

The potentiostat is used for performing tests utilizing potentiostatic anodic polarization. The potential of a test sample is maintained at a desired level by the potentiostat. It monitors the potential between the working electrode and a reference electrode, and automatically alters the current between the working electrode and a counter electrode to maintain the desired potential.

CHAPTER III

METHODS AND MATERIALS

I. SAMPLE DESCRIPTION

The wire samples were obtained from three manufacturers (“A” Co., San Diego, California; Ormco Co., Glendora, California; and 3M Unitek, Monrovia, California). Round wires with a diameter of 0.016 inches were utilized. At least two samples of each type were tested (a third was tested if required) making a total of 24 samples that were tested for this study. Two different bracket types were utilized: Orthos stainless steel and Transcend ceramic (Ormco Co., Glendora, California). The Transcend caramic bracket has no metal slot.

A. Archwires used in this study

  1. 0.016” stainless steel (“A” Co.)
  2. 0.016” NiTi (Ormco)
  3. 0.016” titanium-molybdenum alloy (Ormco)
  4. 0.016” 24k gold plated stainless steel (Unitek)

B. Bracket used in this study

  1. Ormco Orthos stainless steel 0.022” slot: mandibular central incisor
  2. Ormco Ceramic bracket 0.022” slot: mandibular central incisor

The metal compositions of the samples are reported in Table 1 below.

	Ni	Cr	Fe	Ti	Sn	Zr	Mo
S.S. (“A” Co.)	**9%**	**18%**	**73%**				
NiTi (Ormco)	**55%**			**45%**			
TMA (Ormco)				**78%**	**4%**	**6%**	**11.5%**
S.S. Bracket (Ormco)	**14%**	**18%**	**65%**				**3%**

Table 1. Percentage by weight of element composition in test samples, (from manufacturers Material Safety Data Sheets).

C. Surface exposure of the alloys

1. A 30 mm length of archwire was exposed to anodic polarization with a calculated surface area of 0.38 cm^2.
2. The bracket face minus adhesive portion of the base was exposed to anodic dissolution. The posterior bracket base surface was protected with resin (acrylic fingernail polish). The calculated surface area was .35 cm^2. This was calculated manually by measuring individual parts of the bracket using electronic calipers to arrive at a sum surface area.

D. Preparation of the samples

1. The wire samples were measured from one end and marked so that 30 mm of the wire could then be placed in the solution accurately. All

samples were tested in the condition that they arrived from the manufacturer to simulate actual clinical use.

2. The bracket samples had to be attached to the end of a 0.30” stainless steel wire so that the current could be delivered to the sample when placed into the testing solution. This was accomplished by using a conducting metal paint (Ladd Industries, Burlington, Vermont) to join the adhesive base of the bracket to the carrier wire. After the two parts were bonded together, the back of the bracket and the length of wire were covered with resin (acrylic fingernail polish) to isolate the bracket face for the corrosion study.
3. The combined samples of brackets and wires were prepared by first cutting a 30mm length of wire and ligating it into the bracket slot by the use of an elastomeric tie (Ormco “O” tie). The bracket was then attached to the end of a stainless steel wire so that the current could be delivered to the area of interest when placed into the testing solution. This was accomplished the same way as the bracket samples in #2. To verify the methodology, an additional bracket/wire assembly was tested. The bracket was ligated to one of the stainless steel archwires by using an elastomeric tie and the mesh backing was covered with acrylic. Both the bracket and 30 mm of the archwire were submerged into the solution. The electrode was attached to the stainless steel wire as in #1.

II. RESEARCH DESIGN

Potentiostatic anodic polarization curves for wires, brackets and wire-bracket combinations were recorded using an electrochemical corrosion cell (Bank Elektroniks, Clausthal, Germany) with 0.9% NaCl solution (Baxter Healthcare Corp., Deerfield, Illinois). Photographs of the surface morphology using standard photography were made.

Each sample was tested as it arrived from the manufacturer to simulate normal use in a clinical orthodontic setting. The sample was then placed into the working electrode fixture and adjusted so that it was submerged in 900 ml of saline solution in the polarization cell. The tip of the Haber-Luggin probe was positioned approximately 2mm from the working electrode. All electrodes were then connected to the potentiostat at this point. Equilibration was then allowed for 60 minutes at room temperature. This allowed for the determination of a resting potential. At 60 minutes, potential and current density measurements were started and readings taken at intervals of one minute. At 65 minutes the potential was increased to 50 mV and subsequent steps will be 50 mV every 5 minutes. This process was continued until the breakdown potential for the sample, or until the 2000 mV potentiostat maximum was reached.

To verify testing accuracy as recommended by the American Society for Testing and Materials (ASTM), at least two samples each were tested. If one of a particular sample varied significantly, then a third sample was tested. Potentiostatic anodic polarization curves were constructed for each. The breakdown potential for each bracket/wire individual and coupled sample types was then determined from the polarization curves. This point was determined manually from the graphs by the ascending slope of the polarization curve and finding the corresponding millivolt value. The samples were then evaluated and photographed. To evaluate any confounding effects of crevice conditions, a stainless steel wire was tested when coupled with a ceramic bracket. Photographs of the alloys' surfaces were then taken using standard black and white photography to demonstrate the surface characteristics following potentiostatic anodic polarization.

A 24k gold-coated stainless steel wire from 3M Unitek was also tested. Additionally, the gold wire was scratched by using a slow speed handpiece with a heatless stone. This removed 2mm of the gold wire coating, exposing the underlying stainless steel. The scratched wire was tested using anodic polarization.

II. EQUIPMENT

The equipment needed for this research investigation was:

A. Wenking MP 95 potentiostat for anodic polarization (Bank Elektronik, Clausthal, Germany) (Figure 1).

B. Computer, screw board terminal (STP 37, Keithley Instruments, Tauton, Massachusetts), data acquisition board (DAS 1602, Keithley Instruments), and data acquisition program (CPC-RP potentiostat software, Bank Elektronik).

C. Zelledn electrochemical corrosion cell (Bank Elektronik) (Figure 2).

1. The polarization cell consists of a 1000 ml flask with a teflon lid. The lid has six holes, three of which will be closed with neoprene stoppers.

The remaining three holes hold glass fixtures that receive the working electrode (wire and bracket sample) fixture, the auxiliary or counter electrode (platinum foil), and a Haber-luggin probe. The working electrode fixture is constructed of glass tubing and teflon drilled with a small hole enabling wire samples to be held in place.

2. Reference cell with reference electrode (saturated calomel electrode, B3410, Schott Gerate, Hoffheim, Germany). The reference cell is connected to the polarization cell by way of an electrolyte (0.9% NaCl).

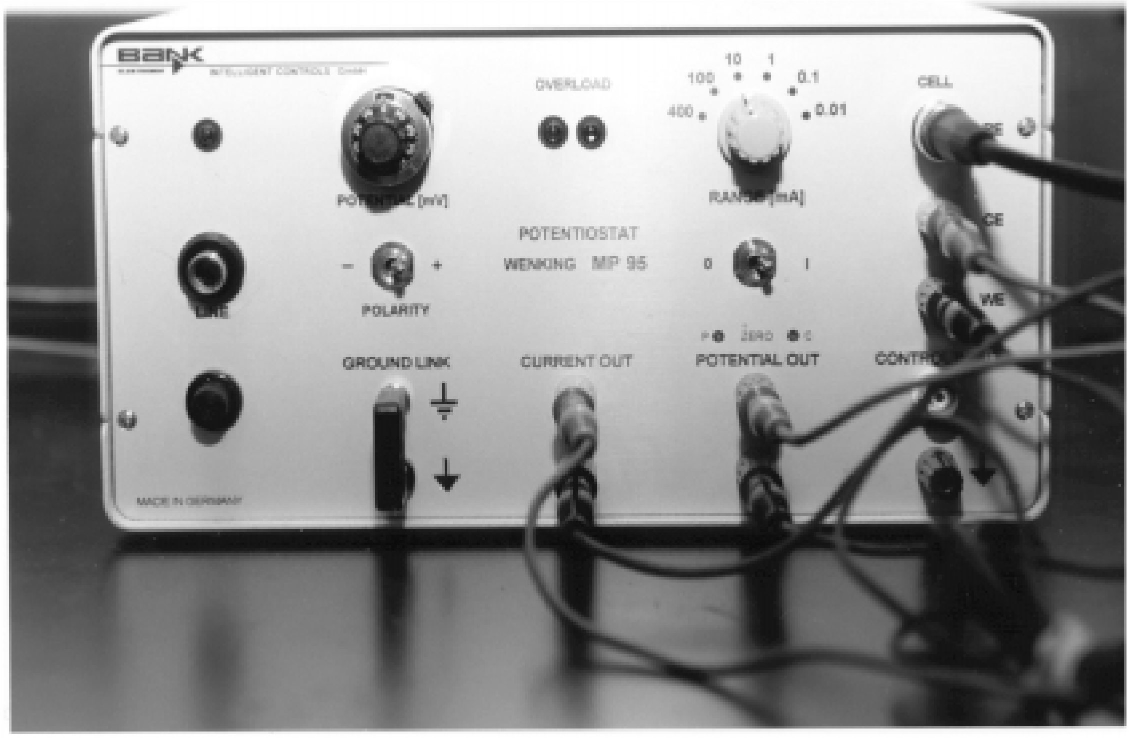

Figure 1. Potentiostat

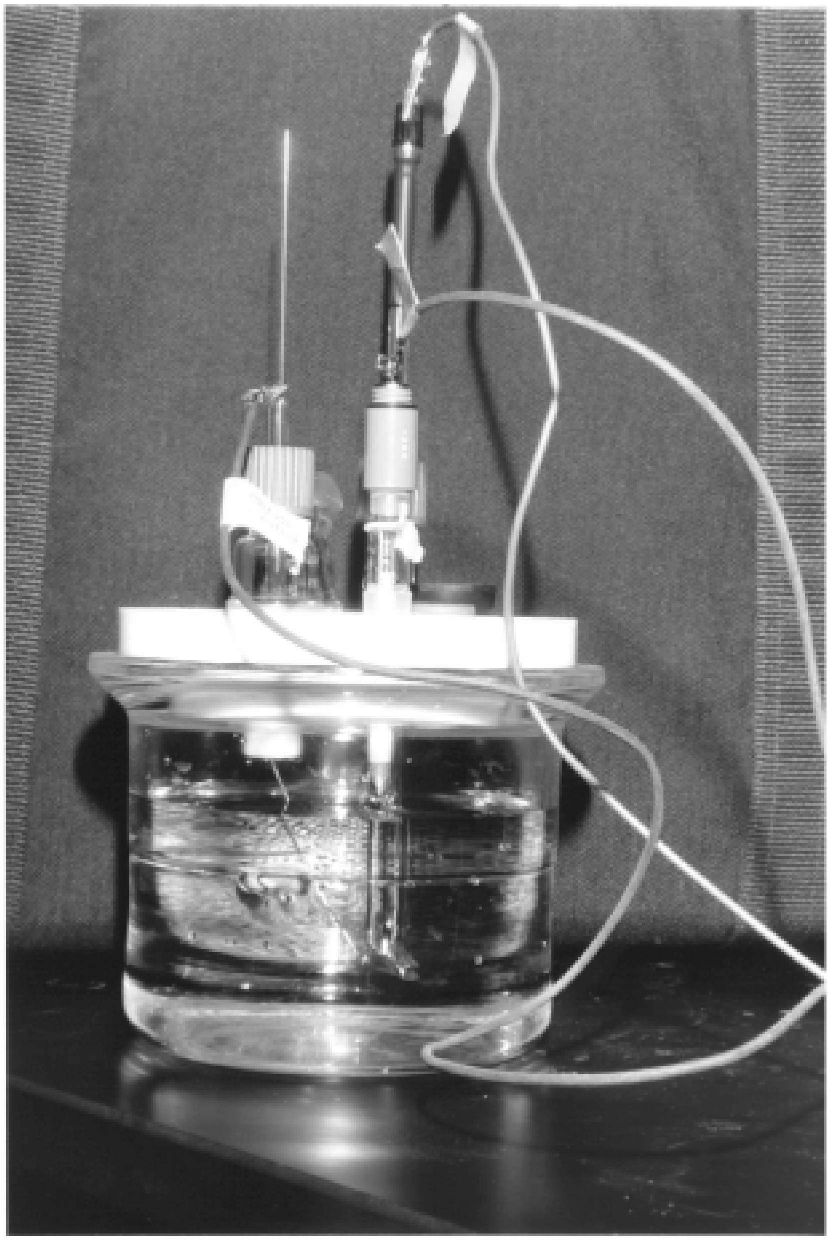

Figure 2. Polarization cell

IV. STATISTICAL TREATMENT

The mean and standard deviation for breakdown potential and maximum current density were computed. Potentiostatic anodic polarization curves were constructed for each wire, bracket, and bracket/wire combination. Data was compared using ANOVA and Tukey-Kramer least significant difference tests.

CHAPTER IV

RESULTS AND DISCUSSION

RESULTS

After completion of the experiments, potentiostatic anodic polarization curves were constructed and breakdown potentials were determined for each of the samples (Figures 5-14). The breakdown potentials of the individual samples are seen in Table 2.

Stainless Steel Bracket	**200 mv**	**200 mv**	**200 mv**
Stainless Steel wire	**600 mv**	**600 mv**	**800 mv**
NiTi	**1600 mv**	**1600 mv**	**1600 mv**
TMA	**>2000 mv**	**>2000 mv**	**>2000 mv**

Table 2. Breakdown potentials of individual samples.

The ANOVA showed the difference in breakdown potential was statistically significant ($p<0.001$). The Tukey-Kramer test showed each product in table 2 to be statistically different from all other products ($p<0.05$).

The results indicate that corrosion occurred more readily in stainless steel brackets and somewhat slower in stainless steel wires. The value of 800 mv obtained for the stainless steel wire was out of line with the other values for unknown reasons, but was not disregarded. The NiTi wires were much more corrosion resistant, but ultimately broke down. The breakdown potential of the TMA wire could not be reached throughout the 2000 mv range of testing.

Visual inspection of the tested samples of stainless steel brackets, stainless steel wires and NiTi wires revealed extensive pitting and changes in surface morphology (Figures 3,4). The most notably corroded were the stainless steel brackets which not only corroded earlier but also more extensively. This was seen throughout the bracket face, on the base and the tie wings. Changes in color were noted and even fracturing of the stainless steel wire occurred when taken throughout the entire 2000 mv testing range. NiTi wires exhibited a color change from silver to dark gray after being subjected to potentiostatic anodic polarization. TMA did not exhibit any notable changes in surface morphology or structural integrity. Note the discoloration and pitting on the stainless steel brackets in Figures 3 and 4.

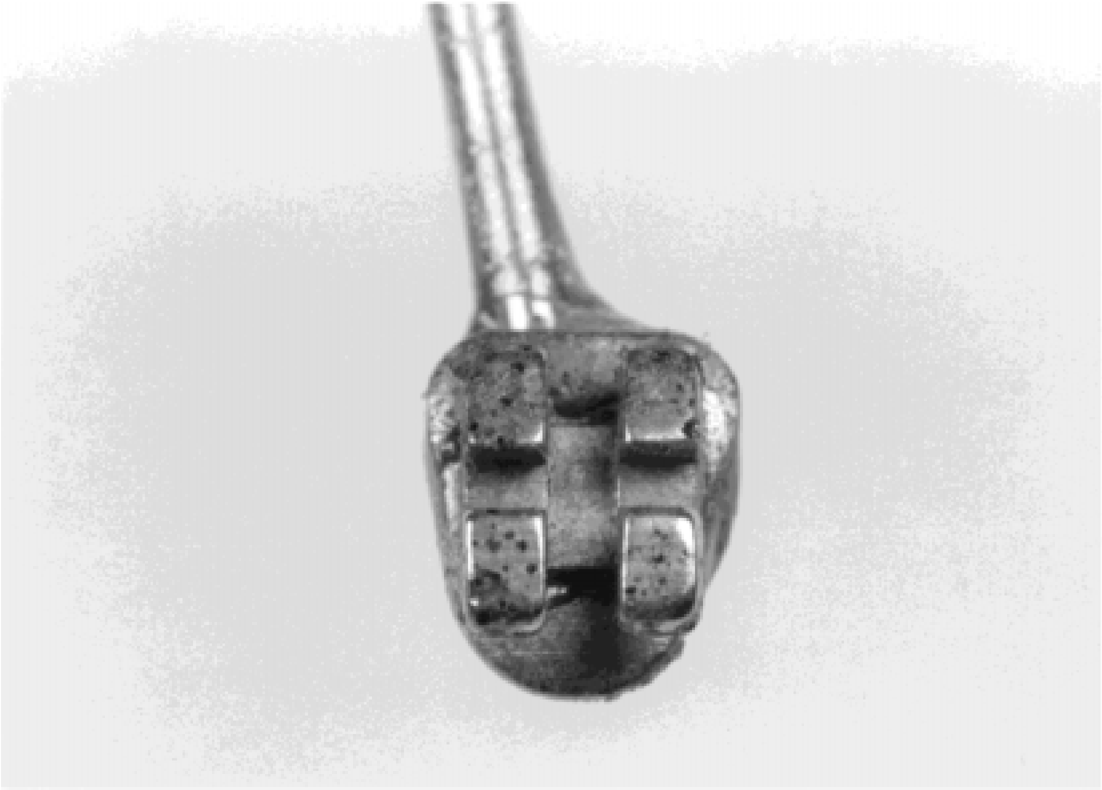

Figure 3. Stainless steel bracket after testing

Figure 4. Stainless steel bracket after testing

The breakdown potentials for the wires when combined with a stainless steel bracket are seen in Table 3.

Stainless steel	**200 mv**	**200 mv**	
NiTi	**200 mv**	**200 mv**	
TMA	**200 mv**	**200 mv**	**200 mv**

Table 3. Breakdown potentials of coupled samples

When galvanically coupling these wires with a stainless steel bracket and subjecting them to potentiostatic anodic polarization, the results were quite surprising. The corrosive potential of the stainless steel bracket seemed to determine the level at which the coupled samples would begin to breakdown. The breakdown potential was independent of the type of wire that was engaged in the bracket slot and all samples broke down near the potential that the stainless steel bracket broke down when tested alone. This occurred whether the wire/bracket couple was attached to the potentiostat via the wire in the slot or a coated wire glued to the back of the bracket.

After reaching their breakdown potential, all bracket-wire couples exhibited surface changes associated with corrosion. Color changes and pitting occurred in all of the samples with the exception being the TMA wire (and gold-coated wire). While the TMA wire did not show any visible signs of corrosion, the stainless steel bracket of the couple did exhibit these effects.

To investigate any possible crevice corrosion effects on the wires when coupled with a bracket an additional test was conducted. A 30 mm stainless steel wire sample was engaged in the slot of a ceramic bracket and tested using potentiostatic anodic polarization. The breakdown potential was found to be 550 mv. The corrosive potential was nearly the same as the potential of the stainless steel wire when tested alone.

The gold-coated wire did not breakdown throughout the 2000 mv testing range. The scratched gold-coated wire had a breakdown potential of 500 mv. This level was very close to the value found (600 mv) when testing a stainless steel wire alone. The slight variation in values could be due to different stainless steel of the two samples or lack of a complete passivation layer on the wire. It should be noted that the gold coating was difficult to disrupt and the use of a handpiece was required to alter the breakdown potential of the gold wire sample.

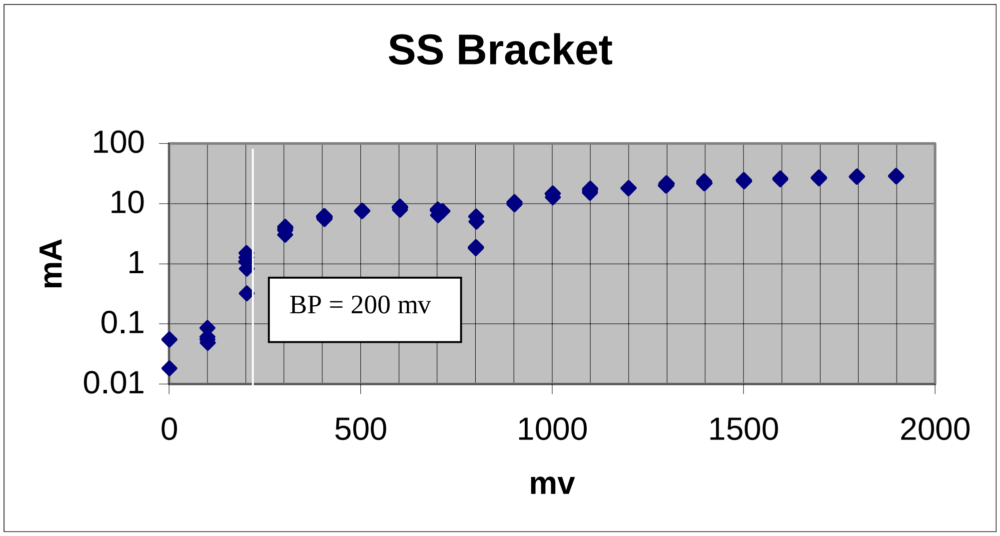

Figure 5. Potentiostatic anodic polarization curve for stainless steel bracket. Breakdown potential was found to be 200mv.

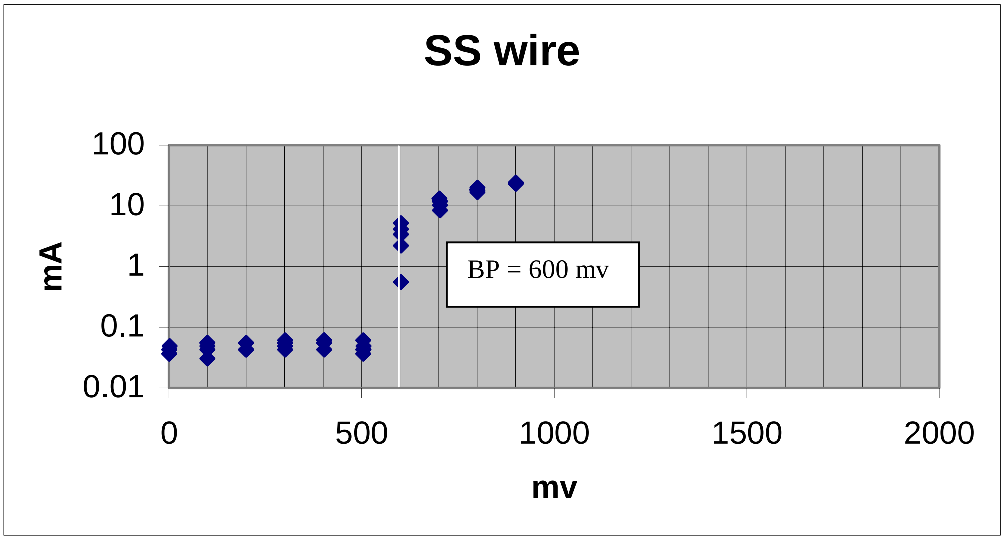

Figure 6. Potentiostatic anodic polarization curve for stainless steel wire. Breakdown potential was found to be 600mv.

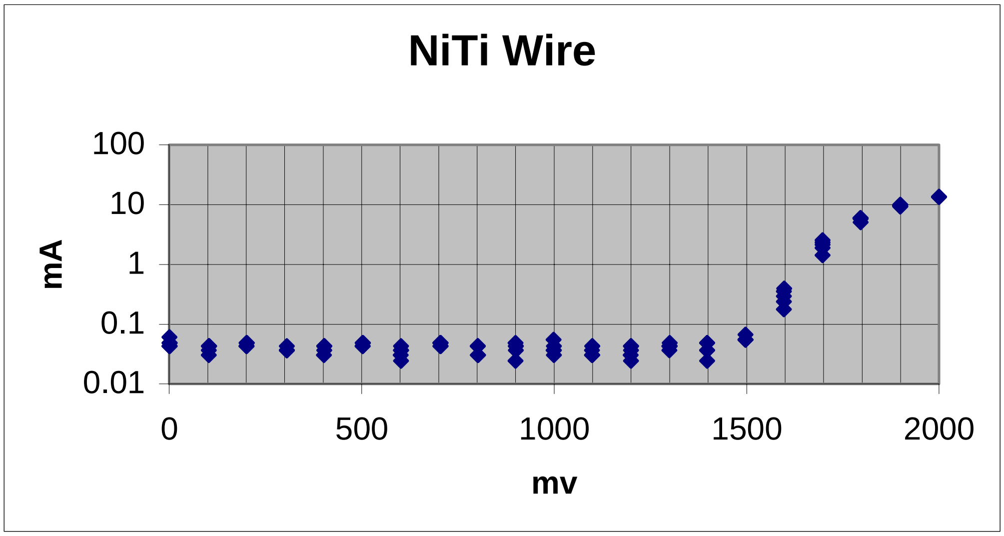

Figure 7. Potentiostatic anodic polarization curve for NiTi wire. Breakdown potential was found to be 1600mv.

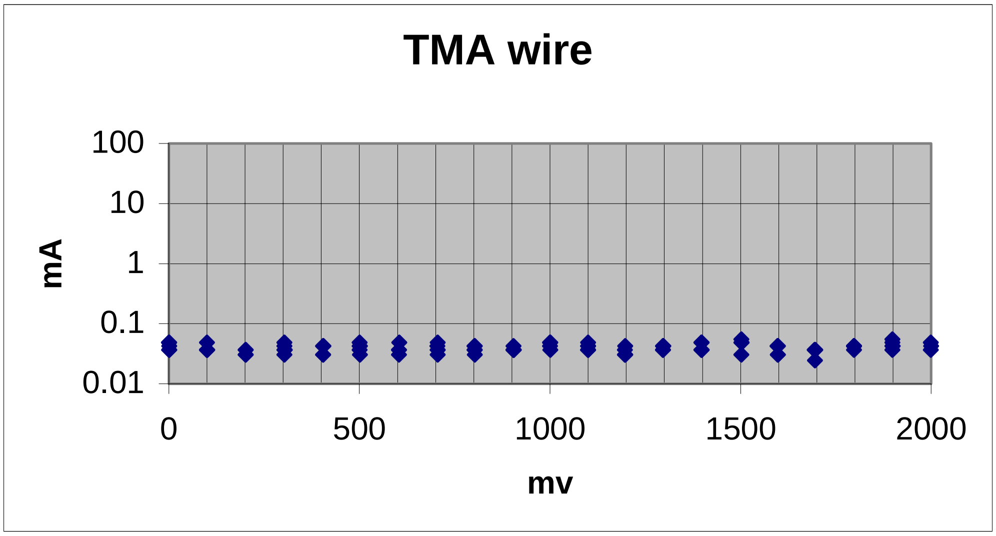

Figure 8. Potentiostatic anodic polarization curve for TMA wire. Breakdown potential was found to be >2000mv.

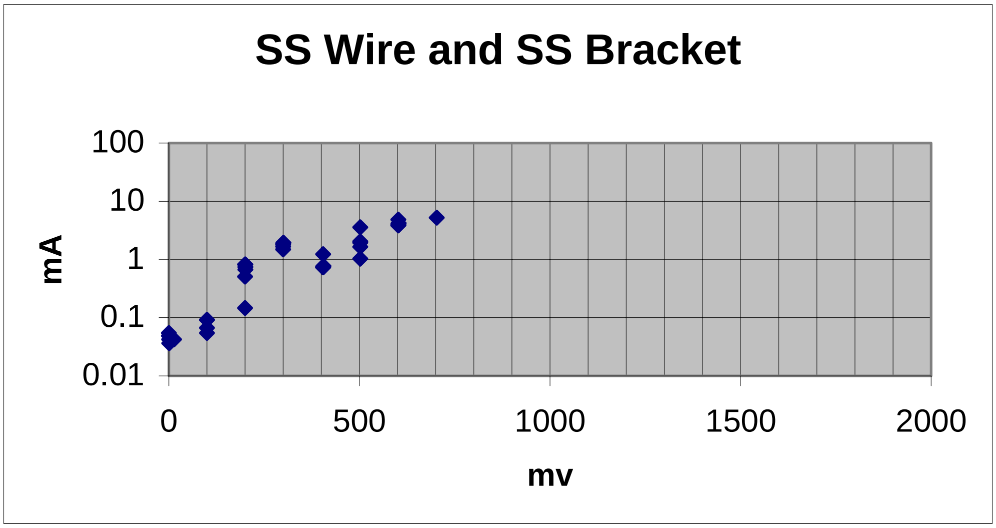

Figure 9. Potentiostatic anodic polarization curve for stainless steel wire and stainless steel bracket combination. Breakdown potential was found to be 200mv.

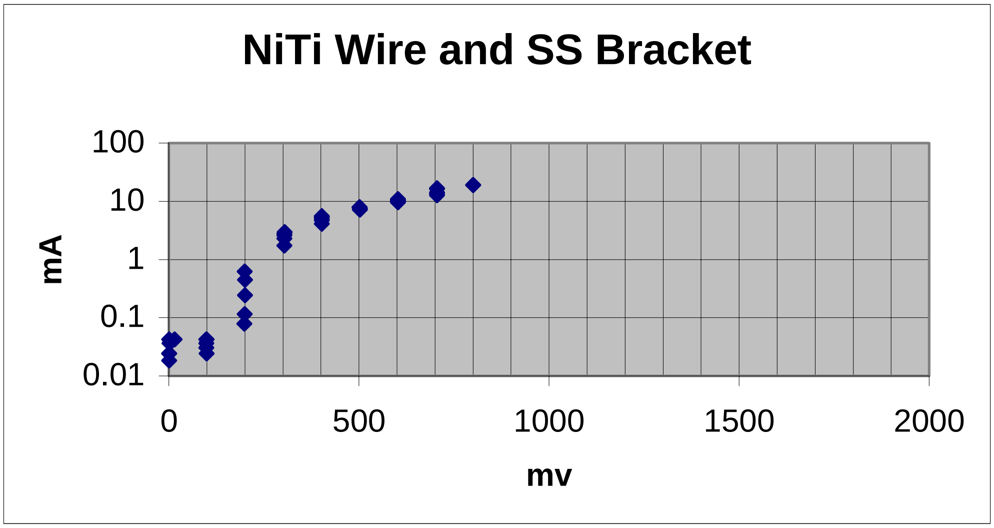

Figure 10. Potentiostatic anodic polarization curve for NiTi wire and stainless steel bracket combination. Breakdown potential was found to be 200mv.

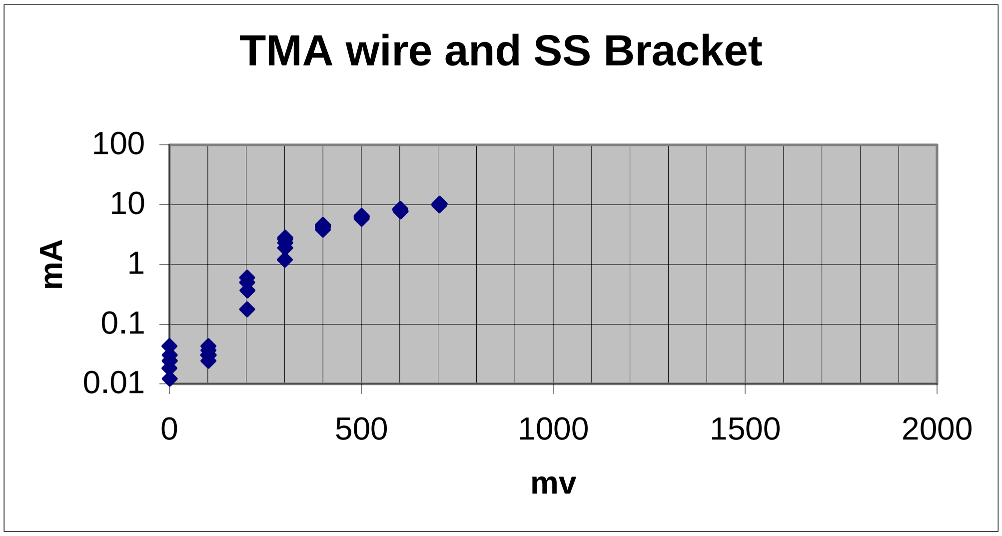

Figure 11. Potentiostatic anodic polarization curve for TMA wire and stainless steel bracket combination. Breakdown potential was found to be 200mv.

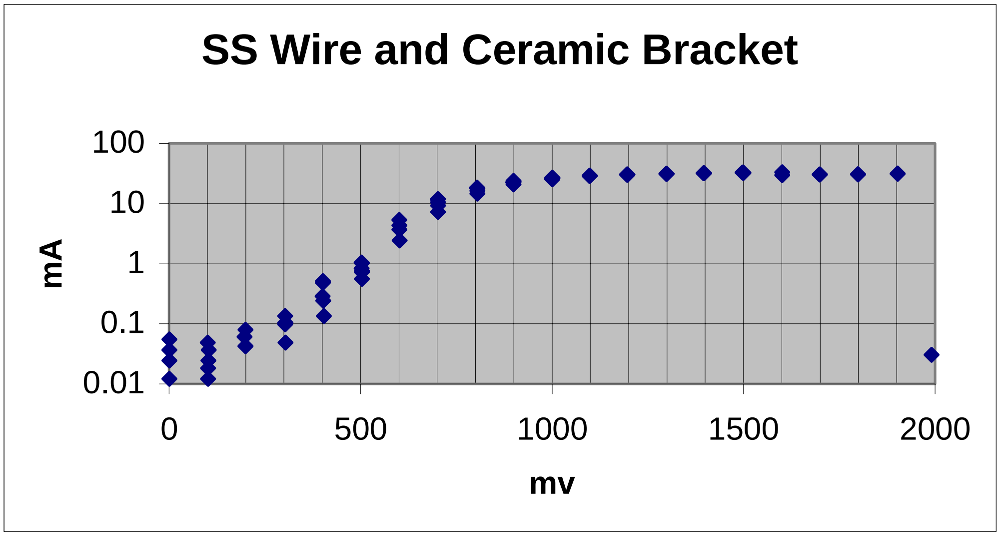

Figure 12. Potentiostatic anodic polarization curve for stainless steel wire and ceramic bracket combination. Breakdown potential was found to be 550mv.

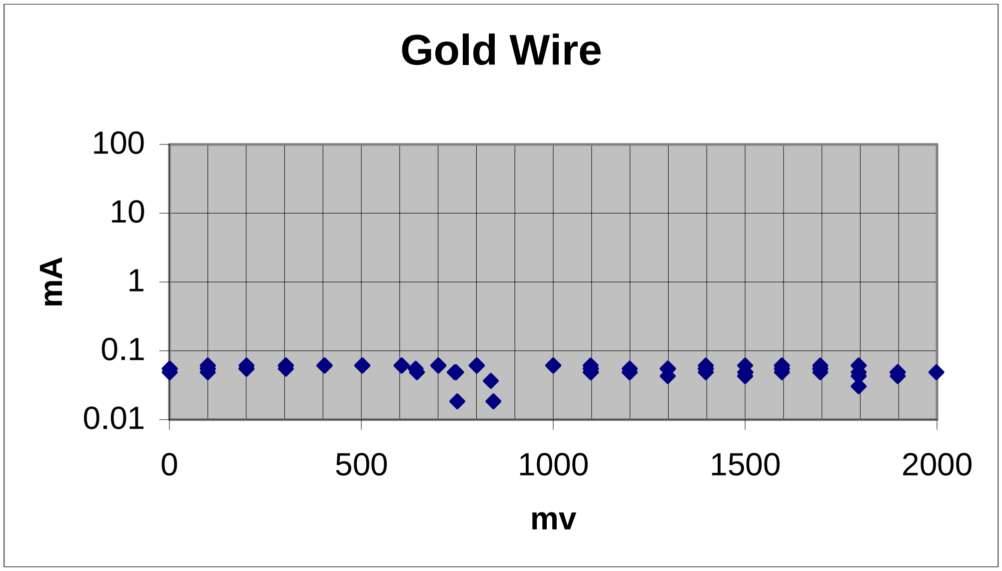

Figure 13. Potentiostatic anodic polarization curve for gold-coated stainless steel wire. Breakdown potential was found to be >2000mv.

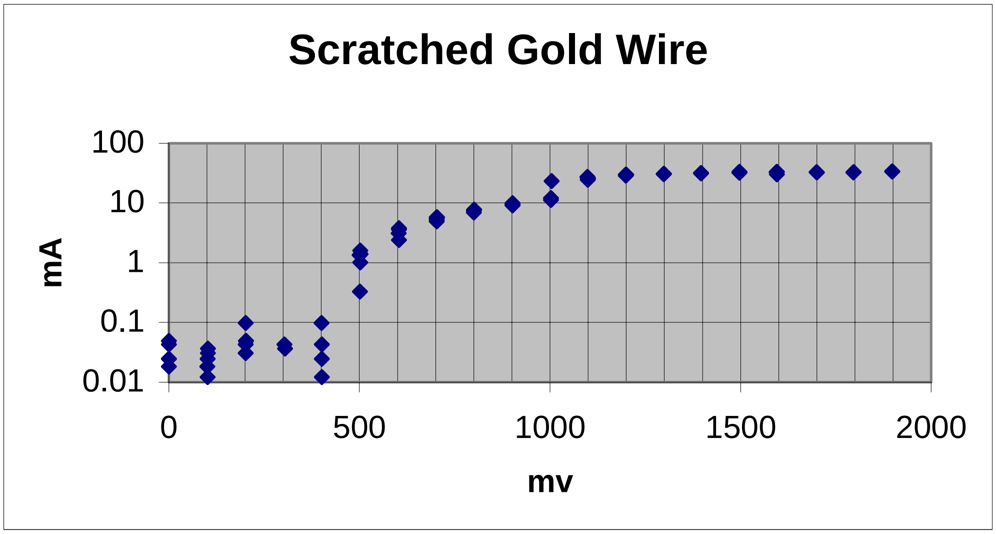

Figure 14. Potentiostatic anodic polarization curve for "scratched" gold-coated stainless steel wire. Breakdown potential was found to be 500mv.

DISCUSSION

The breakdown potential was determined for all of the samples tested by using potentiostatic anodic polarization. The breakdown potentials indicate the point at which the oxide film of the metal is interrupted and the dissolution of the metal begins. The lower the value of the breakdown potential, the higher the susceptibility to corrosion. Among the wires, the greatest susceptibility to corrosion was seen in stainless steel followed by nickel-titanium. The breakdown potential of gold coated and TMA wires could not be reached. As noted earlier, the most susceptible was the stainless steel bracket, which recorded a value of 200 mv.

When coupling the wires and the stainless steel bracket, the outcomes were all essentially the same. All of the three wire types tested with the stainless steel bracket recorded breakdown potentials of 200 mv**.** The samples all corroded at the level where the stainless steel bracket was found to corrode when tested alone. The bracket determined the corrosive potentials of the combination samples regardless of the wire that was placed in the slot.

To confirm this finding, a stainless steel wire was tested with a ceramic bracket. The ceramic bracket was considered to be a control in that it contains no metal and has no corrosion potential. The results indicated that the breakdown potential of the sample was approximately the same as the value that the stainless steel wire would have yielded if tested alone. The breakdown potential for the sample was found to be 550 mv. This supported the theory that the stainless steel bracket was the weak link in the corrosion potentials of the combined samples.

Additionally, a 24k-coated stainless steel wire from 3M Unitek was tested. The gold wire remained inert throughout the entire 2000 mv range. The experiment was unable to reach its breakdown potential. The gold wire was then scratched to remove the outer protective gold layer. The sample was then tested using potentiostatic anodic polarization. The breakdown potential was then found to be 500 mv. This value corresponds to the value found for the other stainless steel wire samples. This finding shows that the protective gold layer is only effective against corrosion when intact. However it should be pointed out that the gold coating was not easy to remove. Throughout orthodontic treatment, the appliances are subjected to a dynamic environment that could possibly abrade the surface of the wire and change the corrosive potential. In addition, clinically bending or cutting the archwire could alter the corrosive properties of the wire and the appliance system. Additionally, the reuse or recycling of appliances could affect the corrosion resistance of the system.

Different manufacturers could have different corrosive potentials for their wires or brackets. Various compositions of the metals could change the breakdown potential. Also, the manufacturing process could have a significant effect. The surface smoothness or finish of the metals would play a role in the corrosive potentials of the wires or brackets. Finally, the shape of a particular bracket design could affect the crevice conditions, which may alter the corrosive potential.

The two wires tested that had the greatest corrosive resistance were the TMA and gold-coated wires. Both titanium and gold are noble metals with very high corrosive resistance and these wires demonstrated such when subjected to potentiostatic anodic polarization. TMA is very unlikely to release ions intraorally and also contains no nickel (stainless steel contains 9% and NiTi contains 55% nickel by weight). Because of its flexibility and elastic properties, it would be a good substitute for NiTi in nickel sensitive patients. Twenty-four carat gold-coated wires are now being used for cosmetic purposes and may be found useful in patients with nickel allergies. The resistance of the gold allows for little ion release intraorally. However, if the protective gold coating were removed or abraded then the underlying metal would be subject to the intraoral elements and corrosion and ion release could occur. These wires are used in conjunction with gold-coated brackets. These bracket types were not tested for corrosion resistance, but they may be more resistant than a standard stainless steel appliance system. The gold-coating would also be susceptible to scratching in the same manner as the gold-coated wires. In theory, their resistance to corrosion would then be reduced as a result of exposure of the underlying metal. There may be a tendency for the clinician to use and re-use the gold-coated wires and brackets due to their increased expense. The additional time spent intraorally could lead to an increase in the amount of wear and corrosion of the alloys. This has not been investigated at this point.

Stainless steel brackets were found to be the most susceptible to breakdown when subjected to potentiostatic anodic polarization. The brackets had a breakdown point of 200 mv and showed significant surface corrosion. In addition, the brackets contain nickel and make up a significant amount of surface area of the orthodontic appliance system. The brackets are used throughout the mouth and are in almost constant contact with the oral mucosa. The nickel sensitive patient would be well served to avoid the use of a stainless steel bracket system. The leaching of nickel ions may cause contact dermatitis or other allergic conditions. In addition, the shape of the brackets and the nature of the wire/slot relationship allows for crevice corrosion. Metals that contain crevices encourage the corrosion process to intiate and propogate. A smooth surface is much more corrosion resistant than an irregular or rough surface. Also, intraorally areas of the brackets that are difficult to clean which may lead to localized areas of lowered pH. The lower the pH levels, the greater the likelihood of metal corrosion.

The dynamic environments to which orthodontic alloys are subject, makes the onset of corrosion somewhat variable from case to case. The possibility of wear from mastication and type of diet may disrupt the passive layer. Oral hygiene may play a significant role in the corrosion of the appliances. Scratches and surface irregularities may also have a significant effect.

The samples in this study were subjected to physiologic saline (0.9% NaCl) instead of true saliva. The tests were conducted at room temperature, which was very close to the standard 37°C found intraorally. The experiment was also conducted without purging oxygen into the solution. It should be noted that small changes in pH and temperature were kept to a minimum and should have a very limited effect on the sample outcome. Surface finishes and manufacturing processes could have a more profound effect on the alloys when subjected to potentiostatic anodic polarization.

Addressing the hypothesis directly: there was a significant difference in the corrosive potential of stainless, NiTi, and TMA orthodontic archwires when tested using potentiostatic anodic polarization testing. There was not a significant difference in the corrosive potential of stainless steel, NiTi, and TMA orthodontic archwires when galvanically coupled with a stainless steel bracket. There was a significant difference in the corrosive potential of stainless steel, NiTi, and TMA orthodontic archwires when galvanically coupled with a stainless bracket versus the corrosive potential of the wire alone using potentiostatic anodic polarization testing.

CHAPTER V

SUMMARY AND CONCLUSIONS

The purpose of this study was to compare the corrosive potential of stainless steel, nickel titanium, and TMA orthodontic wires when tested alone versus when paired with a stainless steel bracket. At least two samples of each wire and bracket/wire combination were tested. Each sample was subjected to potentiostatic anodic polarization in 0.9% NaCl solution at room temperature with a neutral pH. Using a Wenking MP 95 potentiostat, the breakdown potential of each sample was determined. The potentiostat was connected to an electrochemical corrosion cell. A data acquisition program was used to record data needed for the construction of potentiostatic anodic polarization curves. Photographs were taken of the samples to demonstrate the surface changes that occurred during the testing.

The breakdown potential of the stainless steel bracket, stainless steel wire, NiTi wire, and TMA wires were 200mv, 600mv, 1600mv, and >2000mv respectively. When coupled with a stainless steel bracket, all wire types yielded a breakdown potential of 200mv. The results indicated that regardless of the type of wire engaged in the slot of a stainless steel bracket, the breakdown occurred at the point where the stainless steel bracket would have corroded if tested alone. The bracket was the weak link and reached its breakdown point equally early in all of the samples tested. When tested alone, the most corrosion resistant wires were the TMA wires. TMA could be a suitable alternative in treating nickel sensitive patients. In addition, gold coating seemed to protect the underlying stainless steel wires from their characteristic corrosion tendency. This type of wire might also be considered when treating a patient with a severe nickel allergy. However, the predominating factor appears to be the stainless steel bracket which breaks down readily and will leach nickel ions into the oral cavity. If the orthodontist is truly concerned about a nickel allergy, an alternative appliance system should be employed such as ceramic, polycarbonate or gold brackets.

Surface evaluation revealed significant discoloration and pitting in all of the samples except TMA and 24k gold-coated wires. Other studies in the literature indicate irregularities and internal stresses may influence corrosion resistance of metals with similar compositions. Therefore, metals with more irregularities and internal stresses would be more prone to corrosion breakdown. This may be one reason that the stainless steel bracket yielded the lowest breakdown value and controlled the corrosion properties of the coupled samples.

Further research could include investigation of the surface characteristics of these alloys after intraoral use versus when subjected to potentiostatic anodic polarization. Conducting experiments in a dynamic system may increase corrosion potential from the formation of localized areas of wear and disruption of the passive film layer. Simple bends placed in an archwire could affect its resistance to corrosion; especially when bending a gold coated wire. Analysis of the solution after anodic polarization may yield some interesting results. The amount and types of elements present would give an indication of the possible alloys to be avoided for use in certain patients. The pH of the solution may have a marked effect on the corrosion resistance of metals and yield strong clinical applications. Finally, SEM photographs could be taken of orthodontic appliances after use intraorally to evaluate surface characteristics.

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APPENDIX

Potentiostatic Anodic Polarization Data

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HEADERBANKMDT01
Recording Current - Potential Curves
stainless steel bracket to completion
A:\FSSBR.DAT
    2/24/00

ss bracket
.9% NaCl


SCE (sat)
         242
  0.976563
     0.3454
Wenking MP 95
           99
           60
(Startpotential)
(Endpotential)
            1
            0
Extra9
Extra8
Extra7
Extra6
Extra5
Extra4
Extra3
Extra2
Messdaten: E [mV], I [mA]
  0.732422   -0.05493
  0.976563   -0.05493
   -0.24414  -0.04883
  0.610352   -0.05493
  0.366211   -0.01831
  100.5859   -0.04883
  100.2197   -0.05493
  100.4639   -0.04883
  99.85352   -0.06104
  100.3418   -0.08545
  202.3926   -0.32349
  202.8809   -0.83008
  201.2939   -1.08643
  202.0264   -1.26343
  201.5381   -1.50146
  302.6123   -3.01514
  303.1006   -3.60107
  302.7344     -3.8147
  303.7109   -3.95508
  303.3447   -4.09546
```

405.5176	-5.52979
406.0059	-5.76782
404.6631	-5.85327
405.3955	-5.9082
406.25	-5.95703
405.0293	-6.073
403.6865	-6.13403
405.2734	-6.12793
405.3955	-6.12793
405.5176	-6.15845
405.0293	-6.15234
404.541	-6.18286
503.9063	-7.55615
503.9063	-7.58057
503.9063	-7.48901
503.1738	-7.48901
602.2949	-8.72803
602.7832	-8.91113
602.2949	-8.71582
603.2715	-8.64868
603.1494	-8.49609
602.7832	-7.87354
701.6602	-7.73315
701.6602	-7.94067
701.6602	-7.83691
702.6367	-6.39038
713.8672	-7.49512
801.7578	-1.88599
800.9033	-1.87378
802.6123	-5.01099
800.5371	-1.81885
801.2695	-6.0791
901.8555	-9.76563
901.7334	-10.1135
901.9775	-10.4919
901.7334	-10.5469
1001.953	-12.6648
1001.709	-14.7766
1000.854	-14.5203
1099.243	-15.1428
1099.854	-17.6575
1098.755	-16.3879
1098.633	-15.7043
1099.365	-17.1753
1199.585	-18.0237
1199.829	-18.2495
1298.706	-19.9951
1297.974	-20.0806
1296.753	-20.0928
1298.34	-20.4163
1298.584	-21.3928

1299.194	-21.46
1298.584	-21.7957
1397.095	-23.5352
1397.095	-21.9421
1398.193	-21.936
1396.973	-21.936
1397.583	-21.8506
1397.583	-21.8506
1501.587	-23.5657
1501.709	-23.8342
1501.587	-23.9075
1500.61	-24.0784
1501.099	-24.3713
1501.099	-24.6216
1595.947	-25.4028
1595.947	-26.2695
1696.777	-26.8311
1696.777	-26.3062
1696.533	-26.8738
1696.655	-26.8188
1697.388	-27.0935
1796.265	-28.0762
1796.753	-28.2837
1795.532	-27.7283
1898.926	-28.3569
1898.438	-29.0283
1898.315	-28.5461
2002.686	-28.9978

HEADERBANKMDT01
Recording Current - Potential Curves

A:\SSB1.DAT
1/31/99
O'Leary
s.s. bracket
.9% saline
7
room
SCE (sat)
242
0.854492
0.3454
Wenking MP 95
60
60
(Startpotential)
(Endpotential)
1
0

```
Extra9
Extra8
Extra7
Extra6
Extra5
Extra4
Extra3
Extra2
Messdaten: E [mV], I [mA]
  0.854492    -0.05493
  0.732422    -0.05493
  1.220703    -0.04883
  0.854492    -0.06104
  0.732422    -0.04883
  0.732422    -0.05493
  100.0977    -0.06104
  100.2197    -0.06104
  100.5859    -0.06104
  100.2197    -0.06104
  100.2197    -0.06104
  201.2939    -0.12207
   201.416    -0.06104
  201.9043    -0.06104
  201.6602    -0.06104
   201.416    -0.04883
  305.7861    -0.06104
  305.6641    -0.05493
  305.1758    -0.05493
  305.4199    -0.05493
  305.1758    -0.06104
  402.5879    -0.05493
  403.3203    -0.05493
  402.9541    -0.06104
    402.71    -0.06104
   402.832    -0.06104
   503.418    -0.06104
  503.2959    -0.06104
  503.6621    -0.06104
  503.9063    -0.06104
  504.0283    -0.06104
  601.4404    -0.06104
  601.5625    -0.07935
  600.8301    -0.09155
  600.8301    -0.24414
  601.5625    -0.06104
  601.3184    -0.06104
  701.6602    -0.07935
  701.6602    -0.10986
  702.0264    -0.10376
  700.8057    -0.12207
  700.8057    -0.12207
```

```
 802.6123      -0.177
  803.833   -0.24414
 802.6123   -0.22583
 802.2461   -7.32422
 802.7344   -6.05469
 900.7568   -10.7422
 900.6348   -11.9019
 900.8789   -0.79346
 901.3672   -0.79346
 901.2451   -1.09863
 997.6807   -14.4653
 997.6807   -19.4824
 997.5586   -22.2168
 997.4365   -22.7661
 997.1924   -23.1812
 1097.778   -25.0244
 1097.656   -25.2075
 1098.022   -25.2686


HEADERBANKMDT01
Recording Current - Potential Curves
stainless steel wire
A:\SSB2.DAT
       2/2/00

Ss bracket
.9% NaCl


SCE (sat)
          242
 0.610352
    0.3454
Wenking MP 95
           30
           60
(Startpotential)
(Endpotential)
            1
            0
Extra9
Extra8
Extra7
Extra6
Extra5
Extra4
Extra3
Extra2
Messdaten: E [mV], I [mA]
 0.854492   -0.04272
 0.366211   -0.02441
```

```
  0.244141    -0.01831
  1.220703    -0.11597
  1.953125    -0.09766
  98.63281    -0.03662
  100.3418    -0.03662
  99.73145    -0.04883
  98.51074    -0.14648
  100.0977    -0.09766
  205.3223    -0.25024
  204.9561    -0.43335
  204.9561    -0.57373
  205.0781      -0.7019
  205.5664    -0.83618
  304.4434      -1.7395
  304.0771    -2.18506
  303.5889    -2.50854
   303.833    -2.70996
  304.3213    -2.88696
  404.2969    -4.15649
  404.2969    -4.41895
  403.8086    -4.63257
  404.1748    -4.92554
  404.9072    -5.13916
  503.0518      -6.5918
   501.709    -6.92139
  502.8076      -7.1167
  502.4414    -7.22046
  602.7832    -8.99048


HEADERBANKMDT01
Recording Current - Potential Curves
stainless steel bracket
A:\SSB3.DAT
      2/2/00

ss bracket
.9% NaCl


SCE (sat)
         242
  0.610352
    0.3454
Wenking MP 95
          36
          60
(Startpotential)
(Endpotential)
           1
           0
Extra9
```

```
Extra8
Extra7
Extra6
Extra5
Extra4
Extra3
Extra2
Messdaten: E [mV], I [mA]
  0.244141    -0.03052
  0.610352    -0.03662
  0.488281    -0.04883
  0.732422    -0.03662
  0.488281    -0.04883
  101.8066    -0.08545
  101.1963    -0.10986
  101.5625    -0.09766
  101.3184    -0.10986
  101.8066    -0.12817
  101.1963    -0.10376
  201.6602    -0.40283
   201.416    -0.59204
  201.2939    -0.65918
  201.6602    -0.74463
  202.1484    -0.83008
  301.8799    -1.69067
   302.002    -1.88599
  302.4902    -2.02026
  302.8564    -2.06299
  400.3906    -2.92358
  400.8789     -3.1311
  400.7568    -3.17383
  400.7568    -3.26538
  400.8789    -3.38135
  499.0234    -4.41895
  498.4131    -4.70581
  498.9014    -4.85229
  498.7793    -4.93774
   498.291    -5.10254
  602.0508    -6.28662
  602.7832    -6.37207
  601.5625    -6.70776
  601.8066    -6.80542
  601.9287    -6.78101
  698.1201    -7.87964


HEADERBANKMDT01
Recording Current - Potential Curves
ss  #2  50mv/5min
A:\SSW1.DAT
     1/31/00
```

```
stainless steel
.9% saline
         7
room
SCE (sat)
       242
  0.610352
     0.384
Wenking MP 95
        60
        60
(Startpotential)
(Endpotential)
         1
         0
Extra9
Extra8
Extra7
Extra6
Extra5
Extra4
Extra3
Extra2
Messdaten: E [mV], I [mA]
  0.976563  -0.05493
  0.488281  -0.05493
  0.854492  -0.04272
  0.366211  -0.04272
  0.732422  -0.05493
  100.3418  -0.04272
  99.97559  -0.05493
  100.0977  -0.04272
  100.0977  -0.04883
  99.73145  -0.04883
  99.36523  -0.04883
  200.9277  -0.05493
  201.0498  -0.04883
  201.0498  -0.06104
   201.416  -0.04883
   201.416  -0.04883
   303.833  -0.04272
   303.833  -0.04272
  303.5889  -0.04883
  303.4668  -0.04883
  303.3447  -0.04272
   402.832  -0.05493
    402.71  -0.04272
    402.71  -0.03662
  402.2217  -0.04883
    402.71  -0.05493
   501.709  -0.05493
```

501.4648	-0.04883
501.8311	-0.04272
501.5869	-0.03052
501.2207	-0.05493
601.4404	-0.03662
601.1963	-0.04272
601.9287	-0.05493
600.708	-0.05493
601.4404	-0.04883
701.2939	-0.04883
701.6602	-0.03052
701.5381	-0.04883
702.0264	-0.04272
701.9043	-0.04883
799.6826	-0.04883
800.0488	-0.14038
799.8047	-0.43945
799.8047	-0.61035
799.4385	-0.95215
800.6592	-1.39771
899.292	-1.96533
898.4375	-2.81372
899.0479	-3.35693
998.9014	-4.3335
999.0234	-5.06592
998.4131	-6.16455
999.2676	-6.30493
998.5352	-7.37305
999.2676	-8.47778
1099.243	-10.2905
1098.511	-10.6506
1098.999	-12.1765
1196.411	-12.0605

HEADERBANKMDT01
Recording Current - Potential Curves
ss #2 50mv/5min
A:\SSW2.DAT
1/31/00

stainless steel
.9% saline
7
room
SCE (sat)
242
1.342773
0.384
Wenking MP 95
46
60

```
(Startpotential)
(Endpotential)
               1
               0
Extra9
Extra8
Extra7
Extra6
Extra5
Extra4
Extra3
Extra2
Messdaten: E [mV], I [mA]
  1.342773    -0.04883
  0.610352    -0.03662
  0.854492    -0.04272
  0.366211    -0.04272
  0.976563    -0.03662
   99.4873    -0.04272
  99.36523    -0.05493
   99.4873    -0.04883
  99.12109    -0.03052
  99.12109    -0.05493
   199.707    -0.05493
   199.707    -0.05493
  199.8291    -0.04272
  199.9512    -0.04272
  199.8291    -0.05493
  301.5137    -0.04883
  301.3916    -0.05493
  301.1475    -0.06104
  301.2695    -0.05493
  301.2695    -0.04272
    402.71    -0.05493
   402.832    -0.06104
  402.9541    -0.06104
  402.5879    -0.05493
  402.9541    -0.04272
  504.5166    -0.04272
  504.2725    -0.06104
  503.9063    -0.03662
  504.8828    -0.04883
   505.249    -0.04272
  601.9287    -0.55542
  601.9287    -2.20337
   602.417    -3.36304
  602.1729    -4.09546
  601.9287    -5.15747
  703.8574    -8.42896
  703.2471    -10.1746
  703.4912    -11.7981
```

```
  703.125   -11.8835
 702.2705   -13.0737
 800.9033   -16.7236
 800.7813   -17.5598
  800.293   -18.4387
 800.9033   -19.7571
 900.6348   -23.0713
 900.2686    -24.231


HEADERBANKMDT01
Recording Current - Potential Curves

A:\NITIW1.DAT
   2/3/99

niti wire 1
.9 nacl


SCE (sat)
      242
 1.342773
    0.384
Wenking MP 95
      109
       60
(Startpotential)
(Endpotential)
        1
        0
Extra9
Extra8
Extra7
Extra6
Extra5
Extra4
Extra3
Extra2
Messdaten: E [mV], I [mA]
 0.854492   -0.06104
 1.098633   -0.04883
 0.976563   -0.04883
 0.610352   -0.04272
 0.854492   -0.04272
 1.342773   -0.04272
 102.7832   -0.04272
 103.5156   -0.04272
 102.7832   -0.03052
 102.9053   -0.03662
 103.5156   -0.04272
  201.416   -0.04883
```

200.9277	-0.04272
201.1719	-0.04272
201.0498	-0.04272
200.9277	-0.04883
305.4199	-0.03662
305.6641	-0.04272
305.542	-0.03662
305.4199	-0.03662
305.4199	-0.03662
403.0762	-0.03662
401.9775	-0.03052
402.5879	-0.04272
402.5879	-0.04272
402.71	-0.04272
502.6855	-0.04272
502.3193	-0.04883
502.6855	-0.04272
503.1738	-0.04883
502.5635	-0.04272
602.1729	-0.04272
602.2949	-0.03662
602.0508	-0.02441
601.9287	-0.03662
601.9287	-0.03662
601.5625	-0.03052
704.5898	-0.04272
705.0781	-0.04272
705.2002	-0.04883
704.7119	-0.04883
704.4678	-0.04883
801.6357	-0.03052
802.124	-0.03052
801.7578	-0.04272
802.002	-0.04272
801.8799	-0.04272
900.7568	-0.04272
899.9023	-0.02441
899.9023	-0.04883
900.2686	-0.03662
900.3906	-0.04272
998.9014	-0.03662
999.1455	-0.04272
999.7559	-0.03662
999.5117	-0.03052
998.9014	-0.05493
1098.511	-0.03662
1098.389	-0.03052
1098.999	-0.04272
1099.121	-0.04272
1098.755	-0.03052
1199.341	-0.04272

1199.341	-0.03662
1198.975	-0.03052
1199.219	-0.04272
1199.341	-0.02441
1199.463	-0.04272
1299.683	-0.03662
1299.561	-0.04272
1300.049	-0.04272
1300.049	-0.04883
1299.561	-0.04272
1299.927	-0.04272
1397.217	-0.02441
1397.217	-0.03662
1397.095	-0.04883
1397.339	-0.04883
1397.339	-0.03662
1496.704	-0.05493
1497.07	-0.05493
1496.826	-0.05493
1496.948	-0.05493
1497.07	-0.06714
1596.68	-0.177
1596.924	-0.23804
1596.924	-0.29297
1596.558	-0.354
1597.29	-0.39673
1697.388	-1.42212
1697.632	-1.89819
1697.266	-2.13623
1697.021	-2.34375
1697.144	-2.53906
1796.509	-5.05981
1796.509	-5.82886
1796.509	-5.91431
1795.776	-5.99365
1796.509	-5.94482
1796.387	-5.98145
1899.292	-9.96094
1899.17	-9.82666
1898.682	-9.63745
1899.536	-9.42993
1899.292	-9.31396
1999.878	-13.5376
2000.122	-13.4705
2000	-13.4033
2000.366	-13.3118

HEADERBANKMDT01
Recording Current - Potential Curves

A:\NITIW2.DAT

2/3/00

niti wire 2
.9 nacl

SCE (sat)
242
0.854492
0.384
Wenking MP 95
98
60
(Startpotential)
(Endpotential)
1
0
Extra9
Extra8
Extra7
Extra6
Extra5
Extra4
Extra3
Extra2
Messdaten: E [mV], I [mA]

0.854492	-0.04272
0.366211	-0.05493
0.610352	-0.05493
0.732422	-0.04272
0.976563	-0.04272
0.854492	-0.03662
100.9521	-0.05493
100.2197	-0.05493
100.4639	-0.05493
100.3418	-0.06104
100.4639	-0.04883
199.3408	-0.04272
199.9512	-0.03052
200.3174	-0.04883
200.0732	-0.03662
200.1953	-0.05493
301.2695	-0.04272
301.2695	-0.03662
301.1475	-0.04883
301.7578	-0.03662
300.7813	-0.04883
400.0244	-0.04883
400.5127	-0.03052
401.001	-0.05493
399.9023	-0.04883

400.5127	-0.04883
503.9063	-0.04272
504.0283	-0.04272
503.418	-0.04272
503.7842	-0.03662
503.9063	-0.03662
600.2197	-0.06104
600.3418	-0.04272
600.3418	-0.02441
600.3418	-0.03662
600.4639	-0.04272
599.8535	-0.03052
702.1484	-0.04883
702.5146	-0.04883
702.1484	-0.03052
702.0264	-0.04883
702.2705	-0.04272
798.8281	-0.04272
798.584	-0.04272
798.4619	-0.03662
798.584	-0.03662
898.6816	-0.04883
898.6816	-0.04272
898.9258	-0.04883
898.5596	-0.04883
898.6816	-0.02441
999.3896	-0.04272
999.7559	-0.04272
999.3896	-0.03662
999.6338	-0.03662
999.2676	-0.04272
1095.215	-0.04272
1095.215	-0.04272
1095.337	-0.04272
1095.459	-0.04883
1094.971	-0.03662
1196.289	-0.04883
1196.045	-0.05493
1196.045	-0.03662
1196.045	-0.04883
1195.801	-0.04883
1298.096	-0.03662
1298.096	-0.05493
1297.852	-0.05493
1297.974	-0.04272
1298.34	-0.04272
1396.484	-0.03662
1396.362	-0.05493
1396.24	-0.04272
1396.484	-0.03662
1396.118	-0.05493

```
 1489.014   -0.06104
 1499.023   -0.06104
  1499.39   -0.06104
 1499.756   -0.06104
 1499.023   -0.06104
 1598.022   -0.10986
 1597.168   -0.15259
 1597.534   -0.19531
  1597.29   -0.23804
 1596.802   -0.26855
 1597.412   -0.29907
 1694.946   -1.26953
  1695.19   -1.46484
  1695.19   -1.60522
 1797.119   -3.88184
 1798.218   -4.26636
 1797.607   -4.54712
 1797.363   -4.67529
 1900.757   -8.27637
 1998.169   -11.7798
 1997.925   -12.2986
 1997.681   -12.4451


HEADERBANKMDT01
Recording Current - Potential Curves

A:\NITIW3.DAT
   2/3/00

niti wire 3
.9 nacl


SCE (sat)
      242
 0.732422
    0.384
Wenking MP 95
       93
       60
(Startpotential)
(Endpotential)
        1
        0
Extra9
Extra8
Extra7
Extra6
Extra5
Extra4
Extra3
```

Extra2

Messdaten: E [mV], I [mA]

1.342773	-0.04883
1.098633	-0.06104
0.854492	-0.05493
1.098633	-0.05493
1.220703	-0.06104
102.6611	-0.05493
102.7832	-0.05493
102.6611	-0.04272
102.6611	-0.05493
102.5391	-0.03052
102.2949	-0.05493
203.8574	-0.05493
204.3457	-0.02441
204.4678	-0.05493
204.2236	-0.02441
204.4678	-0.04883
302.2461	-0.05493
302.2461	-0.01831
302.124	-0.04883
301.7578	-0.03662
402.71	-0.04272
402.4658	-0.05493
402.832	-0.01831
402.832	-0.06104
402.832	-0.06104
500	-0.04272
500.7324	-0.01831
500.6104	-0.03662
500.2441	-0.06104
500.9766	-0.06104
602.1729	-0.02441
601.6846	-0.05493
601.5625	-0.04883
600.9521	-0.03662
704.3457	-0.01831
704.7119	-0.04272
704.7119	-0.03662
704.7119	-0.04883
705.2002	-0.04883
799.6826	-0.04883
799.8047	-0.04272
799.9268	-0.04272
799.0723	-0.03662
799.6826	-0.04272
799.6826	-0.03662
900.5127	-0.04272
900.3906	-0.02441
900.6348	-0.05493
900.2686	-0.04272

```
 900.3906   -0.05493
 999.8779   -0.04883
 999.7559   -0.05493
 999.6338   -0.06104
     1000   -0.05493
 1099.243   -0.03662
 1099.487   -0.04883
 1099.609   -0.04883
 1099.487   -0.06104
 1098.633   -0.05493
 1099.487   -0.04272
 1200.684   -0.04272
 1200.439   -0.03662
 1200.195   -0.04883
 1199.829   -0.03662
 1199.707   -0.03662
 1298.828   -0.05493
  1298.95   -0.04883
 1298.828   -0.04272
  1298.34   -0.03662
 1299.072   -0.04883
 1398.438   -0.06104
 1397.827   -0.06104
 1398.315   -0.04272
 1397.461   -0.03052
 1397.705   -0.03662
 1499.512   -0.05493
     1500   -0.04272
 1500.244   -0.06104
 1499.878   -0.05493
 1500.122   -0.06104
 1595.581   -0.14648
 1595.337   -0.12817
 1595.093   -0.18311
 1595.459   -0.18311
 1595.581   -0.23804
 1695.923   -1.10474
 1696.167   -1.28174
 1696.533   -1.44043
 1796.509   -3.54614
 1795.776   -3.66211
  1899.17   -6.57349
 1899.292    -6.9519
 2002.808   -10.8826


HEADER   HEADER   HEADERBANKMDT0
BANKMD   BANKMD   3
T01      T02
Recording Current - Potential Curves

A:\TMAW1.DAT
```

```
      2/4/00

tma wire 1



SCE (sat)
         242
  0.854492
       2.384
Wenking MP 95
         102
           60
(Startpotential)
(Endpotential)
             1
             0
Extra9
Extra8
Extra7
Extra6
Extra5
Extra4
Extra3
Extra2
Messdaten: E [mV], I [mA]
  0.854492    -0.03662
  1.098633    -0.04272
  0.366211    -0.04272
  0.610352    -0.05493
  0.488281    -0.04883
  0.976563    -0.05493
  99.36523    -0.04883
  98.87695    -0.04883
  98.87695    -0.03052
    99.4873    -0.04883
  201.2939    -0.04883
  201.6602    -0.04272
  201.0498    -0.04883
  202.1484    -0.04883
  201.9043    -0.04883
  301.2695    -0.05493
  301.6357    -0.03662
  301.5137    -0.03052
  301.6357    -0.04272
  301.1475    -0.03662
  403.3203    -0.03662
  403.4424    -0.04272
  402.9541    -0.04883
  403.0762    -0.03052
  403.4424    -0.03662
```

501.5869	-0.03662
501.709	-0.04272
501.8311	-0.04272
501.8311	-0.03662
501.8311	-0.02441
602.2949	-0.03662
602.417	-0.03052
602.5391	-0.05493
602.2949	-0.03662
602.5391	-0.03052
602.417	-0.04272
703.7354	-0.04883
703.4912	-0.04272
703.3691	-0.03662
703.0029	-0.03052
703.7354	-0.03052
801.0254	-0.02441
801.3916	-0.04272
801.7578	-0.03662
801.1475	-0.04883
801.2695	-0.03662
899.9023	-0.04272
899.292	-0.03662
899.1699	-0.04883
899.0479	-0.04272
899.6582	-0.04272
899.4141	-0.03662
999.2676	-0.04883
999.1455	-0.03052
998.7793	-0.04883
998.6572	-0.04272
1097.29	-0.03662
1097.29	-0.03662
1096.802	-0.03662
1097.29	-0.04272
1096.924	-0.03052
1195.435	-0.04883
1197.144	-0.04272
1196.167	-0.03662
1197.144	-0.04883
1196.533	-0.03662
1298.462	-0.05493
1298.34	-0.04272
1298.706	-0.05493
1297.974	-0.04272
1298.218	-0.04883
1394.653	-0.04272
1394.531	-0.04272
1394.653	-0.03662
1395.02	-0.04272
1495.605	-0.04272

```
 1495.483   -0.03662
 1495.605   -0.04272
 1495.483   -0.03662
 1495.361   -0.04272
 1593.384   -0.05493
 1593.018   -0.04272
 1593.262   -0.03662
  1593.14   -0.03662
 1593.384   -0.04272
 1698.608   -0.04272
  1698.73   -0.03662
 1698.975   -0.03662
 1698.486   -0.03662
 1698.364   -0.04272
 1797.119   -0.03662
 1797.119   -0.04272
 1796.875   -0.03662
 1796.631   -0.03662
 1797.241   -0.03662
 1898.193   -0.03662
 1897.827   -0.03662
 1897.949   -0.03662
 1897.705   -0.04272
 1898.193   -0.03052
 2000.366   -0.04272
 2001.099   -0.04272


HEADERBANKMDT01
Recording Current - Potential Curves

A:\TMAW2.DAT
     2/4/00

tma wire 2




SCE (sat)
        242
  0.732422
      0.384
Wenking MP 95
        103
          60
(Startpotential)
(Endpotential)
            1
            0
Extra9
Extra8
Extra7
```

Extra6
Extra5
Extra4
Extra3
Extra2
Messdaten: E [mV], I [mA]

0.732422	-0.03662
1.464844	-0.03662
0.610352	-0.04883
0.732422	-0.03662
1.220703	-0.04272
0.854492	-0.04883
100.0977	-0.03662
100.4639	-0.04883
100.4639	-0.03662
100.708	-0.03662
100.2197	-0.03662
201.6602	-0.03052
201.6602	-0.03052
201.2939	-0.03662
201.6602	-0.03662
303.4668	-0.03052
303.3447	-0.03662
303.7109	-0.03662
303.4668	-0.04272
302.8564	-0.04883
303.7109	-0.03662
404.9072	-0.04272
404.9072	-0.03052
405.2734	-0.04272
404.541	-0.04272
405.1514	-0.03052
500.7324	-0.04272
500.7324	-0.04883
500.9766	-0.04272
500.7324	-0.03662
500.9766	-0.03052
604.0039	-0.03052
604.248	-0.04883
603.3936	-0.03662
603.7598	-0.03662
705.3223	-0.03052
705.0781	-0.03662
704.5898	-0.04272
705.5664	-0.04883
705.3223	-0.03662
802.6123	-0.04272
801.7578	-0.03662
802.3682	-0.03052
802.4902	-0.03662
802.124	-0.04272

904.541	-0.03662
904.9072	-0.03662
904.4189	-0.04272
904.0527	-0.03662
904.2969	-0.03662
904.1748	-0.03662
1000.488	-0.04883
999.6338	-0.04272
1000.122	-0.04883
1000.61	-0.03662
1100.098	-0.03662
1100.22	-0.03662
1099.854	-0.04272
1100.098	-0.04272
1099.976	-0.04883
1100.098	-0.03662
1196.411	-0.03662
1196.899	-0.03052
1196.777	-0.03052
1197.144	-0.03052
1197.144	-0.04272
1296.631	-0.04272
1296.875	-0.04272
1296.509	-0.03662
1296.631	-0.03662
1296.997	-0.04272
1397.583	-0.04883
1397.705	-0.03662
1397.583	-0.03662
1397.339	-0.04883
1396.973	-0.03662
1501.831	-0.03052
1502.441	-0.04883
1502.075	-0.05493
1502.075	-0.04883
1597.656	-0.03052
1597.534	-0.04272
1596.924	-0.04272
1597.29	-0.03052
1597.29	-0.04272
1694.58	-0.03662
1695.557	-0.03662
1694.946	-0.03662
1695.068	-0.03662
1695.068	-0.02441
1797.363	-0.04272
1797.363	-0.04272
1797.241	-0.03662
1797.852	-0.04272
1797.852	-0.04272
1898.56	-0.04272

```
  1898.804    -0.04272
  1898.438    -0.03662
  1898.071    -0.04883
  1898.438    -0.05493
  1999.634    -0.04272
  1999.268    -0.04883
  1998.901    -0.03662



HEADERBANKMDT01
Recording Current - Potential Curves
stainless steel wire 1 and ss bracket
A:\SSC1.DAT
       2/8/00

ss wire 1 and ss bracket
.9% NaCl


SCE (sat)
          242
  0.366211
     0.7294
Wenking MP 95
           35
           60
(Startpotential)
(Endpotential)
            1
            0
Extra9
Extra8
Extra7
Extra6
Extra5
Extra4
Extra3
Extra2
Messdaten: E [mV], I [mA]
  0.488281    -0.05493
  0.610352    -0.05493
  0.854492    -0.04272
            0    -0.03662
            0    -0.05493
  0.976563    -0.04272
  99.85352    -0.04883
  99.24316    -0.06104
    99.4873    -0.05493
  99.73145    -0.05493
  203.9795    -0.06104
  203.4912    -0.12207
```

204.2236	-0.18311
204.2236	-0.21973
203.4912	-0.29907
303.1006	-0.53101
302.4902	-0.61646
302.6123	-0.72632
302.8564	-0.75073
302.6123	-0.73242
401.8555	-1.09863
401.2451	-1.29395
401.6113	-1.37939
401.6113	-1.5625
402.3438	-1.58691
501.2207	-2.05688
501.4648	-2.2583
501.2207	-2.40479
501.3428	-2.53906
500.8545	-2.6123
603.6377	-3.43018
602.9053	-3.59497
603.2715	-4.26636
602.6611	-4.5166
701.416	-5.65796

HEADERBANKMDT01
Recording Current - Potential Curves
stainless steel wire 2 and ss bracket
A:\SSC2.DAT
2/8/00
O'Leary
ss wire 2 and ss bracket
.9% NaCl

SCE (sat)
242
0.732422
0.7294
Wenking MP 95
38
60
(Startpotential)
(Endpotential)
1
0
Extra9
Extra8
Extra7
Extra6
Extra5
Extra4

```
Extra3
Extra2
Messdaten: E [mV], I [mA]
  0.366211    -0.04883
  0.610352    -0.05493
  0.732422    -0.04272
  0.854492    -0.03662
  0.976563    -0.04272
  13.91602    -0.04272
  100.4639    -0.05493
  100.4639    -0.06714
  100.4639    -0.09155
  100.2197    -0.09155
  200.1953    -0.14648
  200.3174    -0.50659
  200.5615    -0.67139
  200.8057    -0.73853
  200.5615    -0.82397
  200.1953    -0.82397
   300.293    -1.48315
  300.0488    -1.66016
   300.293    -1.79443
   300.415    -1.93481
  299.9268     -1.9043
  404.6631    -1.23901
  405.3955    -0.76904
  404.7852    -0.73242
  405.1514    -0.75684
  404.6631    -0.73242
  501.8311     -1.0376
  502.1973    -1.95313
  502.4414    -1.64795
  502.1973    -2.05688
  502.3193    -3.57056
   602.417    -4.83398
  602.5391    -4.22363
   602.417    -3.86963
  602.0508    -3.86963
  601.6846    -4.06494
  601.8066    -4.06494
  702.5146    -5.23682


HEADERBANKMDT01
Recording Current - Potential Curves
NiTi wire and SS bracket combo
A:\NC1.DAT
      2/8/00

NiTi Combo
.9% NaCl
```

```
SCE (sat)
      242
 0.854492
   0.7294
Wenking MP 95
       42
       60
(Startpotential)
(Endpotential)
        1
        0
Extra9
Extra8
Extra7
Extra6
Extra5
Extra4
Extra3
Extra2
Messdaten: E [mV], I [mA]
 0.854492  -0.04883
 0.244141  -0.06104
 0.610352  -0.04883
 0.854492  -0.04883
 0.732422  -0.03662
 101.9287  -0.04272
 102.1729  -0.04883
 101.6846  -0.05493
 101.4404  -0.04883
 102.0508  -0.05493
 200.9277  -0.13428
 201.2939  -0.26245
 200.9277  -0.40894
 200.8057  -0.49438
 201.0498  -0.64087
 303.3447  -1.72729
 303.5889   -2.2644
 303.7109  -2.56958
 303.9551  -2.64282
  303.833  -2.81372
  402.832  -3.96118
 403.3203  -4.30908
 403.5645  -4.65088
 403.3203  -5.26733
 403.5645  -5.68848
 500.1221   -7.6416
 498.7793  -8.19702
 499.6338  -8.88062
      500  -9.34448
```

```
 499.3896   -9.74121
 604.3701   -11.7981
  604.248   -12.3352
  604.248   -13.1104
 604.0039   -13.5986
  604.248   -14.0381
 700.0732   -16.5649
 700.0732   -17.4988
 700.0732   -18.1824
  699.707   -19.1772
 699.9512   -19.2627
 801.8799   -22.4182
  802.124   -23.1201



HEADERBANKMDT01
Recording Current - Potential Curves
niti wire and ss bracket 2
A:\NC2.DAT
   2/8/00
O'Leary
niti wire and ss bracket 2
.9% NaCl


SCE (sat)
      242
 0.366211
   0.7294
Wenking MP 95
       42
       60
(Startpotential)
(Endpotential)
        1
        0
Extra9
Extra8
Extra7
Extra6
Extra5
Extra4
Extra3
Extra2
Messdaten: E [mV], I [mA]
 1.098633   -0.03662
 0.488281   -0.01831
 0.610352   -0.02441
 0.854492   -0.04272
 0.732422   -0.02441
 14.52637   -0.04272
```

98.2666	-0.03662
98.87695	-0.04272
98.38867	-0.04272
98.87695	-0.02441
98.38867	-0.03052
198.7305	-0.07935
199.4629	-0.11597
200.1953	-0.24414
199.9512	-0.44556
199.585	-0.62256
303.833	-1.72729
303.833	-2.28271
303.833	-2.58789
304.0771	-2.771
304.1992	-2.93579
402.2217	-4.09546
402.4658	-4.73022
402.4658	-5.10864
402.0996	-5.36499
401.9775	-5.5603
501.9531	-7.18994
502.5635	-7.55005
501.8311	-7.8064
501.5869	-7.93457
602.2949	-9.53979
602.6611	-9.96094
602.6611	-10.3149
602.6611	-10.5347
602.6611	-10.8398
704.834	-12.6709
705.0781	-13.5681
705.3223	-14.1052
705.3223	-16.2292
705.0781	-16.687
800.415	-18.9331
800.6592	-18.9514

HEADERBANKMDT01
Recording Current - Potential Curves
tma wire 1 and ss bracket
A:\TC1.DAT
2/8/00

tma wire 1 and ss bracket
.9% NaCl

SCE (sat)
242
0.610352

```
      0.7294
Wenking MP 95
          38
          60
(Startpotential)
(Endpotential)
           1
           0
Extra9
Extra8
Extra7
Extra6
Extra5
Extra4
Extra3
Extra2
Messdaten: E [mV], I [mA]
  0.976563   -0.02441
  0.610352   -0.04272
  1.220703   -0.02441
  0.732422   -0.03052
  0.366211   -0.01831
  1.220703   -0.01221
  102.0508   -0.02441
   102.417   -0.03052
  101.4404   -0.04272
  101.6846   -0.03662
  101.1963   -0.03052
  202.7588     -0.177
   203.125   -0.36621
  203.0029   -0.50049
  202.6367   -0.59814
  301.3916   -1.19629
  301.5137    -1.9043
  301.7578   -2.30713
  301.5137   -2.63062
  301.7578   -2.79541
  400.5127    -3.8147
  400.0244   -4.14429
  400.2686    -4.3457
  400.3906    -4.5105
  400.5127   -4.62646
  500.7324   -5.81665
  501.2207   -6.10352
  500.8545      -6.25
  500.6104   -6.43921
  500.9766   -6.49414
  602.1729   -7.73315
  602.0508   -8.06885
  601.9287   -8.26416
  602.0508    -8.3252
```

```
 602.0508   -8.5022
 703.3691 -9.80835
  703.125  -10.1929
 703.8574  -10.3882



HEADERBANKMDT01
Recording Current - Potential Curves
tma wire 2 and ss bracket
A:\TC2.DAT
  12/2/99

tma wire 2 and ss bracket
.9% NaCl


SCE (sat)
      242
 0.976563
   0.7294
Wenking MP 95
       46
       60
(Startpotential)
(Endpotential)
        1
        0
Extra9
Extra8
Extra7
Extra6
Extra5
Extra4
Extra3
Extra2
Messdaten: E [mV], I [mA]
 1.586914  -0.08545
 0.244141  -0.04272
 0.610352  -0.02441
        0  -0.03662
 0.732422         0
 101.4404  -0.01221
 101.4404  -0.04883
 101.5625  -0.03052
 100.9521  -0.03662
 101.4404  -0.02441
 201.1719  -0.03662
 201.2939  -0.07324
 201.6602  -0.13428
 201.6602  -0.20752
 202.0264  -0.37231
```

303.4668	-0.94604
303.4668	-1.58691
303.4668	-1.99585
303.3447	-2.22778
303.7109	-2.37427
401.4893	-3.42407
401.6113	-3.76587
402.0996	-3.90625
401.7334	-4.01611
401.8555	-4.20532
501.9531	-5.41382
501.8311	-5.57861
502.3193	-5.61523
501.4648	-5.74341
501.9531	-5.88379
603.6377	-7.45239
604.126	-8.19092
604.0039	-8.53882
604.248	-8.6792
604.9805	-8.83179
702.7588	-10.2783
701.9043	-10.3943
702.3926	-10.4309
702.2705	-10.3943
703.3691	-10.4309
805.2979	-11.8286
805.1758	-12.0178
803.9551	-12.0483
804.3213	-11.8042
803.7109	-7.51343
901.9775	-8.46558

HEADERBANKMDT01
Recording Current - Potential Curves
TMA WIRE 3 AND SS BRACKET
A:\TC3.DAT
2/9/00
O'Leary
tma wire 3 and ss bracket
.9% NaCl

SCE (sat)
242
0.732422
0.7294
Wenking MP 95
36
60
(Startpotential)
(Endpotential)

```
        1
        0
Extra9
Extra8
Extra7
Extra6
Extra5
Extra4
Extra3
Extra2
Messdaten: E [mV], I [mA]
 1.342773  -0.05493
 1.220703  -0.03662
 0.976563  -0.05493
  0.12207  -0.03662
 0.610352  -0.04272
 101.4404  -0.06104
 101.6846  -0.04272
 101.6846  -0.05493
 101.6846  -0.05493
 101.8066  -0.05493
 203.3691  -0.06714
 203.7354  -0.14038
 203.3691  -0.21362
 204.1016  -0.27466
 204.1016  -0.32349
 300.9033    -0.8606
  302.002    -1.5686
 300.6592  -1.82495
 301.0254  -2.13623
 301.0254  -2.30713
  402.832  -3.36914
 402.9541  -3.85742
 402.5879  -4.14429
 402.4658  -4.45557
 402.3438  -4.52271
 502.8076    -5.5603
 503.1738  -6.04858
 503.1738  -6.21948
 502.9297  -6.39038
 503.0518  -6.50024
 573.3643  -7.35474
 601.9287  -8.24585
 601.4404  -8.60596
 601.1963  -8.66089
 601.1963  -8.72803
 700.1953  -10.1318


HEADERBANKMDT01
Recording Current - Potential Curves
ss wire and ceramic bracket
```

```
A:\CERAM.DAT
    2/23/00

ss wire and ceramic bracket
.9% NaCl


SCE (sat)
       242
  0.610352
    0.7294
Wenking MP 95
        83
        60
(Startpotential)
(Endpotential)
         1
         0
Extra9
Extra8
Extra7
Extra6
Extra5
Extra4
Extra3
Extra2
Messdaten: E [mV], I [mA]
  0.366211  -0.05493
  0.244141  -0.03662
  0.488281  -0.02441
  -0.85449  -0.01831
  0.610352  -0.01221
  101.0742  -0.04883
  103.0273  -0.03662
  102.0508  -0.01831
  102.6611  0.024414
  101.5625  0.012207
  199.0967         0
  199.2188  -0.04272
  198.8525  0.006104
  199.8291  -0.07935
  197.1436  -0.06104
  303.7109  -0.10376
  302.8564  -0.13428
  303.7109  -0.04883
  303.2227  -0.09766
  303.3447  -0.10376
  403.6865  -0.13428
  402.4658  -0.24414
   401.123  -0.28687
  401.6113  -0.48218
```

401.8555	-0.5127
503.418	-0.55542
503.418	-0.72632
503.1738	-0.75684
502.5635	-0.84229
503.1738	-1.01318
502.4414	-1.0376
602.0508	-2.4231
601.5625	-3.69263
601.5625	-4.32739
601.4404	-5.29785
702.0264	-7.21436
702.3926	-9.28955
701.9043	-10.4492
701.0498	-11.6821
702.1484	-11.853
804.9316	-14.5874
804.8096	-16.3269
804.5654	-17.8345
804.1992	-17.8406
804.4434	-18.4631
899.6582	-20.7825
899.292	-22.6196
898.9258	-22.4487
899.292	-23.2788
899.4141	-23.6938
1000.732	-25.7813
1000.366	-25.3845
1000.244	-25.3357
1000.732	-25.592
1001.343	-26.6418
1000.732	-26.9653
1098.267	-28.6987
1098.389	-28.9124
1098.511	-28.8452
1099.121	-28.833
1196.777	-30.1331
1195.557	-30.3528
1196.411	-30.0659
1195.923	-30.3284
1196.777	-30.2368
1298.462	-31.0059
1299.316	-31.2134
1298.828	-31.073
1395.63	-31.8359
1397.095	-31.8726
1499.634	-32.3608
1498.413	-32.605
1498.901	-32.8674
1497.314	-32.7637
1601.318	-33.1665

1601.074	-29.6997
1699.341	-30.4749
1698.486	-30.481
1798.706	-30.9143
1799.194	-30.4749
1902.588	-30.9998
1902.588	-31.3416
1990.723	-0.03052

HEADERBANKMDT01
Recording Current - Potential Curves
gold wire
A:\GOLDW.DAT
12/2/99

gold wire
.9% NaCl

SCE (sat)
242
1.098633
0.384
Wenking MP 95
101
60
(Startpotential)
(Endpotential)
1
0
Extra9
Extra8
Extra7
Extra6
Extra5
Extra4
Extra3
Extra2
Messdaten: E [mV], I [mA]

1.098633	-0.05493
1.098633	-0.04883
1.098633	-0.05493
0.976563	-0.04883
1.220703	-0.05493
100.5859	-0.06104
100.4639	-0.04883
100.4639	-0.05493
100.5859	-0.05493
100.4639	-0.06104
100.3418	-0.05493

100.4639	-0.05493
201.416	-0.05493
201.416	-0.06104
201.416	-0.05493
303.7109	-0.05493
303.7109	-0.06104
303.4668	-0.06104
303.3447	-0.06104
303.4668	-0.06104
404.1748	-0.06104
404.0527	-0.06104
404.0527	-0.06104
404.0527	-0.06104
404.0527	-0.06104
502.9297	-0.06104
502.8076	-0.06104
502.9297	-0.06104
502.8076	-0.06104
502.8076	-0.06104
605.4688	-0.06104
605.4688	-0.06104
605.4688	-0.06104
605.4688	-0.06104
605.4688	-0.06104
700.6836	-0.06104
700.6836	-0.06104
700.6836	-0.06104
700.6836	-0.06104
800.7813	-0.06104
800.7813	-0.06104
800.7813	-0.06104
801.0254	-0.06104
800.6592	-0.06104
642.0898	-0.05493
645.2637	-0.04883
746.9482	-0.04883
750.1221	-0.01831
747.0703	-0.04883
743.5303	-0.04883
844.3604	-0.01831
837.1582	-0.03662
1000.122	-0.06104
999.7559	-0.06104
1000.244	-0.06104
1097.656	-0.06104
1097.778	-0.04883
1097.9	-0.04883
1097.9	-0.05493
1097.778	-0.05493
1198.975	-0.05493
1198.975	-0.05493

1198.853	-0.04883
1198.853	-0.04883
1198.853	-0.04883
1298.462	-0.04272
1298.584	-0.05493
1298.096	-0.05493
1298.34	-0.05493
1298.706	-0.05493
1397.583	-0.05493
1397.583	-0.04883
1397.339	-0.06104
1397.705	-0.05493
1397.705	-0.05493
1500.244	-0.04883
1500.244	-0.04272
1500.366	-0.04883
1500.244	-0.06104
1500.244	-0.04272
1595.703	-0.04883
1595.581	-0.05493
1595.459	-0.05493
1595.947	-0.06104
1595.459	-0.06104
1695.435	-0.05493
1695.557	-0.05493
1695.557	-0.05493
1695.557	-0.06104
1695.557	-0.04883
1795.654	-0.06104
1795.654	-0.04272
1795.654	-0.03052
1795.776	-0.04883
1795.776	-0.06104
1897.339	-0.04883
1896.973	-0.04883
1896.973	-0.04883
1896.973	-0.04272
1897.217	-0.04883
1997.803	-0.04883

HEADERBANKMDT01
Recording Current - Potential Curves
gold wire scratched
A:\SCGOLDW.DAT
2/23/00

gold wire scratched
.9% NaCl

```
SCE (sat)
         242
  0.854492
       0.384
Wenking MP 95
           95
           60
(Startpotential)
(Endpotential)
             1
             0
Extra9
Extra8
Extra7
Extra6
Extra5
Extra4
Extra3
Extra2
Messdaten: E [mV], I [mA]
  1.098633    -0.05493
  1.098633    -0.04883
  0.976563    -0.04272
  1.098633    -0.04272
  0.976563    -0.05493
  100.3418    -0.04272
  100.4639    -0.05493
  100.3418    -0.05493
  100.5859    -0.06104
  100.3418    -0.04883
    201.416    -0.05493
    201.416    -0.06104
    201.416    -0.06104
    201.416    -0.04883
    201.416    -0.04883
  301.5137    -0.04883
  301.5137    -0.04883
  301.6357    -0.04883
  301.5137    -0.06104
  301.5137    -0.04883
  404.0527    -0.06104
  404.1748    -0.04883
  404.0527    -0.04883
  404.0527    -0.06104
  404.0527    -0.05493
  502.9297    -0.04883
  503.2959    -0.06104
  503.0518    -0.04883
  503.0518    -0.05493
  503.0518    -0.04883
  603.0273    -0.04272
```

602.6611	-0.04272
602.6611	-0.03662
602.9053	-0.04883
603.0273	-0.04883
702.7588	-0.04883
703.125	-0.04883
703.125	-0.03052
703.0029	-0.04272
703.125	-0.04883
801.6357	-0.03662
802.002	-0.06104
801.7578	-0.05493
801.8799	-0.05493
801.7578	-0.04883
899.1699	-0.05493
898.8037	-0.05493
898.9258	-0.04272
999.3896	-0.05493
999.7559	-0.05493
999.6338	-0.06104
1100.098	-0.04883
1100.22	-0.05493
1100.342	-0.04883
1099.854	-0.05493
1099.854	-0.03662
1100.464	-0.05493
1202.393	-0.04883
1202.393	-0.06104
1202.393	-0.04272
1202.393	-0.04272
1299.194	-0.04883
1298.95	-0.04272
1299.683	-0.04883
1299.316	-0.06104
1399.536	-0.05493
1399.17	-0.05493
1399.292	-0.06104
1399.17	-0.05493
1399.292	-0.04883
1495.361	-0.04272
1495.361	-0.04272
1495.483	-0.03052
1495.361	-0.05493
1495.361	-0.05493
1598.755	-0.04272
1599.121	-0.04883
1599.121	-0.04883
1598.877	-0.04883
1598.877	-0.04883
1696.533	-0.04272
1696.533	-0.04272

```
  1696.411    -0.04883
  1696.411    -0.04883
  1696.655    -0.03662
  1796.997    -0.04883
  1797.119    -0.04272
  1797.119    -0.03662
  1796.997    -0.04883
  1796.997    -0.04272
  1899.414    -0.03662
  1899.414    -0.04883
  1899.414    -0.04883
  2001.465    -0.03662
  2001.709    -0.04883



HEADERBANKMDT01
Recording Current - Potential Curves
scratched gold wire 2
A:\SGW2.DAT
     2/24/00

scratched gold wire 2
.9% NaCl


SCE (sat)
           242
  0.366211
       0.384
Wenking MP 95
             76
             60
(Startpotential)
(Endpotential)
               1
               0
Extra9
Extra8
Extra7
Extra6
Extra5
Extra4
Extra3
Extra2
Messdaten: E [mV], I [mA]
  0.244141    -0.04883
    0.12207    -0.02441
  0.366211    -0.01831
  0.244141    -0.04272
    0.12207    -0.02441
  102.9053    -0.03662
```

101.0742	-0.01831
101.4404	-0.01221
102.9053	-0.03052
101.9287	-0.02441
201.9043	-0.03052
202.1484	-0.04883
201.5381	-0.04272
202.1484	-0.04883
201.7822	-0.09766
304.4434	-0.0061
304.0771	0.006104
304.5654	-0.03662
304.4434	-0.0061
303.4668	-0.04272
401.7334	-0.02441
401.3672	-0.01221
401.123	-0.04272
401.001	-0.09766
501.709	-0.32959
501.8311	-1.00708
500.4883	-1.34888
503.418	-1.3855
501.8311	-1.59302
603.3936	-2.38647
603.2715	-3.09448
603.7598	-3.58887
603.8818	-3.76587
702.5146	-4.88281
702.8809	-5.18799
702.8809	-5.50537
703.6133	-5.76782
703.0029	-5.74341
800.1709	-6.95801
800.293	-7.4646
801.0254	-7.71484
901.4893	-9.26514
901.4893	-9.14307
902.0996	-9.375
901.4893	-9.8938
1002.197	-11.1633
1002.808	-12.0544
1004.028	-23.2117
1098.999	-24.4385
1099.731	-25.7446
1098.145	-27.1484
1097.9	-26.8005
1199.097	-28.5217
1198.975	-29.7852
1199.829	-29.6387
1198.608	-29.5959
1200.073	-29.5715

1298.096	-30.4993
1298.706	-30.5054
1298.95	-30.7373
1396.362	-31.3538
1396.362	-31.5613
1395.874	-31.6528
1497.192	-31.9824
1496.948	-33.1482
1496.948	-32.8369
1594.971	-33.313
1594.116	-32.7881
1595.337	-30.0354
1699.707	-32.2144
1699.219	-32.7698
1796.387	-32.8247
1795.532	-32.5928
1898.071	-33.5083
1897.461	-33.4534
2000.732	-33.3496

VITA

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1997 – 2000	West Virginia University School of Dentistry Department of Orthodontics Morgantown, West Virginia Master of Science
1993 – 1997	Medical University of South Carolina College of Dental Medicine Charleston, South Carolina Doctor of Dental Medicine
1987 – 1991	Virginia Polytechnic Institute College of Engineering Blacksburg, Virginia Bachelor of Science

Memberships	American Association of Orthodontists American Dental Association Academy of General Dentistry Southern Association of Orthodontists
Honors/Awards	South Carolina Dental Association *Outstanding General Dentistry Award* Medical University of South Carolina *Service and Leadership Award* Carolina Children’s Charity *Outstanding Service Award* Medical University of South Carolina *Dean’s List 1993, 1994, 1995, 1996*
Future Plans	Orthodontic Private Practice Columbia, SC