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EXPERIMENTAL INVESTIGATION OF FACTORS AFFECTING THE ELECTRICAL PERFORMANCE OF THE STUB TO CARBON CONNECTION

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Abstract

A facility has been built and commissioned to enable research into improving the electrical energy efficiency (and reducing associated greenhouse gas emissions) of very large metal-metal and metal-carbon electrical connections used by energy intensive metal-winning processes (aluminium, copper, zinc, ferro-alloys). The facility is able to test large-scale and full-scale industrial electrical connections up to 1000 kg, at up to 5000 A DC and 1200 °C in an inert atmosphere.

This paper presents the first results of an experimental investigation using the facility to study the main influencing factors affecting the electrical contact resistance for the stub to carbon connection, which is one of the major electrical connection resistances found in aluminium smelting plants.

The investigation clearly shows increasing electrical contact resistance for; (i) decreasing stub diameter, (ii) increasing gap under stub and (iii) stub eccentrically positioned in the stub hole.

Introduction

This paper studies the electrical contact resistance of the steel stub to cast iron thimble to anode carbon, referred to as the stub to carbon (STC) connection, which is part of the anode rod assembly, Figure 1. In-situ measurements of the STC performance [1] reveal that the voltage drop through the connection can be approximately 120 mV, which represents the same order of magnitude as the average voltage drop in the anode block during service. It is now well recognised that relatively small improvements in STC performance can translate to considerable operational savings for smelter operations [2]. Similarly, deterioration of the steel stub due to cyclic loading in operation as well as in-process fit-up issues will lead to a net increase in STC voltage drop for the operation [3][4].

In practice there are many factors affecting the condition and position of the stub within the stub hole that will cause a larger than desired casting void, and subsequently larger air gap formation and poorer electrical connection [4]. The main factors are: (i) permanent deformation of the steel cross bar and stubs, known as toe-in, which will result in an unevenly distributed casting void around the stub (eccentricity) and potentially a very large thimble thickness on only one side of the thimble, (ii) misalignment between the anode rod assembly and the carbon anode at the casting station, which will also result in an unevenly distributed casting void, (iii) stub erosion due to attack of the steel stub by the molten electrolyte, which will often present as localised wastage across the bottom edge of a stub and hence create a large section of cast iron, (iv) systematic deterioration of the stub tip due to very high localised stub stresses during cell operation, which will result in a more evenly distributed increase in casting void around base of the stub hole, and (v) variation in stub length whereby one or more stubs will have a gap underneath which subsequently allows the formation of a 'pancake' of cast iron under the stub. All of these factors will cause an increase in STC contact resistance. A net penalty of 50 mV or more is possible for a deteriorated anode rod fleet.

Figure 1. Typical anode rod assemblies ready for use in aluminium smelting (image used with permission of Century Aluminium). Stub to carbon (STC) connection highlighted.

Recently, Beier et al [2] and Ding et al [4][5] have started to study the systematic deterioration in stub diameter and its effect on STC voltage drop and hence smelter operating costs using finite element analysis (FEA). With significant advancements in computational capability to conduct FEA studies for complex electrical connections, there has been a renewed need for an experimental validation facility to be established. CSIRO has established such a facility that can test full scale industrial electrical connections at full operating conditions and this data is being used to validate such models [6].

Previous Experimental Methods

Several researchers have documented experimental methods used to study anode resistance as well as STC contact resistance. Some researchers have elected to study full sized components and others have elected to undertake testing on cylindrical samples of materials representative of the STC system. A brief review of the main published methods is discussed.

In the early 1970s Seger patented [7] and presented [8] a novel multi-probe experimental setup to quantify electrical resistance of aluminium smelting anodes using whole anodes, with and without stubs cast in. The primary purpose of the experimental setup was centered around studying the variation in anode manufacturing conditions, such as pitch content and baking temperature, to deduce the impact of these on average anode resistance. Whilst not specifically presented as being used for STC connection assessment, it is clear that the arrangement could be very easily utilised for such, and may well have been by Seger and colleagues at the time.

In 1978 Peterson presented an experimental test using full scale anodes that were instrumented with voltage and thermocouple probes, placed in an experimental furnace and then heated from the bottom to simulate operating temperate whilst applying a test current of 1000 A DC [9]. It is not completely clear why Peterson chose to saw off the top half of the stub hole region, perhaps to focus on the mid region of the stub hole. However this action will have considerably altered the distribution of current flow through the STC connection being studied, additionally the sawing action will have almost certainly disrupted the intimate contact conditions created between the solidifying cast iron and textured stub hole wall, which heavily influence the early stages of STC contact resistance. Peterson's work did identify that there was a dependence of the cast iron thickness on connection tightness, and this subsequently affected STC performance. This early investigation of this effect has been subsequently cited by many researchers in this field.

In 1985 Rhedey and Castonguay [10] published extremely valuable data relating to smaller-scale testing of the effects of pressure and temperature for steel to carbon contact, and this was followed up by Sørlie and Gran in 1992 [11] with a similar study. Both studies targeted the application of carbon ramming paste to steel collectorbar contact and employed smaller scale cylindrical samples. The publications have served researchers well to understand the influence of the critical parameters of pressure and temperature on similar systems and has most recently been used by Molenaar et al to develop the industry benchmark FEA model to study variations in STC contact resistance [12]. One main limitation with the results is that the surface of the carbon and steel are relatively smooth and that the reported values do not take into consideration any mirco-mechanical keying that would be expected between stub hole carbon and cast iron thimble surfaces.

In 2007 Wilkening and Cóte [1] presented a combination of in-plant and experimental methods specifically designed to study the STC connection performance. The relatively recent in-plant measurements have been widely cited by researchers in this field and are often used to assist with FEA model validation. The smaller bench-scale testing undertaken utilised steel bars representing the stub of similar sizes to actual stubs. Unfortunately, the anode components were made from machined graphite blocks and thus the study did not include the effects of micro-mechanical keying expected between the carbon stub hole wall and the cast iron thimble surface. Further, the testing utilised current loading of only 20-40 A DC and thus the effect of Joule heating across the STC contact would not have been observed in the experiment. It is not specifically stated, but it can be interpreted by the clear observation of iron α-γ phase transformation, that the testing was undertaken isothermally.

Most recently in 2012 Chollier et al [13] presented a portable experimental device called MIREA to test the electrical resistance of a complete unstubbed anode. The MIREA device is largely based off the system presented by Seger in the 1970s. The MIREA device uses an inflatable metallic bag to create electrical contact in the walls of the stub hole, simulating the flow of current into the top of the anode. However, the device is reported to only operate at ambient temperature, and with a total current of only 200 A DC it will not be able to fully simulate the effect of Joule heating within the anode. The application of the device, as it is described, is presently limited to anode-only studies.

The experimental methods published have provided valuable techniques for advancing research into STC connection system performance as well as anode quality effects, however no one method has been able to exactly simulate all of the required physics involved in this complex system.

High Amperage Testing Facility

A multi-function facility has been built to enable full physics research into improving the electrical energy efficiency (and reducing associated greenhouse gas emissions) of very large metal-metal and metal-carbon electrical connections used by energy intensive metal-winning processes (aluminium, copper, zinc, ferro-alloys). The facility is able to test full scale industrial samples up to 1000 kg in weight, at up to 5000 A DC and 1200 °C in an inert atmosphere. The data being produced supports the development and validation of CSIRO's advanced modelling capability [6], which CSIRO is collaborating on with academia in Australia, Canada and Chile, as well as CSIRO's high performance computing group. The advanced modelling tool is a high-end tool for ongoing numerical studies in this field.

<u>General Specifications</u>

The facility consists of a rolling hearth (bogie hearth) furnace of internal dimensions 1400 mm wide × 1000 mm deep × 900 mm high, Figure 2. The experimental facility has a maximum current output capability of 5,000 A DC being provided by dual 2,500 A DC switch-mode power supplies. The 5000 A DC supply enables contact current densities exceeding 0.2 A/mm^2 for large-scale samples to achieve full physics (i.e. Joule heating). The facility is rated to 1200 °C maximum operating temperature. The purpose-built electric furnace has separate wall and hearth heating with independent control to obtain very accurate sample temperature control. An inert argon atmosphere is provided to achieve an O_2 level below 4% to prevent sample oxidation. The facility is able to induce a predefined temperature gradient within samples to simulate plant conditions more accurately. The resultant temperature profile is verified during testing by both embedded thermocouples and infrared imaging through a specially designed port.

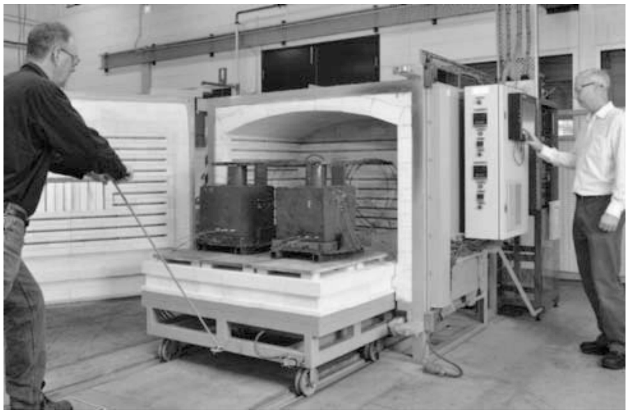

Figure 2. Loading STC test samples into the furnace.

Data Acquisition

All voltage and temperature data are logged using off the shelf components with a purpose written program in LabView 2011. The user interface of this program is shown in Figure 3. The current and voltage output of the power supplies and an in-line DC shunt used for the primary measurement of current in the DC circuit are also logged. All sample voltage drops are recorded as double ended voltage differentials and channel-to-channel isolation to greatly reduce signal noise. Figure 4 shows typical preparation of samples for testing.

Figure 3. System control via integrated touch screen panel.

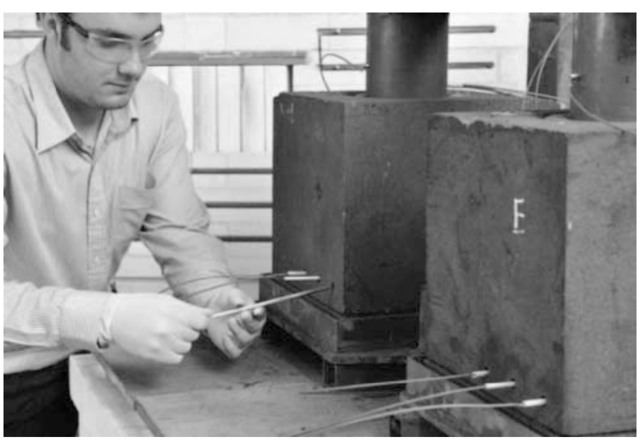

Figure 4. Wiring of the samples for voltage and temperature measurements.

Purpose of this Study

To date there has not been any published experimental data for actual STC performance investigating a range of various stub deterioration and fit-up factors that can contribute up to 50 mV additional STC voltage drop penalty for a smelter. This preliminary study looks to address that deficit for the most common factors being;

- Change in stub diameter
- Gap under stub creating a cast iron ‘pancake’
- Stub located eccentrically in stub hole

Experimental Design

Figure 5 shows the experimental design used for the first testing of STC samples in the new facility. The configurations chosen were similar to those observed in actual operating plants and also similar to those used in computational models that had been published previously [2].

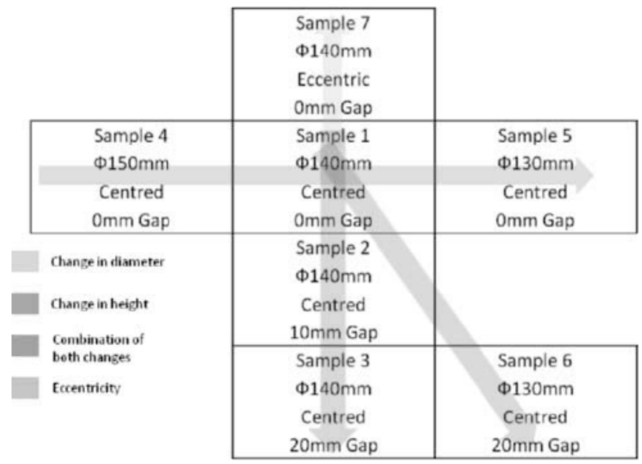

Figure 5. Experimental design.

It was important to have a reference sample that represented normal or baseline conditions (Sample 1). Each variant tested could then be compared back to this reference sample to ascertain the relative effect of the various modes of deterioration and fit-up issues being investigated. The baseline sample used a 140 mm diameter stub placed concentric in the stub hole and flush with the bottom of the anode hole. All stub holes were effectively identical, barring regular production variation experienced in manufacturing operations of real carbon anodes.

From the reference sample the changes were; (i) increase and decrease the diameter of the stub (Samples 4 and 5 respectively), (ii) increase the gap between the bottom of the stub and the base surface of the stub hole in the anode (Samples 2 and 3), (iii) a single sample containing both the smallest diameter and largest gap under stub (Sample 6) to investigate if the effects are additive and finally (iv) one configuration with the stub placed eccentrically within the stub hole such that the stub was placed firm up against one part of the stub hole wall prior to casting to represent toe-in (Sample 7).

Whilst it was preferred to have at least three repeats for each specific sample configuration in the experimental design, there was a scarcity of resources and time to test each of the configurations. Stocks of anodes were limited to those supplied once-off from a donating plant and each test run (two samples at a time) took a full week to set-up and test, excluding the time required to cut the stub hole regions from the donated anodes and casting of each sample in the foundry. Whilst two repeats of each configuration were prepared, only one full pass of the experimental design was completed prior to submission of this paper.

Sample Preparation

Several full sized anodes were received from a smelting plant. The carbon surrounding the stub hole regions was cut out to produce consistent sized samples containing each of the stub holes. Low carbon steel pins were prepared with various diameters and lengths to simulate the required variables, Figure 6. Where a gap was to be introduced underneath the stub, a series of suitably sized chaplets were manufactured and placed inside the stub hole prior to aligning the stub in the stub hole, Figure 7, and securing in place ready for casting.

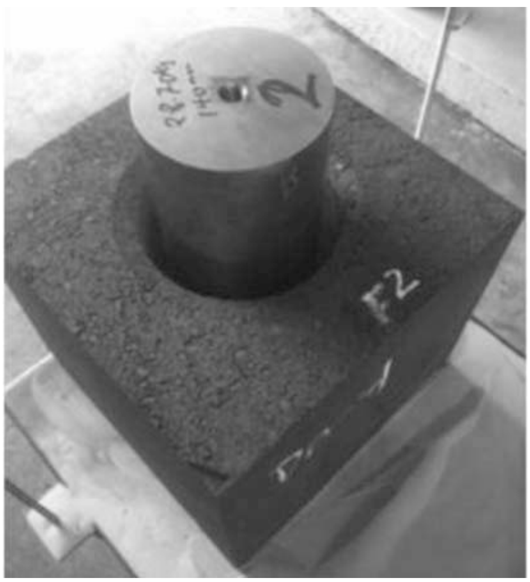

Figure 6. STC sample setup prior to casting.

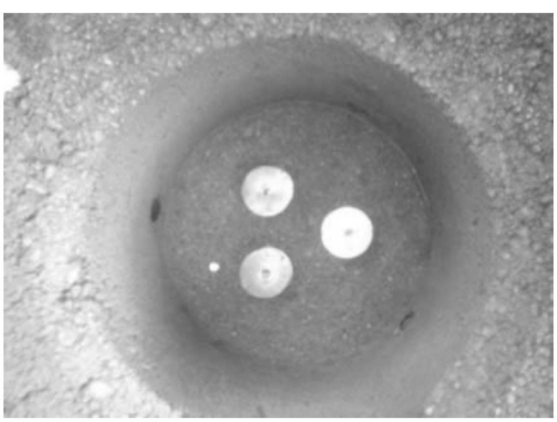

Figure 7. Steel chaplets placed inside stub hole to raise stub up off stub hole base.

Cast iron for rodding was prepared in a 200 kg capacity induction furnace on-site at CSIRO. The cast iron was heated to 1450 °C to ensure thorough mixing of all alloying elements. The furnace power was reduced and the cast iron melt was allowed to cool to 1400 °C. At 1400 °C the furnace power was stopped, samples taken for compositional analysis and the metal poured into the sample, Figure 8, to achieve an actual pouring temperature of 1350 °C. The composition of the standard grey cast iron used in these experiments is shown in Table I.

Table I. Composition of grey cast iron

Element	C	Si	Mn	P	S	Ni	Cr	Fe
Target (%)	3.40	3.40	0.71	0.024	0.008	-	-	Bal.
Actual (%)	3.46	3.19	0.71	0.028	0.016	0.024	0.034	Bal.

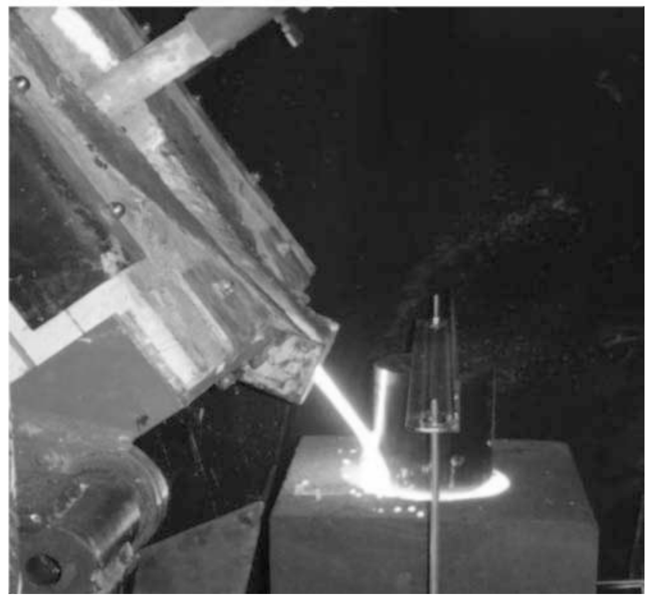

Figure 8. Rodding test samples with cast iron.

Temperature profile during testing

In order to properly simulate the full operating temperature profile experience in a smelter, a method of heating was devised to preferentially heat the STC samples from the base, as shown in Figure 9. The facility has additionally been fitted with a cooling system to enhance the temperature gradient that can be achieved. A temperature differential of up to 120 °C within the stub hole depth can be generated for standard samples.

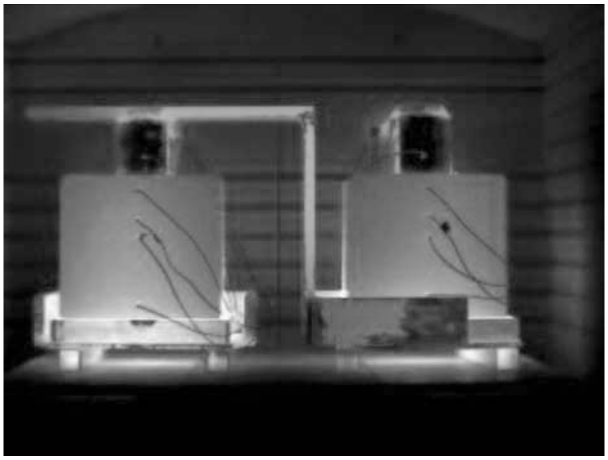

Figure 9. Temperature profile at start of a test.

First results

The following results shown in Figure 10 to Figure 13 represent the first repeat (only) of each of the test conditions from the experimental design. At the time of paper submission the second repeat for each test condition was being undertaken.

STC resistance is calculated from the measured voltage drop recorded between a probe inserted into the steel stub 50 mm above the top surface of the anode and a probe inserted into the carbon in-line with the base of the stub hole, approximately 120 mm down from the top surface of the anode and 70 mm out radially from the interface of the cast iron and the carbon. The temperature data used in the charts was obtained from the same location as the carbon voltage probe.

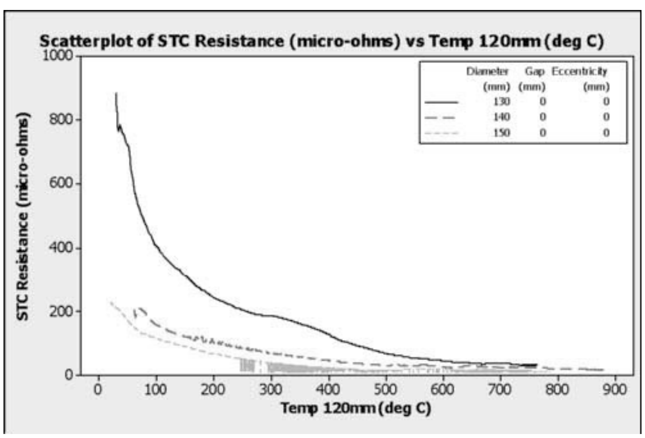

Figure 10. Impact of decreasing stub diameter on STC electrical contact resistance.

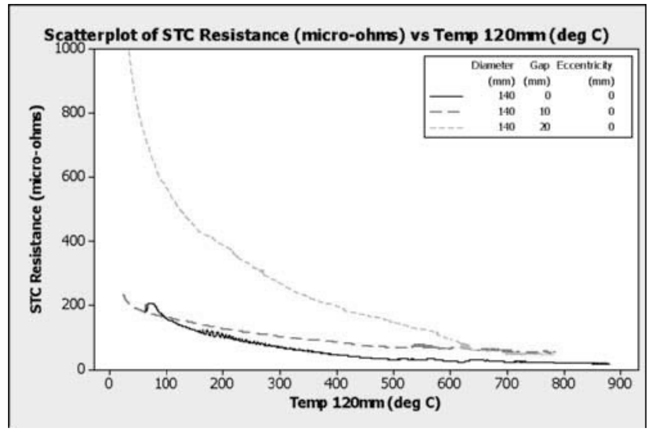

Figure 11. Impact on STC electrical contact resistance of increasing gap under stub.

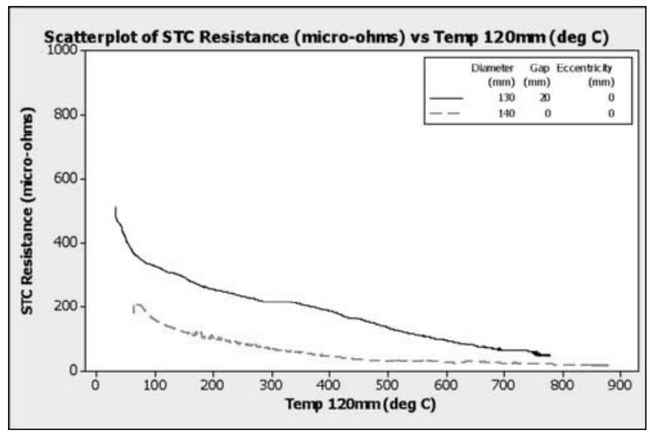

Figure 12. Combined impact on STC electrical contact resistance of both decreasing stub diameter and increasing gap under stub.

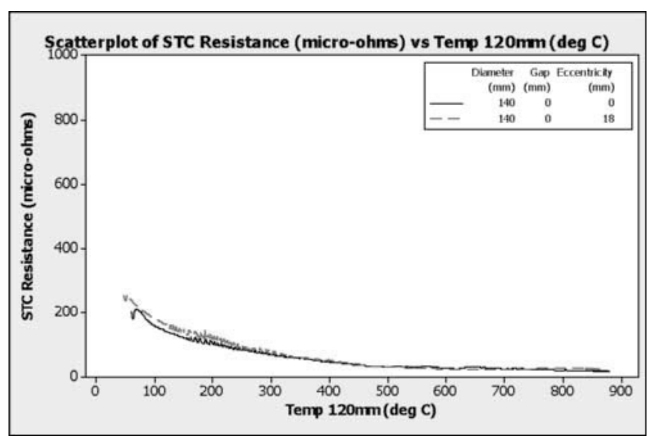

Figure 13. Impact of stub eccentricity in stub hole.

Discussion

The results of the very first tests of STC connections are now discussed.

Reduction in Diameter:
Figure 10 clearly shows the difference in performance between a 150 mm diameter stub, a 140 mm diameter stub and the smaller 130 mm diameter stub, such that the smaller stub (larger cast iron thimble thickness) has a STC resistance some 4 times that of the larger stub (thinner cast iron thickness).

Gap Under Stub:
Figure 11 shows that for a gap that has been introduced to represent variation in stub length there is a quite pronounced effect on STC resistance. Interestingly the effect does not seem to be approximately linear as previously thought, and the impact of the second 10 mm of gap under stub appears to have a substantially greater effect than the first 10 mm.

Combined Diameter and Gap Under Stub:
Figure 12 shows that the effects of both reduced stub diameter and increased gap under stub are not greater than the individual effects. This is contrary to the authors' expectation and further testing is planned to reveal the reasons for this. It is suspected that the samples with the very high STC resistance from Figure 10 and Figure 11 may in fact be due to cracked anodes, either prior to or during testing.

Eccentricity:
Figure 13 shows that for a stub located hard up against the inside edge of a stub hole, as might be expected in the case of an anode assembly having toe-in, there is a small adverse effect on the STC resistance.

The difference in STC resistance for each effect is very much dependent on the specific temperature, and temperature gradient, of the connection in operation. Consequently, a subsequent step in the analysis being undertaken is to convert the data as presented in this paper to a STC resistance difference as a function of operating temperature in the thimble for a target plant.

Additionally, it was observed during the experiments that the current flow shifts across the STC connection with time as the assembly heats up and reaches thermal equilibrium; this effect was also originally observed by Peterson [9].

Concluding Remarks

A robust, accurate and flexible experimental facility has been built to allow investigations for improving the electrical energy efficiency of industrial high amperage electrical connections.

This first investigation for various modes of typical deterioration for the stubs of the anode rod and common assembly fit-up issues shows actual trends of significant increases in electrical contact resistance for the STC connection.

The facility shows promise to undertake more in-depth studies of further factors affecting high amperage electrical connections such as the STC connection. Further work is planned to study the effect of tapered stub tips and loss of lower sections of stub holes representing severe flux wash of the lower part of the stubs.

Recommendations

At least three repeats for each configuration should be tested to confirm the exact response between variables, allowing for potential cracking of, or cracks contained within, samples.

A modification to the testing regime should ensure that voltage readings to be taken across assembly at temperature with current loading 'off' to determine back EMF generated by thermo-electric effect in probe wires, as originally performed by Peterson [9].

Acknowledgments

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