UNIVERSITY OF MANITOBA

Wicket Gate Lever Redesign

Sponsoring Company: Manitoba Hydro

Project Advisor: Paul Labossiere

Team 6: The Wicked Gates

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Letter of Transmittal

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December 5, 2011

Professor P. Labossiere
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Dear Professor Labossiere,

Enclosed is our final design report, submitted by Team 6: Wicked Gates on December 5, 2011. This report details the work we have accomplished on the analysis of the existing wicket gate lever, as well as design details for replacement wicket gate levers. Appropriate engineering justification for the details of the redesign of the wicket gate levers on Manitoba Hydro's Kettle Generating Station is provided.

We would like to thank Manitoba Hydro for their support and support throughout this project. If there are any issues or concerns you may contact any of us on Jump with details and questions regarding this report.

Team 6: Wicked Gates

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Abstract

The purpose of this report is to provide analysis and redesign details on a mechanical component which our client, Manitoba Hydro, has noted are prone to failure. The component in question, a wicket gate lever, serves as a linkage that controls the flow of water in a hydroelectric generating station. After roughly forty years of operation, large cracks have developed in these components. Manitoba Hydro requires a new lever design which will not crack and will remain serviceable until the station is decommissioned.

Strain gauges placed on the wicket gate lever and surrounding components show that the stress at the crack location does not exceed 2.6 ksi. This is in reasonably close agreement with the finite element analysis and hand calculations performed on the part, which evaluated the stress at the crack location as 2.1 ksi and 2.7 ksi respectively. All of these stresses are well below the estimated endurance strength of 8.16 ksi for the ASTM A27 steel used in the wicket gate's construction, which should indicate an infinite fatigue life of the part.

After performing the above analysis and examining the wicket gate levers, our team has determined that the failure of the wicket gate levers cannot be due to excessive stress, and the only other reasonable cause of failure is poor material quality and casting. Surface defects, large deviations in the as-cast part, and large voids would aid in crack initiation and propagation in the wicket gate levers. These flaws are therefore the only plausible cause of failure.

In order to rectify these problems, the material, manufacturing process, and geometry of the part have been changed. Cold wrought ASTM A36 plate steel will be used in order to facilitate the machining and welding processes to create part. Geometric changes have been made to reduce stress concentrations and provide weld surfaces. The machining process will provide a smooth surface finish, allow for very consistent and precise geometry, and eliminate any voids which would occur during the casting process.

Since the strain gauge analysis indicates low stress levels throughout the wicket gate lever relative to the yield stress, and since the new design improves upon the material qualities, cracking will not occur in the part. Overall, the new wicket gate lever is expected to remain in service after it is built, and will last until the station is decommissioned.

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Glossary

Crimp	Sealing edge formed between the wicket gates as they are forced closed to prevent water from entering the turbine pit. The position of the wicket gate assembly and servo motor when crimp occurs is known as the crimp position.
FEA	Finite Element Analysis, a computational method in which a problem, such as stress analysis of a complicated part, is broken down into many smaller problems which can be solved simply
ksi	Thousands of pounds per square inch; 1 ksi = 1000 psi
σ_y, Yield Strength	The maximum stress which a material can withstand before permanent, or plastic deformation occurs
Ultimate Strength	The maximum stress a material can withstand before failure; usually determined for tension tests.
Endurance Strength	The maximum stress which a material can repeatedly withstand under cyclic loading conditions. Endurance strength is estimated as one third of the yield strength as a general guideline for Manitoba Hydro.
GS	Generating Station
Cascading failure	Failure of a component which leads to damage and failure of surrounding components

1 Introduction and Background

The purpose of this report is to provide analysis and redesign details on a mechanical component which our client, Manitoba Hydro, has noted is prone to failure. The following sections will provide detail on the problem background, objectives, specifications, and constraints.

The Manitoba Hydro Kettle Generating Station (Kettle) began producing electrical power in the early 1970s. The station is a large hydroelectric dam, comprised of twelve large electric generators, known as units. Kettle is one of the largest stations in Manitoba: the total output of all units exceeds 1200 megawatts [1].

To produce power for the North American electrical market, the units must run at the correct speed in order to generate electricity at the correct frequency. The flow of water into each unit must be carefully controlled to keep the generator running at the proper speed and power output. If there is too much water flowing into the unit, the generator will run in a condition known as overspeed; if there is too little flow, the generator will not run at the proper frequency or efficiency. To regulate the flow into each unit, a series of large gates are located around the intake of the turbine. These gates are known as wicket gates. A typical turbine is shown in Figure 1.

Figure 1. Turbine units with wicket gate [2]

Each unit at Kettle has twenty wicket gates. Each gate has an aerofoil shape, and runs parallel with the axis of the turbine shaft. The gates can turn between zero and nearly ninety degrees, from fully closed to fully open. Water flows through the gate at a rate dependant on the angle. Every gate is connected at the top of its rotating stem to a large cast steel lever. This lever is connected with pin joints via a linkage to the operating ring. The operating ring is a large steel ring with a diameter nearly the size of the turbine, and is used to control the position of all twenty wicket gates simultaneously. The details of how each component is interconnected are shown in Figure 2.

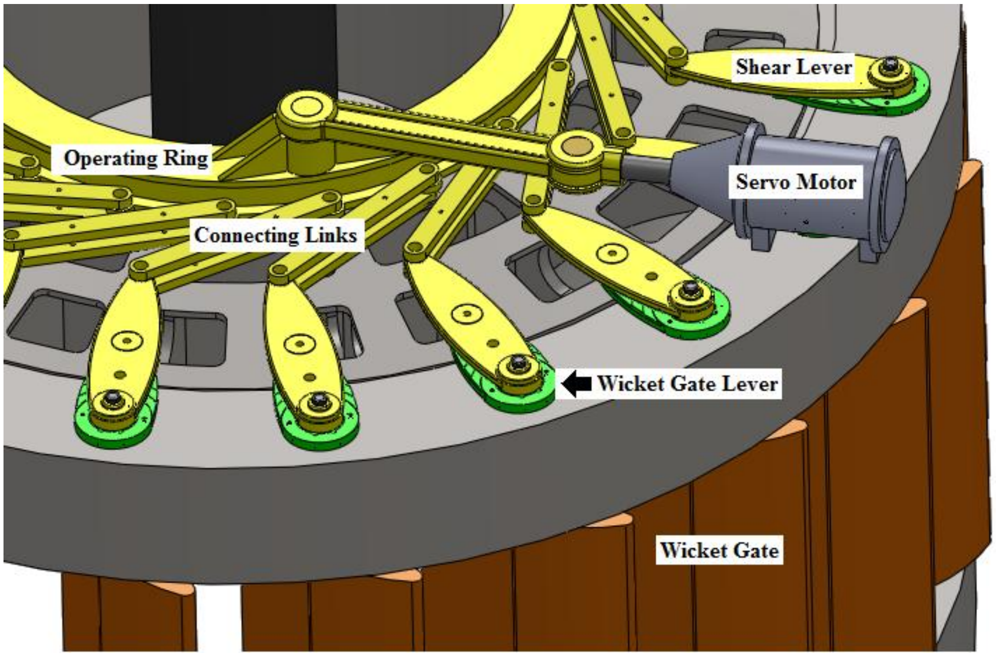


Figure 2. Wicket gate assembly interconnections [3]

The wicket gate lever is the primary focus of this project. This lever transmits all of the force from the operating ring to the wicket gate. Failure of the lever can result in a cascading failure of many of the other components, resulting in severe damage to turbine components.

Previously during a routine inspection of the turbine components, a maintenance crew discovered cracks developing in the wicket gate levers. These units have been running consistently for thirty years without issues in this particular component. Due to the large timeframe between inspections, there could be numerous causes to the cracks; it was unknown whether the cracks are from fatigue, casting imperfections, or some other cause.

Under normal operation, the force transmitted by the wicket gate lever is primarily from water flowing over the gate. This force is theoretically known, and the levers have been designed to handle this type of loading. However, the wicket gates are closed completely any time the unit is shut down. When the wicket gates are closed, they are rotated until they touch, and then rotated slightly further to apply a force to the sealing edge. This process ensures a watertight seal and is known as crimp. During the crimping procedure, the forces acting on the wicket gates and wicket gate levers are unknown. The unknown forces are potentially much larger than the anticipated force, and are a possible cause of the cracking in the levers.

Initial searches for further information regarding wicket gate levers have shown that several patents relating to wicket gates exist, such as [4], [5], [6], and [7]. However, these patents came out around the time at which Kettle GS was built, and have since expired. The geometry for most wicket gate lever designs is quite similar to that shown in Figure 2.

The overall goal of this project is to determine the cause of the cracking in the wicket gates, and create a new design which is more resistant to fracture. The project will be primarily analytical in nature, as the geometry of the system makes radical changes to the current design impractical. The following sections of the report will further discuss the project objectives and constraints.

2 Objectives and Scope

There are two primary objectives for this project. The first objective is to perform a complete analysis of the current wicket gate design in order to determine the cause of the cracks. The second objective is to use the analysis of the current lever in order to design a new wicket gate lever.

These primary objectives are further broken down into several secondary objectives. We have broken down the first objective, analysis of the current design, into a preliminary analysis of the theoretical loads, a secondary analysis of the actual loading situation, and a comparison of the two analytical techniques with conclusions about their implications. The second objective, design of the new wicket gate, will consist of concept generation, selection, and justification of the design.

Analysis of the current wicket gates is detailed in Section 5, Analysis of Wicket Gate Lever, and includes the strain gage analysis, fatigue analysis, and FEA of the wicket gate. The design of the new wicket gate is detailed in Section 6, Proposed Redesign, which provides details on the design features and provides justification for the part.

3 Client Needs and Specifications

The primary requirement of the wicket gate lever is to transmit the forces applied by the shear pin to the wicket gate shaft. The wicket gate lever is required to hold the wicket gate at any required position, and must be capable of applying required force to reach crimp condition. The part must have a long operational life span, on the order of 10^5 operating cycles, or 100 years. The part must fit into the existing geometry. In order to accommodate the long life of the part, the wicket gate lever should be low maintenance, and should not require that the unit be dewatered and shut down for inspection to occur. To address the need for long operational life, Manitoba Hydro's requirement that stresses in the part must not exceed one third of yield stress was used.

Furthermore, Manitoba Hydro has several specifications and standards for the analysis in the report. The modelling must be done using Autodesk Inventor, and the FEA must be performed in ANSYS. Further requirements about the FEA are listed in Section 5.3.

4 Constraints and Limitations

While the project design should ideally meet or exceed all target specifications, there are several limitations and constraints which must be considered, for the new design.

The primary design constraint is one of geometry. As mentioned in Section **Error! Reference source not found.**, the function of the wicket gate lever is to act as a mechanism link to transfer a torque from the control ring through the shear lever to the wicket gates. Therefore, the wicket gate lever redesign must have a compatible interface between the wicket gates and the shear lever. The primary dimensions of the previous design are shown in [8] and summarized in [9]; however, these drawings may not be reproduced. Of the primary dimensions, it is critical that the locations of the shear and dowel pins, as well as internal shaft diameters, remain compatible in the new design. Critical dimensions are shown in the following table.

TABLE I CRITICAL GEOMETRY [9]

Component	Dimension [inch]	Notes
Shear Pin Hole	2.00	Inner Diameter
	28.00	From wicket gate shaft hole
Wicket Gate Shaft Hole	9.50	Inner Diameter
	14.995	Outer Diameter
Taper Pins Holes (3X)	0.658	Radius
	±60°	Locations from centerline of wicket gate shaft hole

In addition to interface compatibility, the design must be sized appropriately, such that it does not interfere with any other components of the turbine structure. For reference, the current design has the following nominal outer dimensions: length 40.5”, height 10.5”, and width 20” [8].

The strict limitations on the design geometry have further implications for the quality of the final design with respect to tolerances and deformability. Current tolerances on the wicket gate lever are on the order of 0.001” [9]. These tolerances should remain tight within the typical operating temperature and during normal loading operations.

A final project constraint is compatibility with Manitoba Hydro standards. These include the use of Autodesk Inventor for the CAD modeling and ANSYS for the FEA.

5 Analysis of Wicket Gate Lever

Analysis of the wicket gate lever was completed in several stages. Hand calculations were performed to estimate the magnitude of the stresses in the part. These were followed by analysis of the part using physical data from strain gauges, as well as analysis using theoretical models with finite element techniques. Fatigue analysis of the current wicket gate lever, as well as a qualitative analysis on the overall quality of the wicket gates, were also performed by the team.

5.1 Strain Gauge Analysis

Prior to the analysis of the wicket gates performed over the course of this project, the force and stress in the wicket gate control system was known only theoretically. Due to the theoretical basis of this information, there have been many questions about the magnitude of the actual loads and stresses the system may experience, both during operation, and while the generator is shut down. The initial concern was that the cracking of the wicket gate lever was due to overloading during crimp when the unit is shut down. However, this was only speculative. To determine the actual loading and stress the system experiences, two gate control assemblies were instrumented with 14 strain gauges and a string potentiometer to measure the strain during various points of operation. An image of a strain gauge applied to the wicket gate lever is shown below in Figure 3.

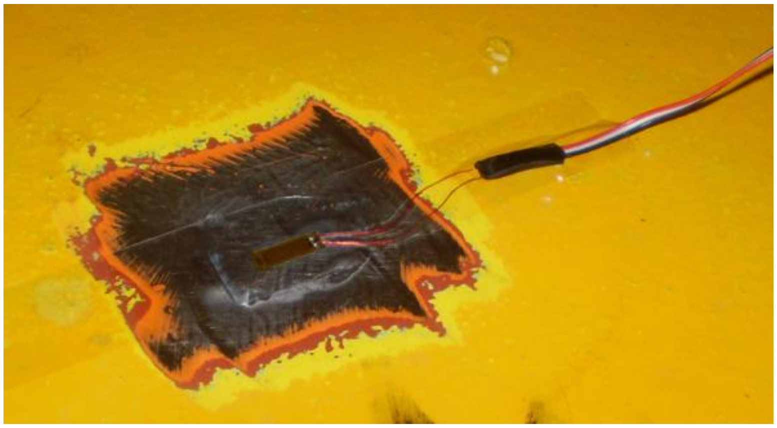


Figure 3. Strain gauge installed on wicket gate lever [3]

The gauges were installed to directly measure the strain at the crack location as well as other positions in both the wicket gate lever and shear lever. Strain was measured in other locations, such as the shear leaver, so that the force on the wicket gate levers could be calculated independently. In addition to the strain gauges, a linear string potentiometer was installed on the generator servo to simultaneously measure the position of the wicket gates. The string potentiometer is shown in Figure 4.

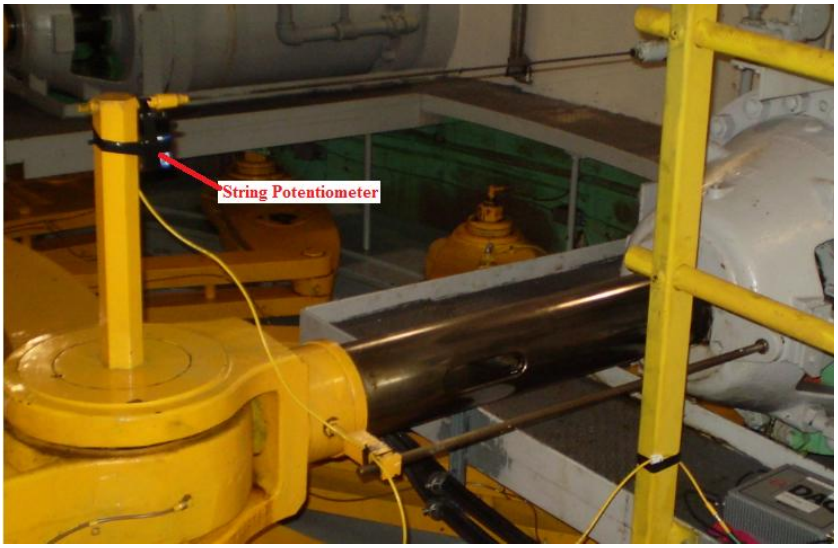


Figure 4. String potentiometer attached to generator servo [3]

All strain gauges and the string potentiometer were connected to a Somat eDAQ data acquisition system to simultaneously record the measured strain and gate position during operation. A full understanding of the loading scenario was obtained by measurement of both the strain and the gate position. Plotting the strain against gate position allowed us to determine the gate position the generator is operating at when maximum stress occurs. Figure 5 below shows how the eDAQ system and instrumentation were connected.

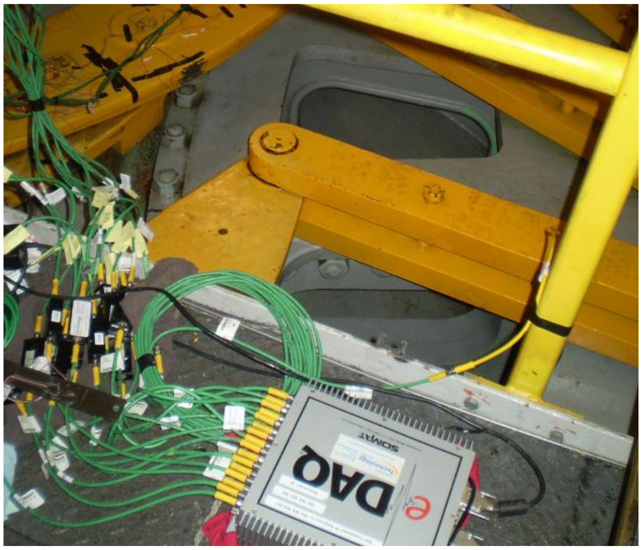


Figure 5. Somat eDAQ data acquisition system [3]

The data acquisition system was used to record over 30 hours of data at a 100Hz sampling rate. Several operating tests were performed to determine the strains at all wicket gate positions. Tests were also performed to determine the strains relating to the crimp position, as well as when the unit was starting up or shutting down. Testing was also performed with the generator connected to the electrical grid to determine operational loading.

After initial application of all strain gauges, all the strain gauges were zeroed with the unit dewatered. Zeroing under these conditions ensured that the set zero point is truly a point of no load on all the wicket gates and control components. Zeroing the strain gauges allowed us to determine the magnitude and direction of all loads on the wicket gate levers, as measured from an absolute reference point.

Due to the rough nature of the cast parts, application of the strain gauges proved to be more difficult than expected. In some cases, the surface roughness required a large amount of material removal in order to create an area of sufficient size and surface finish to apply the strain gauges. This surface roughness may have resulted in an imperfect bond between the strain gauges and the wicket gate assembly. Typical surface roughness is shown below in Figure 6.

Figure 6. Casting imperfections and surface roughness on the cast components [3]

Initially, the cracks were thought to have occurred due to overloading of the levers while in the crimp position. However, analysis of the strain data shows that the greatest stresses do not occur from crimp. The highest stress occurs during normal operation of the unit. Figure 7 shows the stress at the crack location for various positions of operation. The plot includes data from offline testing of the unit as well as loading when the generator is online and connected to the electrical grid. It should be noted that during online operation the generator operating position is beyond our control. Due to this limitation, data for online operation could only be collected while the wicket gates were between 40% open and 90% open, and not for the full range of motion of the wicket gate assembly. During the offline testing of the unit, the wicket gates were forced from the crimp position up to 90% open in order to determine when the maximum stress occurs. Figure 7 shows the stress in the wicket gate lever at the crack location during both online and offline operation.

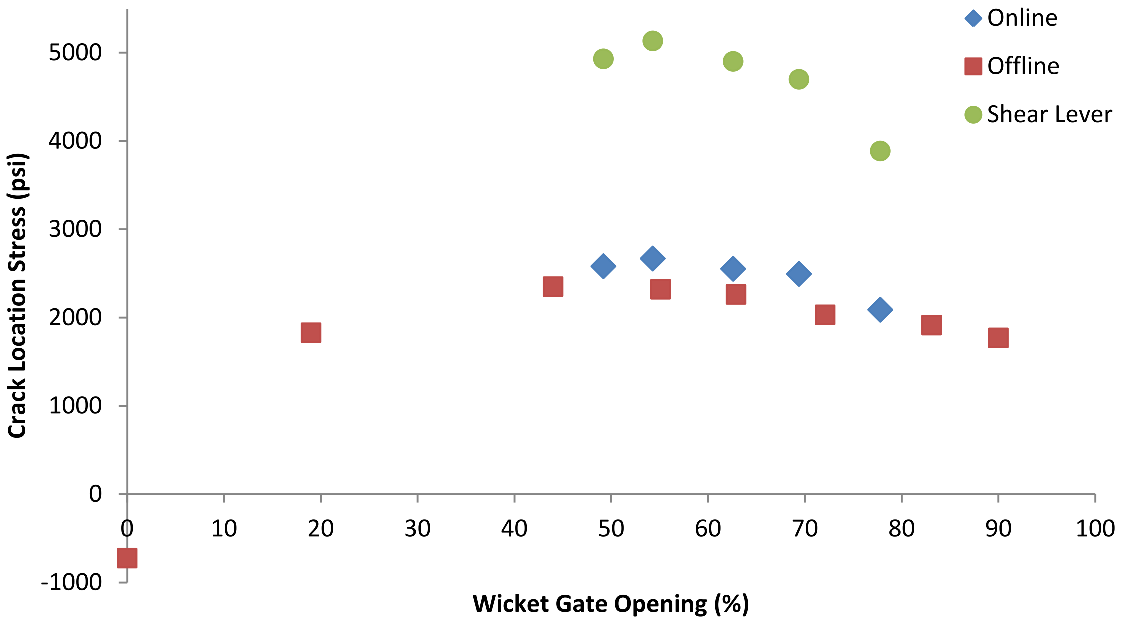


Figure 7. Stress at the location of the crack during unit operation

The crack location of the lever is under compression while in the crimp position (0% wicket gate opening), then reverts to tension as soon as the gates open. From this point, the stress increases to their maximum value at 55% gate opening, then begins to decrease. At the operating position of maximum loading, the stress at the crack location is 2,600 psi; this is well below the yield strength of 27,000 psi for A27 steel.

As a comparison, operating stress in the shear lever is also shown in Figure 7. The shear lever is cast from the same material as the wicket gate lever, and experiences nearly double the stress during operation. However, there has not been any indication of cracking or failure of any kind in the shear lever. If failure had occurred due to excessive stress in the wicket gate lever, then similar failure would have already been apparent in the shear lever.

In addition to determining the stress at the crack location, the data from the strain gauges has been used to determine the loads the system is subject to during operation. Figure 8 shows the force transmitted from the operating ring to the shear lever at various gate positions. The data in Figure 8 was used to determine the input loads for our FEA on the current lever and to help with the design of the replacement lever. In order to design a replacement lever, it was necessary to determine the maximum force which the lever must bear. Load data was used to determine appropriate sizing for the welds and overall geometry of the design.

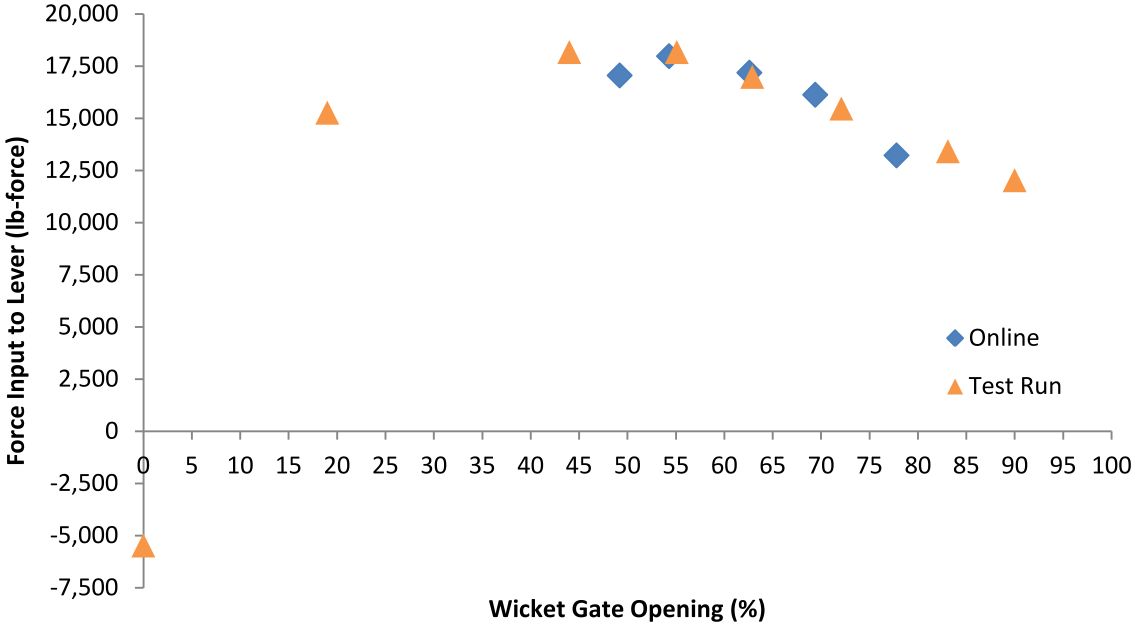


Figure 8. Input force to the shear lever during operation

Figure 8 shows that the force necessary to control each wicket gate approaches 20,000 pounds at maximum loading. Crimp loading of the gates involves only 5,500 pounds of force.

5.2 Fatigue Analysis

The fatigue analysis began by calculating the endurance strength of the material, using the process identified in [10]. The ultimate tensile strength of the material is found from [11]The nominal endurance strength is then calculated based on this value; since the A27 of the original design is as-cast, the nominal endurance strength is lower than that of the machined A36. The material factor for cast steel effectively lowers its endurance strength by a further 80%. Since these parts are quite large, and fatigue data is usually obtained from small test specimens, a size factor of 0.6 is applied to both parts, in order to account for the increased probability of local defects. From these factors, the actual endurance strength is calculated, and compared to the one-third of yield stress criterion which Manitoba Hydro uses. The reliability factor is ignored in favour of a safety factor, which is preferred by Manitoba Hydro. Results from the fatigue analysis are summarized in Table II.

TABLE II FATIGUE PROPERTIES

Material	A27	A36
Ultimate Tensile Strength [ksi]	65	58
Yield Stress [ksi]	35	36
Nominal Endurance Strength [ksi]	17	24
Material Factor	0.8	1
Size Factor	0.6	0.6
Actual Endurance Strength [ksi]	8.16	14.4
Design Endurance Strength [ksi]	8.16	12

The fatigue analysis gives a rough estimate for the maximum allowable stress amplitude for cyclical loading. Since the maximum stress in the wicket gate lever does not even reach half of the design endurance strength, the fatigue analysis can be stopped here, as it is not possible for the part to fail under fatigue given these values for the endurance stress without another external factor.

The fatigue analysis approach is limited in that it is difficult to account for the exact surface conditions and finish, as well as the difficulty in finding endurance data due to the large amount of work required to perform such tests. Overall, the fatigue analysis can only serve as an estimate to the allowable stresses in the material, and generous safety factors are required when the parts are of particularly low quality, such as the original cast wicket gates.

5.3 Finite Element Analysis

One of the analysis tools used to conduct an analysis of the wicket gate lever was FEA. This type of analysis is used to provide insight into the behaviour of the wicket gate lever, and to determine relative stresses. Accurate and consistent FEA requires that the stresses in discrete elements converge as the number of elements increase, and that the stresses show smooth transitions between elements.

Early in the project, an initial FEA was conducted. This analysis was used only to examine relative stresses. In this preliminary analysis, it was determined that the crack locations are not the locations of highest stress, and that the stress magnitude was on the order of one tenth of the yield stress at the crack location.

After we completed our strain gauge testing, the data collected with the strain gauges was taken and used to find the load applied to the wicket gate lever: approximately 20 000 lb. This load value was used in the FEA to find the strains at the locations the strain gauges were applied. The values from the

FEA and the values from the strain gauge testing could then be compared. The process of FEA requires checking to see if the results are valid by checking that the values will converge when refining the mesh ad to check that the mesh is free from large errors. Stresses were analyzed in depth at three critical locations: location 1, where the crack initiated; location 2, directly opposite to the crack; and location 3, the location of maximum stress on the side of the lever. These locations are shown in the figure below.

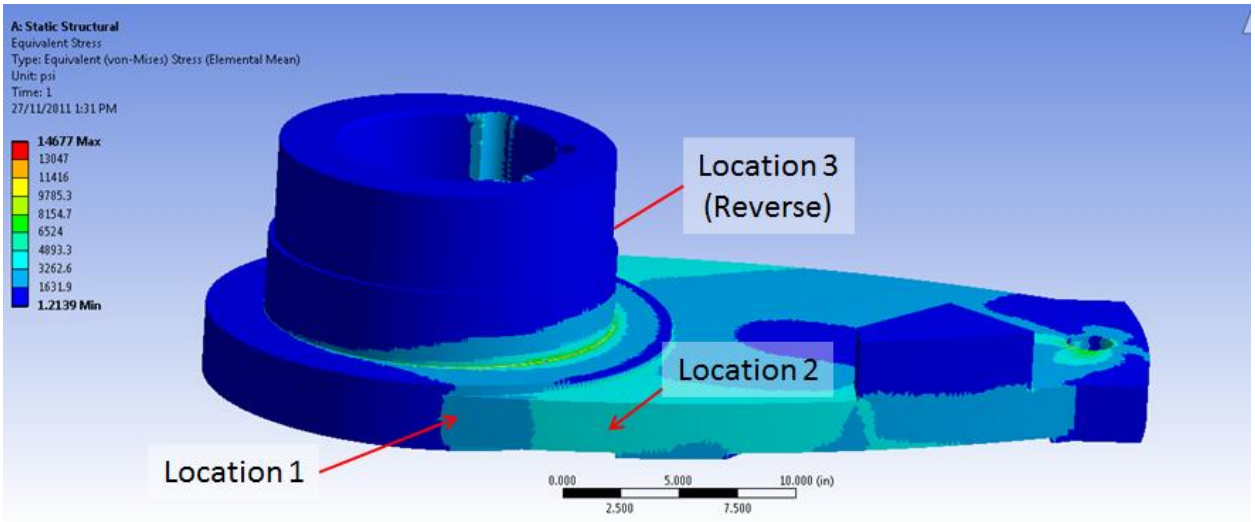


Figure 9. FEA results and locations of interest

5.3.1 Element Size and Convergence

The FEA needs to have conditions checked to make sure that the results are meaningful. The results must be convergent; that is, as the size of the mesh decreases and the number of elements increases, the value of the results must converge. Furthermore, there must not be large discrepancies of the values of stress between adjacent elements. Manitoba Hydro stated that the criterion for FEA is that grid independence be 5%. Therefore, the value of stress in an element cannot be more than 5% less than or greater than any adjacent element. To check for convergence of the FEA, the analysis was run at several grid sizes. The grid size is defined by the average length of one edge of the tetrahedral elements used. The mesh size for the first iteration was set to 1.00”, and was decreased by intervals of 0.25” down to 0.25”. The testing was not conducted at elements smaller than 0.25” because system was returning acceptable results, and further size reduction resulted in prohibitively long computational time. Table IV and Table V show the results of the FEA for four different elements sizes at the three most critical locations on the wicket gate lever.

TABLE III CONVERGENCE OF STRAIN FOR MESH REFINEMENT

Strain (με)	Average Mesh Size			
Location	**1.00 in**	**0.75 in**	**0.5 in**	**0.25 in**
1	72.8	72.8	72.1	71.6
2	-61.3	-61.3	-60.2	-59.6
3	-113	-113	-112	-111

TABLE IV CONVERGENCE OF STRESS FOR MESH REFINEMENT

Stress (ksi)	Average Mesh Size			
Location	**1.00 in**	**0.75 in**	**0.5 in**	**0.25 in**
1	2.097	2.096	2.072	2.056
2	2.098	2.105	2.071	2.055
3	3.890	3.890	3.837	3.808

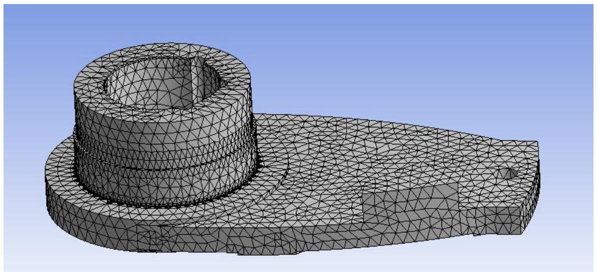


Figure 10. FEA with 1" mesh

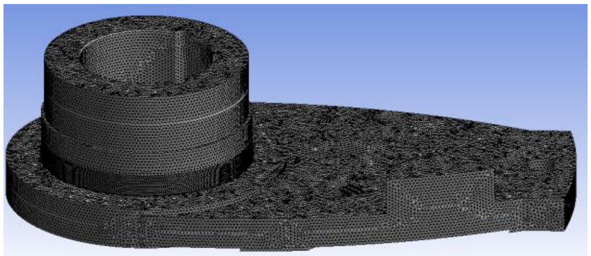
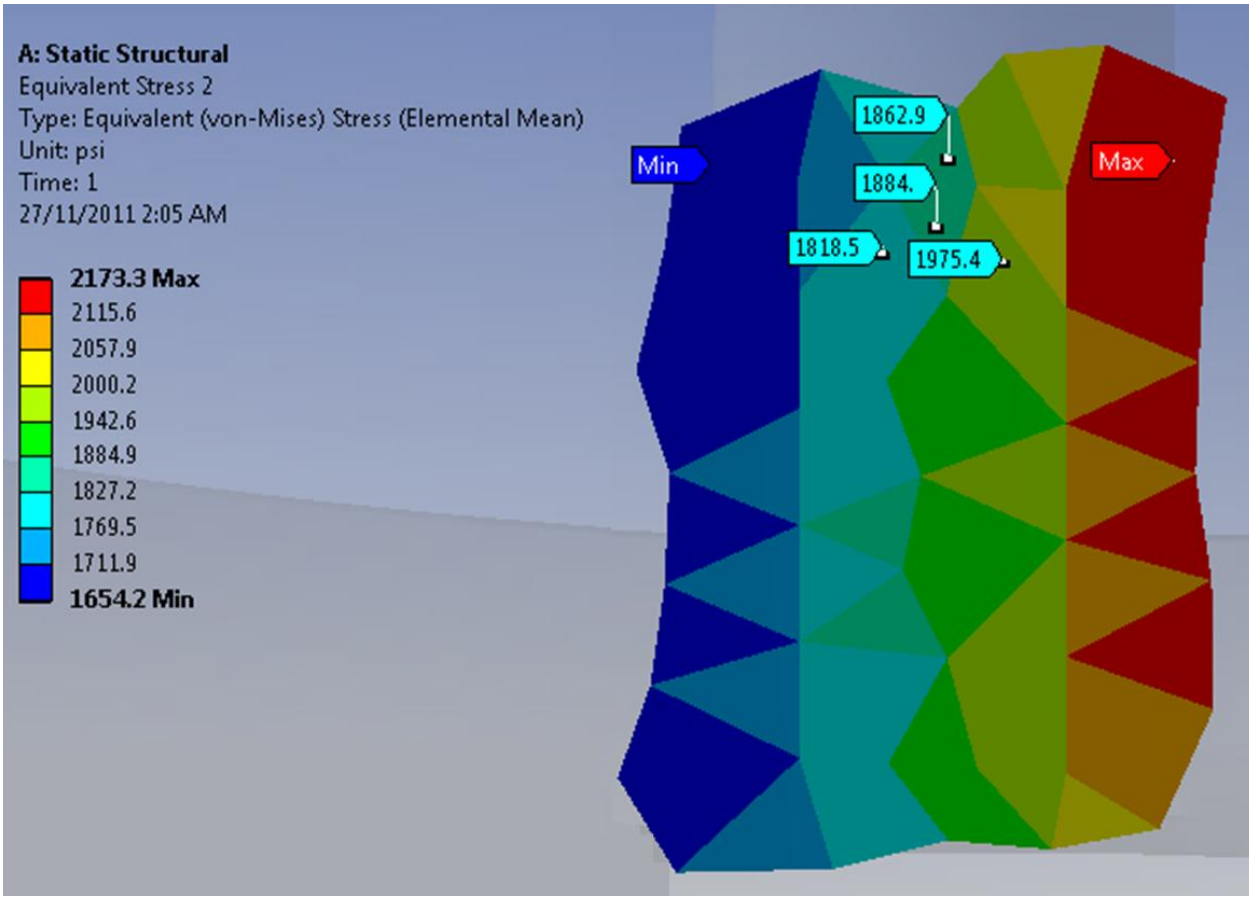


Figure 11. FEA with 0.25" mesh

In each step for all locations the change of stress is less than one percent. This shows that the stresses are converging and the results have an accuracy of 1%. To check the elements for their relative stresses, an evaluation of these results was conducted. A detail of the ANSYS results for the FEA around the crack location is shown in Figure 12. The flags show the stress of an element and the four surrounding elements. The value difference between these elements is well under the 5% required by Manitoba Hydro.



A: Static Structural
Equivalent Stress 2
Type: Equivalent (von-Mises) Stress (Elemental Mean)
Unit: psi
Time: 1
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Figure 12. Detail of FEA results at crack location, showing less than 5% variation between adjacent elements

With the FEA showing convergence and grid independence, the data can now be compared to the strain gauge data.

5.3.2 FEA Reults

The data from the FEA and the data from the strain gauge testing is summarized below for the three points of interest on the wicket gate lever.

TABLE V COMPARISON OF STRAIN DATA FROM FEA TO STRAIN GAUGES

Strain (με)	FEA	Strain Gauge
Location 1	71.6	92.0
Location 2	-59.6	-36.0
Location 3	-111	-55.0

TABLE VI COMPARISON OF STRESS DATA FROM FEA TO STRAIN GAUGES

Stress (ksi)	FEA	Strain Gauge
Location 1	2.06	2.67
Location 2	-2.06	-1.04
Location 3	-3.81	-1.60

The FEA data and strain gauge data for location one, the crack location, matches within predicted levels. The FEA data for the other two locations does not match with the strain gauge data, but are still within the same order of magnitude and are well below the maximum acceptable stress in the part. The cause of the discrepancies needs to be examined. The discrepancies found between the FEA and strain gauge data are to be expected because of problems in the geometry and surface finish of the part. The part has a very rough surface finish causing the location of the strain gauge placement to be very important to the results generated by the testing. If the strain gauge is placed out of alignment or on a rough spot the value generated by the strain gauge will not be accurate. This surface finish problem coupled with the fact that the parts as manufactured do not match the drawings geometry as discussed in the qualitative analysis below. These defects cause the data of the strain gauges to have the potential for a large error. The nature of FEA also causes the possibility of error in the results generated, and therefore the fact we have data showing that the stresses are within the same order of magnitude gives us an estimate of the level of stress the part is experiencing. Also, as both FEA and Strain gauge data shows that the stresses are very far below the maximum design stress, the stresses in the part should not be a cause of failure.

The data collected from the strain gauge and the results of the FEA are close for the crack location. This data was used to create a correction factor for the crack location. The strain gauge data at the other tested points is a larger magnitude larger than in the FEA. The stress at the crack location according to the strain gauge data was 2668 psi and the stress according to the FEA was 2056 psi. The correction factor is 1.298.

5.4 Qualitative Analysis

The casting of the current wicket gate lever is an extremely poor quality. There are major surface defects and this suggests that there may also be significant internal defects. Manitoba hydro never did any metallurgy analysis on the parts so the internal quality is unknown but the surface defects alone could cause stress concentrations on the part. As the following picture demonstrates there is porosity that is visible with the naked eye.

Figure 13. Porosity defects [3]

Also the casting leads to the geometry of the part not to correctly match the original drawings. The following picture shows this on several levers the point where the crack is occurring is not a smooth curve onto the stem.

Figure 14. Surface defects [3]

The lever that strain gauge testing was conducted on is shown below. Even though it was one of the best surfaces, it can also be seen to have defects at the crack location.

Figure 15. Tested lever [3]

Finally a note should be taken that some lever may have even larger defects on them. The original supplied information about the levers cracks also included pictures one of which is below, and clearly displays a large void in the surface of the lever only a few inches from the crack.

Figure 16. Casting void, used with permission of Manitoba Hydro

The cracks that did occur are not alarming as the total number of levers that had cracked was 5. This is a low number of the total 240 gates and account only for 2% of the total number of gates. Overall, the current set of wicket gate levers is mostly able to withstand typical loads operating, despite the presence of severe material flaws and inconsistent geometry.

6 Proposed Redesign

In order to solve the problems with the current wicket gate levers, our team has proposed a redesign of the existing levers, for use in the event of future failures. This section overviews the design requirements, design features, drawings, cost estimates, weld design, and overall design justification.

6.1 Design Requirements

The primary requirement of the wicket gate lever is to transmit the forces applied by the shear pin to the wicket gate shaft. The wicket gate lever is required to hold the wicket gate at any required position, and must be capable of applying required force to reach crimp condition. The part must have a long operational life span, on the order of 10^5 operating cycles, or 100 years. The part must fit into the existing geometry. In order to accommodate the long life of the part, the wicket gate lever should be low maintenance, and should not require that the unit be dewatered and shut down for inspection to occur. To address the need for long operational life, Manitoba Hydro's requirement that stresses in the part must not exceed one third of yield stress was used.

6.2 Design Features

There are three primary design changes from the existing wicket gate levers. These changes are to the material, manufacturing process, and geometry of the design.

6.2.1 Material Changes

The wicket gate levers had been designed to be made from Grade 65-35 ASTM A27 steel [11]. For the new design, however, ASTM A36 cold wrought plate steel will be used [12]. Both steels have similar properties, as shown in Table V.

TABLE VII MATERIAL PROPERTIES OF A27 AND A36 [11], [12]

Material	A27	A36
Yield Strength [ksi]	35.0	36.0
Ultimate Strength [ksi]	65.0	58-80

However, A36 steel was chosen for several reasons. The first is cost: A36 steel Is significantly less expensive compared to other grades. Furthermore, A36 is a widely available material, and Manitoba Hydro had noted that they could quickly and easily procure A36 steel in the event that a replacement part is required quickly. Finally, A36 steel is easy both to weld and machine, thus simplifying the manufacturing process.

6.2.2 Manufacturing Changes

Originally, the wicket gate levers had been manufactured using a sand casting process. While this process was relatively simple and fast when the unit was commissioned and a large number of parts were needed, casting for a very small number of replacement wicket gates is not nearly as efficient.

The casting process had likely introduced the many material flaws and defects, which are detailed in Section 5.4. In order to prevent these flaws and defects, the part will now be made of cold wrought plate steel. The part will be machined in three sections, and these sections will be welded together to form the completed design, as shown in the drawings in Section 6.3.

6.2.3 Geometric Changes

In order to provide a surface on which to weld the components of the new wicket gate, the radius around the wicket gate lever stem on the wicket gate lever arm was increased. Furthermore, by making this circular profile tangent to the side of the wicket gate lever arm, stress concentrations are avoided in this design.

Other geometric changes were minimal and not relevant to the stress analysis of the part, such as a minor modification to the stop block location; changes to the material and manufacturing process are sufficient to prevent future failure of the wicket gate lever.

6.3 Drawings

Included below are drawings to show general part geometry. Refer to full drawings appended to this report for further details.

BILL OF MATERIALS			
ITEM	QTY	DESCRIPTION	MATERIAL
1	1	LEVER STEM	ASTM A36 STEEL
2	1	LEVER ARM	ASTM A36 STEEL
3	1	STOP BLOCK	ASTM A36 STEEL

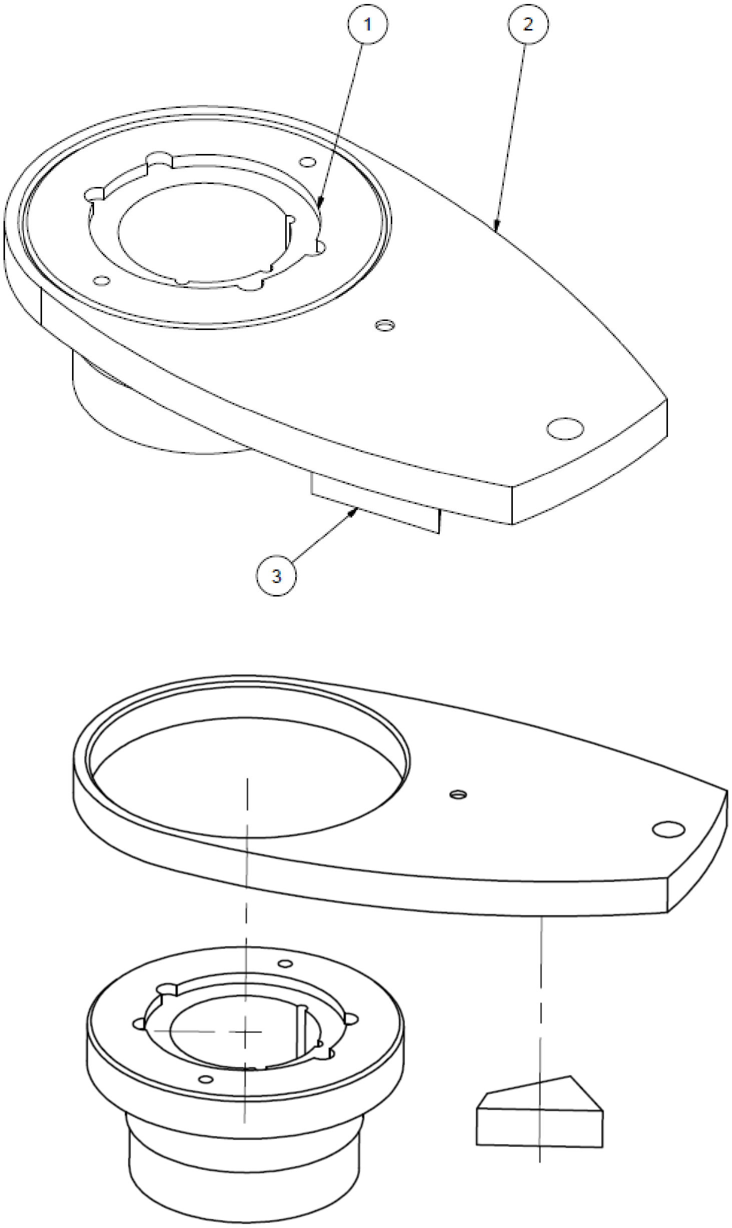


Figure 17. Proposed wicket gate lever assembly with exploded view [3]

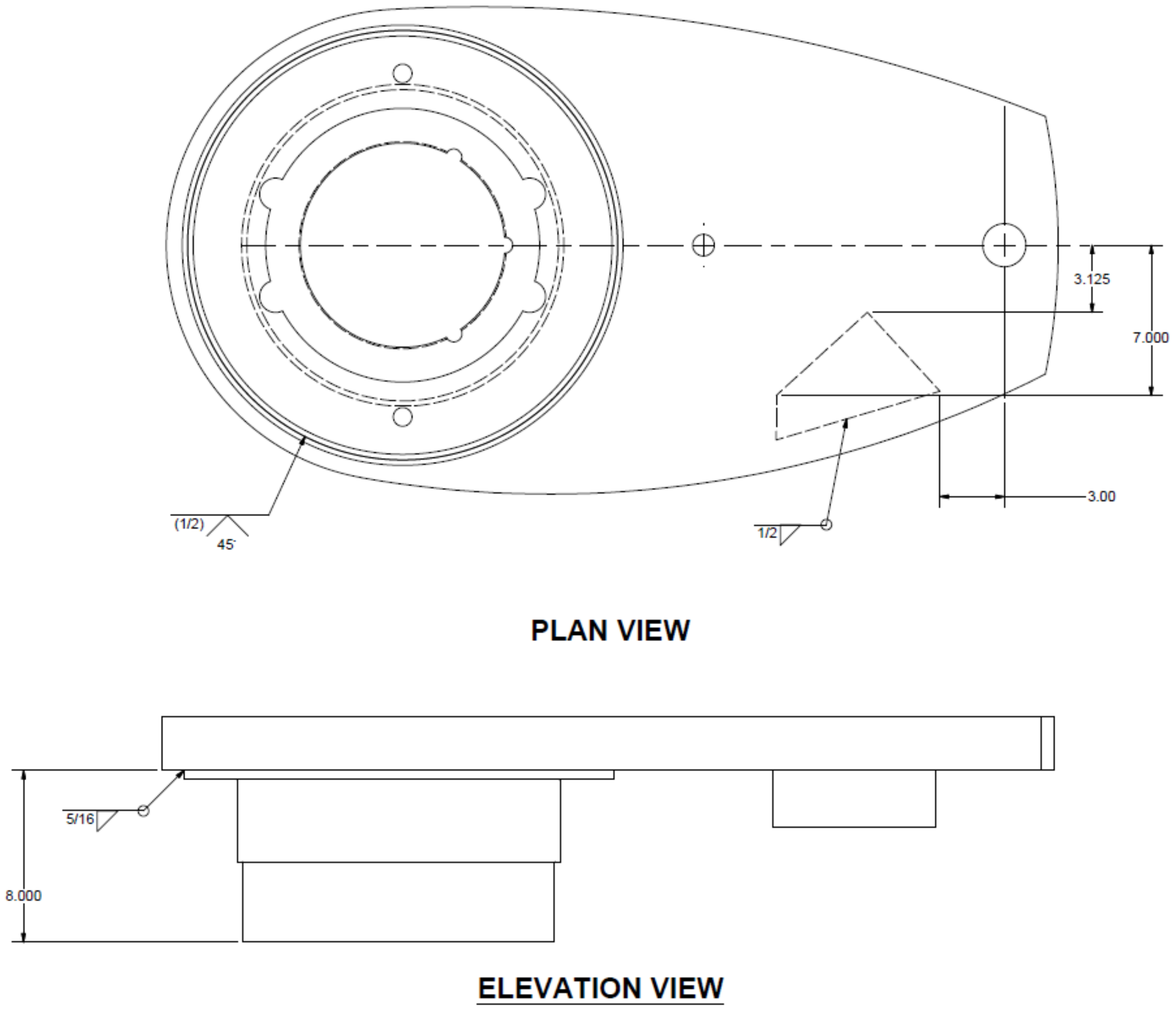
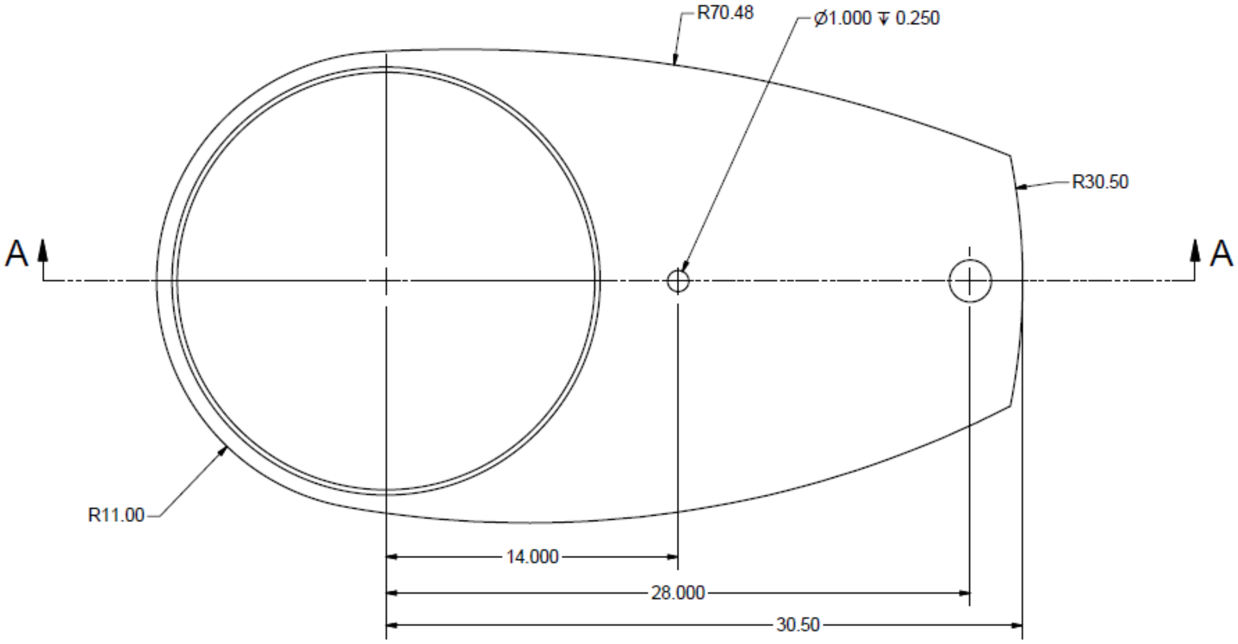
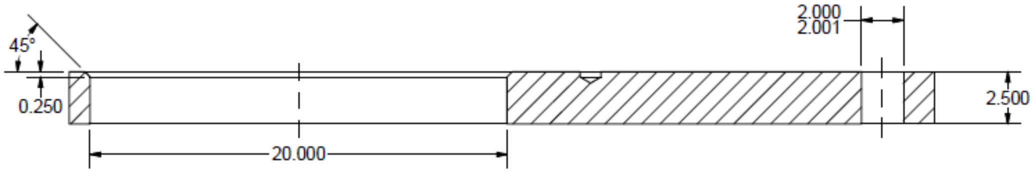


Figure 18. Proposed wicket gate lever assembly with weld details and stop block location [3]



PLAN VIEW



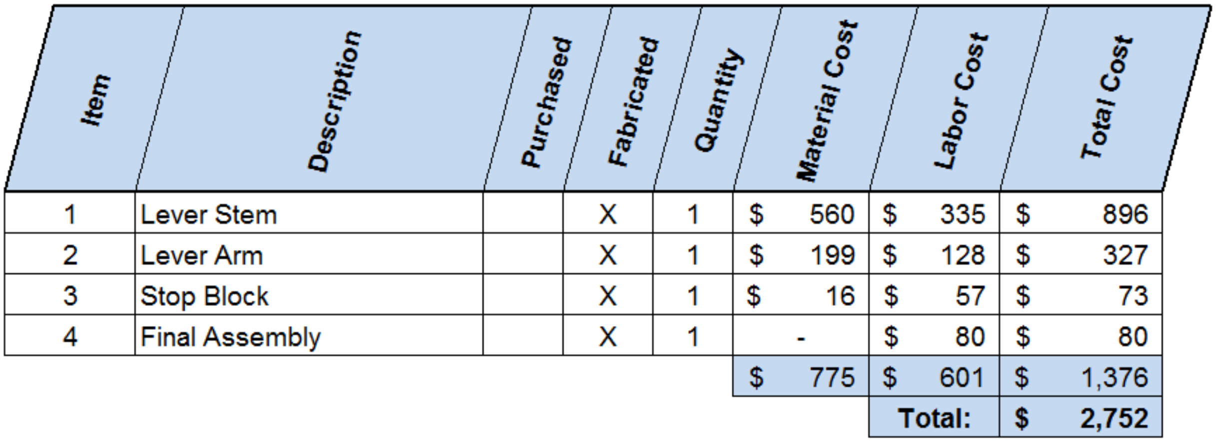
SECTION A-A

Figure 19. Proposed wicket gate lever arm with dimensions [3]

6.4 Cost Estimate

The total cost of the unit is estimated in the following table, based on material and standard labour costs from [13]. The cost of the wicket gate lever is predicted to be small compared to the cost of the downtime of the unit, which is on the order of tens of thousands of dollars per day, depending on energy prices.

TABLE VIII. COST ESTIMATE SUMMARY



Item	Description	Purchased	Fabricated	Quantity	Material Cost	Labor Cost	Total Cost
1	Lever Stem		X	1	$ 560	$ 335	$ 896
2	Lever Arm		X	1	$ 199	$ 128	$ 327
3	Stop Block		X	1	$ 16	$ 57	$ 73
4	Final Assembly		X	1	-	$ 80	$ 80
					$ 775	$ 601	$ 1,376
						Total:	**$ 2,752**

The overall cost is estimated to be approximately $2800, including both material and labour costs, but neglecting the cost of installation. The cost of installation would be difficult to determine, as it would be based on fluctuating energy prices, and would not heavily depend on the design. An item by item cost estimate is appended to this report.

6.5 Weld Design

The design of the welds for the wicket gate lever must take into account both the typical types of weld failures, as well as an analysis of the stresses experienced by the welds.

6.5.1 Weld Failures

Given that we wish to weld the thrust ring collar to the rest of the wicket gate lever, it is necessary to address the various failure modes that could result from welding. While seemingly a simple procedure, the production of high quality welds requires a deep knowledge of metallurgy, a specific weld procedure, and an assurance that the welding will be carried out in accordance to industry standards under proper supervision. If one fails to fully address the complexities of welding, there are various ways in which the integrity of the weld may be sacrificed. Weld failures are commonly caused by overload, joint design, a poor welding method, metallurgical failure, and weld defects [11].

The design of the component to be welded and the various stresses exerted on the part must be considered when determining the proper weld strength. The forces on the welds must also include possible stresses that may occur from transportation and installation of the component [11]. In the instance of the wicket gate lever, the stresses that occur from transportation and installation are very small in comparison to the loads the part is likely to encounter and has been designed for in its service life. For this reason, overloading the welds is extremely unlikely in our design.

Joint design is an important aspect of welding procedures, and should not be overlooked when designing components that require welding. If the welding technician is unable to maneuver the electrode, this will have a negative impact on the quality of the weld. Additionally, the profile of each weld run should be considered during design. Shallow, wide welds and narrow, deep welds tend to increase the likelihood of hot cracking. In order to reduce the chance of hot cracks occurring, the welds were designed with equal width and depth [11].

Weld failures often occur as a result of a lack of due diligence on the behalf of the welding operator and supervisor. Given that most weld specifications and technical data are acquired under ideal laboratory testing, it is important to reproduce the environment and methodology used to create the weld. Only if these environmental considerations are adhered to can the integrity of the weld be guaranteed. Also, occasionally welding occurs on site, and there is a lack of proper electrodes at the welder’s disposal. In this circumstance, welding can alter the existing microstructure, and harden the material in the heat affected zone. This induces a greater amount of residual stress, and may not be visible immediately after welding. Additionally, if the weld is too small and the joint not properly filled, the amount of stress the weld can tolerate may be greatly reduced. For the wicket gate lever, it is assumed that the welding will be completed in a certified facility that will adhere to the environmental and procedural intricacies of our welding design [11].

When welding two metals together, there are large thermal gradients that are produced at the weld location. It is necessary to select materials that respond favorably to these gradients and will not be structurally compromised after welding has taken place. There are certain materials that are to be avoided; some easily manipulated steels contain high amounts of sulphur, which tends to crack after the welding procedure. In order to avoid the potential cracking that may occur from poor material selection, our team has elected to use A36 plate steel, a material that is known for good weldability [11].

6.5.2 Weld Analysis

The weld analysis performed on the part uses a simplified method, as outlined in [6], and based on calculating the force per inch of weld thickness. This method idealizes the weld as a circle with a width, w, and diameter, d, along the weld edge. The following figure shows the weld approximation for the connection between the lever stem and lever arm.

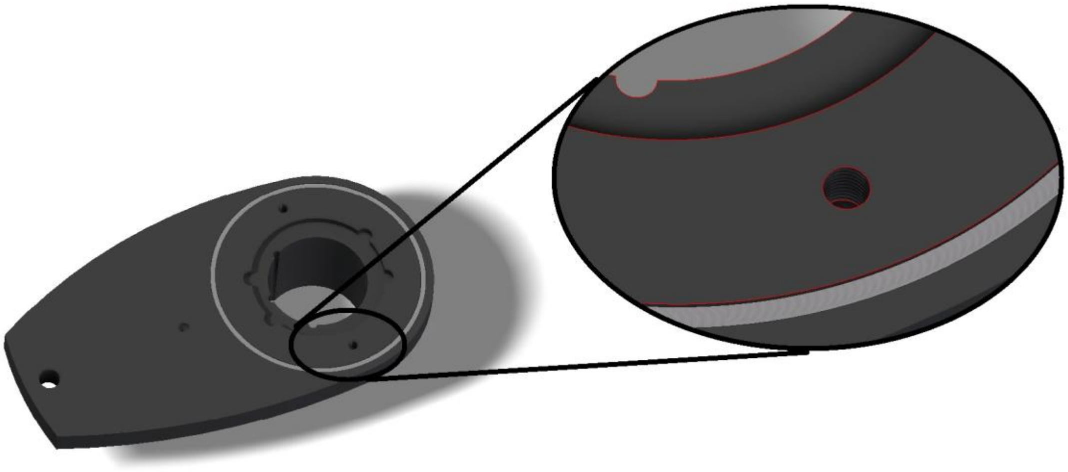


Figure 20. Weld approximation

From this point, the geometric properties, such as area and polar moment of area, can be calculated. Using load data from the strain gauges, the design torque is estimated to be 560 kip in. Since the allowable force per unit weld width is known from [6], the minimum weld width was calculated.

TABLE IX WELD PARAMETERS

Parameter	Value	Unit	Notes
d, Weld Diameter	20	[in]	From Geometry
A_w, Area per weld width	125.7	[in]	Calculated
J_w, Polar moment of area per weld width	12566	[in^3]	Calculated
T, Design Torque	560	[kip in]	Est. from strain gage data
f_t, Force per weld width	445.63	[lb/in]	Calculated
f_{all}, Allowable force per weld width	11200	[lb/in]	E70/E480 electrode [6]
w, minimum weld width	0.040	[in]	

Internal documentation from Hydro [12] suggests an absolute minimum weld thickness of 3/16”. However, the wicket gate lever is quite large, thickness of the lever arm and lever stem both exceed 3/4"; [12] specifies that a minimum weld thickness of 5/16 in is required. Since this value is greater than the required weld size found from stress calculations, the welds should be 5/16 in in size. In order to apply an additional factor of safety, the weld size on the top surface of the lever arm shall be increased to 1/2". This can safely be done due to the large size of the lever, which facilitates the rapid dissipation of heat.

The nominal allowable stress for such a weld is 70 ksi. The weld stresses here are less than 10% of the allowable stresses, and no problems are expected. The electrode should be an E48018 electrode, with a size of 5/32 in. The required current is 130-190 A (DC). In order to ensure high weld quality, the parts should be pre-heat temperature: 225°F based on size of components, and allowed to cool under ambient conditions [12].

6.6 Design Overview

The new wicket gate lever design is expected to last up to the required 100 year design life of the hydroelectric generating station. The measured values from the strain gauge data indicate that the maximum stresses in the existing lever do not exceed 2.7 ksi at the crack location, and the FEA indicates that the maximum stresses throughout the lever are less than 4 ksi. Therefore, stress in the wicket gate lever is well below the allowable design stress for an infinite service life of the part, estimated at one third of the yield stress, or 12 ksi. Welds are similarly designed to have very low stresses, around 10% of their yield stresses. Manitoba Hydro has a number of highly experienced weld technicians, who should be able to perform the welds as specified.

The extrapolation of the strain gauge data from the existing wicket gate levers to the new components is justified by using a very similar geometry, with only slight alterations on non-critical components, and smoother edges to reduce stress concentrations. Improvements to the material and manufacturing process will greatly improve the surface finish, tolerances on external geometry and part consistency, and eliminate voids or other imperfections resulting from the casting process. By allowing for a smoother side profile for the part, stress concentrations are reduced, particularly at the crack location.

Overall, the new design will experience lower stresses and have a much longer fatigue life due to the vastly improved material properties. Based on the fatigue analysis and the expected loads, the design will be effective for its 100 year design life.

7 Conclusion

The strain gauge analysis of the current wicket gate lever shows that the load on the lever is quite small, and on the order of 20 000 lb. For a non-cracked lever, the stress at the crack location was measured as 2.6 ksi. This is in reasonably close agreement with the finite element analysis performed on the part, which evaluated the stress as 2.1 ksi at the crack location, as well as hand calculations for a simplified analysis of the part. All of these stresses are well below the estimated endurance strength of 8.16 ksi for the ASTM A27 steel used in the wicket gate's construction, which should indicate an infinite fatigue life of the part. In fact, the levers have only experienced 2% failure rate.

However, the material quality of the current wicket gate levers is very poor. The levers are riddled with macroscopic pores, and have an extremely rough surface finish. Furthermore, the levers do not have a very consistent geometry, and each wicket gate lever is visually different from every other. The levers are extremely inconsistent around the area of the crack.

Based on the low stresses in the part and the poor material quality, the cracks are most likely the result of repeated stress on the defects in the lever. These defects experience small scale yielding, which produce cracks that grow slowly over time. We can therefore conclude that if the material quality is significantly improved so as to eliminate these defects, the new design will not fail over the design life of the wicket gate lever.

The proposed design, as detailed in section 6 of this report, improves on the material and manufacturing process of the part in order to produce more consistent wicket gate levers with fewer defects. The higher quality material and manufacturing process will ensure that the performance of the redesigned wicket gate levers will be dependable for the design life of the part.

The design is justified by the physical and theoretical analysis performed on the part existing lever. Strain gauges on the existing lever show that the stress at the crack location does not exceed 2.6 ksi. Due to the increase in the area of the wicket gate lever arm around the stem, the smoother transition to a round section near the crack location, and the otherwise similar geometry of the new design, there is no plausible reason that the new wicket gate lever would experience higher stresses.

In order to rectify the problems associated with localized and surface defects, the material and manufacturing process have been altered. Cold wrought ASTM A36 plate steel will be used so that the new lever can be easily machined and welded, at a total cost of approximately $2800. The machining process will provide a smooth surface finish, thus reducing surface defects and minimizing possible locations for crack initiation. This process will also allow for very consistent and precise geometry, thus reducing the risk of any stress concentrations due to sharp transitions in geometric features. Since the part will not be cast, the new design will eliminate any voids which would occur during the casting process.

References

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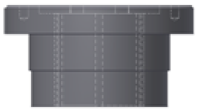
Appendix A. Cost Analysis

Wicket Gate Lever Component Costs

Line	**1**	**BOM**



Description: **Lever Stem**

Material:

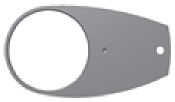
Item	Part Name	Material	Density	Unit	Amount	Weight	$/Unit	Cost
1	Lever Stem	A36 Round Stock	0.283	lb/in^3	3299	933.62	$0.60	$560.17
							Subtotal:	$560.17

Labor:

	Manufacturing Process	Amount	Unit	$/Unit	Cost
2	Manual Turning	4.22	Hour	$ 45.00	$ 189.90
3	Manual Machining	1.20	Hour	$ 60.00	$ 72.00
4	Polishing	1.00	Hour	$ 60.00	$ 60.00
5	Hand Dressing	0.30	Hour	$ 45.00	$ 13.50
				Subtotal:	$335.40

Material Total	$560.17
Labor Total	$335.40
Subassembly Total	$895.57

Line	**2**	**BOM**



Description: **Lever Arm**

Material:

Item	Part Name	Material	Density	Unit	Amount	Weight	$/Unit	Cost
1	Lever Arm	A36 Plate Steel	0.283	lb/in^3	1170	331.11	$0.60	$198.67
							Subtotal:	$198.67

Labor:

	Manufacturing Process	Amount	Unit	$/Unit	Cost
2	Waterjet Cutting	0.22	Hour	$110.00	$ 24.20
3	Manual Machining	1.40	Hour	$ 60.00	$ 84.00
4	Hand Dressing	0.45	Hour	$ 45.00	$ 20.25
				Subtotal:	$128.45

Material Total	$198.67
Labor Total	$128.45
Subassembly Total	$327.12

Line	**3**	**BOM**

Description: **Stop Block**

Material:

Item	Part Name	Material	Density	Unit	Amount	Weight	$/Unit	Cost
1	Stop Block	A36 Plate Steel	0.283	lb/in^3	95	26.89	$0.60	$16.13
							Subtotal:	$16.13

Labor:

	Manufacturing Process	Amount	Unit	$/Unit	Cost
2	Waterjet Cutting	0.08	Hour	$ 70.00	$ 5.60
3	Manual Machining	0.78	Hour	$ 60.00	$ 46.80
4	Hand Dressing	0.10	Hour	$ 45.00	$ 4.50
				Subtotal:	$56.90

Material Total	$16.13
Labor Total	$56.90
Subassembly Total	$73.03

Assembly Labour

	Manufacturing Process	Amount	Unit	$/Unit	Cost
1	Welding	0.44	Hour	$ 80.00	$ 35.20
2	Cleaning	0.50	Hour	$ 45.00	$ 22.50
3	Painting	0.50	Hour	$ 45.00	$ 22.50
				Subtotal:	$80.20

Labor Total	$80.20
Subassembly Total	$80.20

Item	Description	Purchased	Fabricated	Quantity	Material Cost	Labor Cost	Total Cost
1	Lever Stem		X	1	$ 560	$ 335	$ 896
2	Lever Arm		X	1	$ 199	$ 128	$ 327
3	Stop Block		X	1	$ 16	$ 57	$ 73
4	Final Assembly		X	1	-	$ 80	$ 80
					$ 775	$ 601	$ 1,376
						Total:	**$ 2,752**

Appendix B. Additional Strain Gauge Notes

Strain Gauge Locations

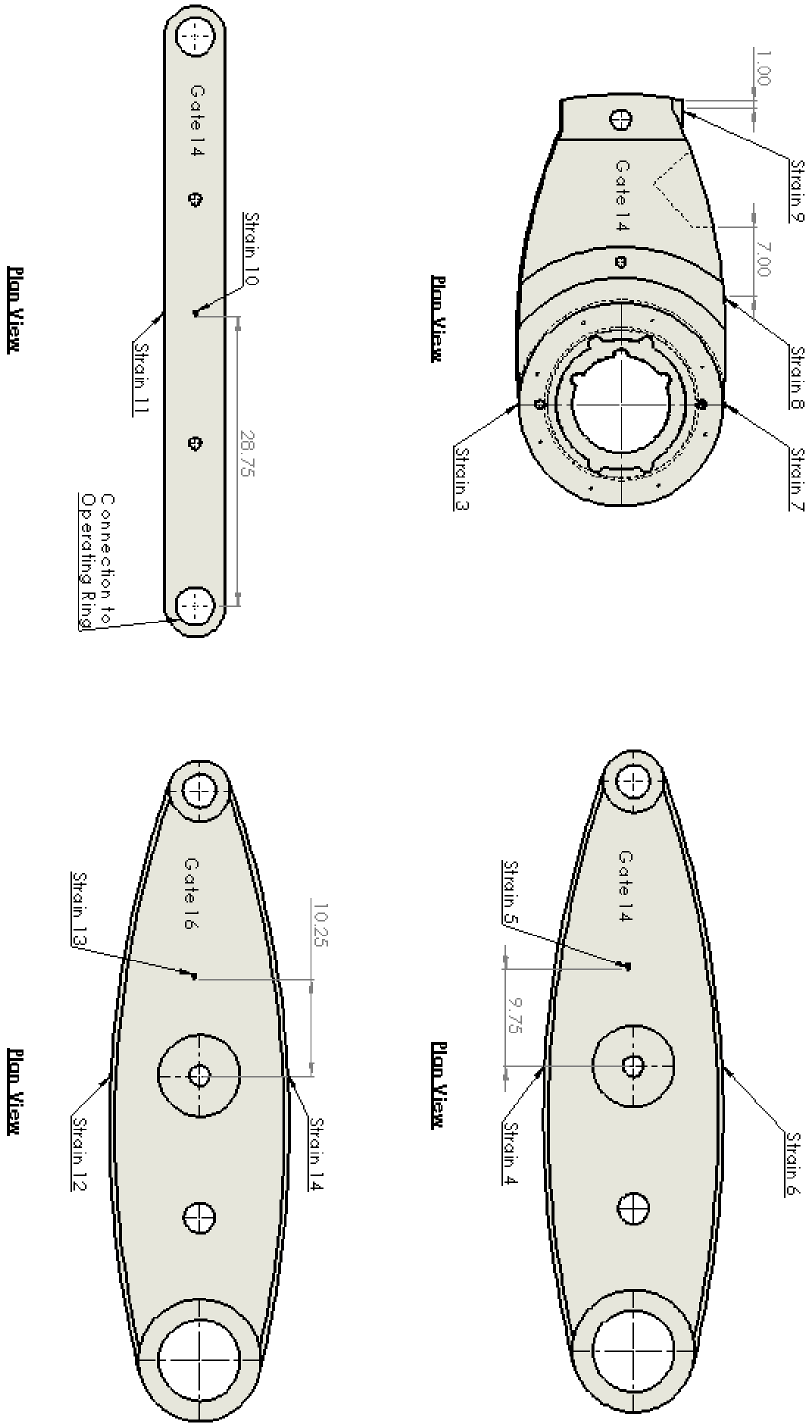


Figure 21. Strain gauge locations

Strain Gauge Testing Notes

Kettle Generating Station
Unit #2
October 31st to November 2nd, 2011

Wicket gates instrumented:
-gate 14 utilizing 11 strain gauges
-gate 16 utilizing 3 strain gauges

October 31:
Run name: Crimp Load Removed
Start time: 11:37am End time: 11:38am
Details:
-unit is dewatered
-gates are crimped closed, then crimp load is removed, gates remain at 0% gate position
Test end
All strain gauges have now been zeroed

October 31:
Run name: Dewatered test 1
Start time: 11:48am End time: 12:51pm
Details:
-unit is dewatered
-testing may have occurred by the electrical testing on the governor system
Test end
October 31:
Run name: Dewatered test 2
Start time: 12:53pm End time: 2:07pm
Details:
-unit is dewatered
-testing of the governor system is being done, servos will move randomly during test
-movement of gates at 1:29pm
-0% to 100% gate movement at 1:32pm
Test end

October 31:
Run name: Dewatered test 3
Start time: 2:15pm End time: 3:13pm
Details:
-unit is dewatered
-testing of the governor system is being done, servos will move randomly during test
Test end

October 31:
Run name: Dewatered test 4
Start time: 3:20pm End time: 4:34pm

Details:
-unit is dewatered
-testing of the governor system is being done, servos will move randomly during test
-gates undergo multiple movements from 3:43pm to 3:58pm
Test end

October 31:
Run name: Dewatered test 5
Start time: 4:35pm End time: 8:39pm
Details:
-unit is dewatered
-testing of the governor system is being done, servos will move randomly during test
Test end

October 31:
Run name: Unit water up
Start time: 8:41pm End time: 11:39pm
Details:
-unit is watered up during this test
-this test may have several hours of dead time prior to watering up and servo movement
Test end

October 31 to November 1:
Run name: Turbine test run 1
Start time: 11:41pm Oct 31 End time: 2:13am Nov 1
Details:
-unit is watered up
-11:42 – unit start up begins
-11:43 unit starts
-11:43 unit performs an "86" (emergency shutdown) and shuts itself down, unit was at around 20% to 30% gate opening before shutdown
-11:46 unit start up initialized again
-11:47 unit starts up, station is shaking above the unit, shut down "86" is again I performed as the unit failed to self excite
-11:51 start up initialized, station is shaking, shut down on "86" again at around 30% gate opening
-After unit has not been able to start testing will be delayed with more diagnosis is to be performed on unit to determine why it won't start/self excite
Test end

November 1:
Run name: Turbine test runs 2
Start time: 2:16am End time: 10:14am
Details:
-unit is watered up during this test
-test left to run overnight
-there may be hours of dead-time before unit is started as unit may not be able to be brought online overnight

-Upon unit start up at 2:41am, the operator ran the units wicket gates through incremental ranges of gate position (approximately 10% increments) and allowed the unit to stabilize before opening the gates to the next increment
Test end

November 1:
Run name: Normal Operation
Start time: 10:21am End time: 5:43pm
Details:
-unit is watered up during this test
-unit is already running at normal operation and is generating power for the grid
-this run is normal weekday operation of the unit
Test end

November 1 to November 2:
Run name: Normal Operation 2
Start time: 5:45pm Nov1 End time: 7:08am Nov 2
Details:
-unit is watered up during this test
-unit is already running at normal operation and is generating power for the grid
-this run ran overnight
Test end

Strain Gauge Testing Data

	Dewatered Crimp Loading					Dewatered test 1		Gates are Crimped								
	Strain															
Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Displacem
93.01	11	-4	-22	-37	1	38	24	26	2	-2	-6	-32	6	35	49	44.29
93.02	10	1	-19	-36	0	37	24	27	-1	-6	-9	-35	7	37	50	44.20
93.03	6	-2	-21	-38	1	36	22	28	2	-6	-1	-37	6	40	50	44.16
93.04	10	-4	-21	-39	1	39	24	27	4	-4	-7	-31	7	37	49	44.19
93.05	8	-3	-22	-40	-4	38	25	26	-1	-7	-7	-36	4	42	50	44.25
93.06	7	-4	-18	-40	2	37	22	30	-6	-2	-3	-34	1	40	52	44.32
93.07	7	-1	-19	-40	1	36	23	28	6	-7	-9	-38	5	41	51	44.37
93.08	8	-2	-18	-38	-1	38	19	27	2	-9	-3	-35	5	38	50	44.42
93.09	12	-4	-20	-38	2	41	26	31	-2	-4	-6	-35	8	37	51	44.50
93.1	12	-1	-18	-39	1	41	20	29	1	-10	-8	-37	11	39	49	44.49
93.11	10	1	-21	-35	0	39	22	32	1	-6	-2	-36	6	40	53	44.35
93.12	8	0	-22	-38	5	38	21	29	3	-1	-6	-37	7	42	50	44.20
93.13	7	-3	-22	-35	3	38	22	25	2	-3	-9	-34	8	41	45	44.15
93.14	7	-5	-16	-38	3	37	20	32	4	-10	-10	-33	6	40	48	44.17
93.15	11	-2	-21	-38	1	38	22	28	4	-6	-7	-35	10	40	47	44.24
93.16	8	-4	-20	-38	2	40	24	27	0	1	-5	-35	4	41	52	44.31
93.17	7	-2	-19	-38	0	39	25	32	1	-9	-5	-35	6	39	47	44.36
93.18	8	-2	-22	-38	0	41	21	28	0	-5	0	-38	5	40	50	44.41
93.19	7	0	-20	-40	-2	40	23	31	2	-4	-10	-37	8	39	52	44.47
93.2	9	-2	-24	-39	0	42	24	27	1	-6	-4	-37	5	42	52	44.49
Average	**9**	**-2**	**-20**	**-38**	**1**	**39**	**23**	**29**	**1**	**-5**	**-6**	**-35**	**6**	**39**	**50**	**44.32**

	Dewatered, servo fully stroked					Dewatered test 2										
	Strain															
Time	1	2	3	4	5	6	7	8	9	10	11	12	12	12	15	Displacem
2443.8	-10	0	29	78	-4	-86	-43	-53	-4	4	15	87	-18	-98	40	7.72
2443.81	-10	6	29	76	-5	-84	-43	-52	-3	6	14	84	-20	-97	41	7.79
2443.82	-15	6	25	76	0	-86	-42	-52	-2	-5	9	83	-20	-98	41	7.83
2443.83	-14	7	28	76	-2	-84	-44	-48	-7	4	9	85	-20	-99	43	7.70
2443.84	-11	2	28	73	-3	-86	-44	-54	-2	4	14	84	-21	-95	37	7.51
2443.85	-5	-3	28	76	-3	-86	-46	-50	-4	4	10	88	-22	-96	44	7.48
2443.86	-15	3	30	75	-3	-85	-45	-52	-1	2	10	87	-18	-95	41	7.53
2443.87	-14	-4	29	73	-1	-86	-46	-53	0	6	15	88	-18	-96	42	7.64
2443.88	-10	2	35	77	-3	-84	-45	-50	-4	2	15	87	-18	-97	45	7.71
2443.89	-15	5	30	76	-2	-87	-42	-48	-2	4	10	86	-21	-95	39	7.78
2443.9	-8	1	31	74	-6	-86	-46	-50	-9	1	12	84	-18	-98	43	7.84
2443.91	-13	6	26	75	-4	-84	-47	-50	1	2	11	89	-21	-98	43	7.70
2443.92	-12	1	25	76	-3	-83	-46	-49	-2	8	9	86	-22	-95	42	7.51
2443.93	-8	3	25	73	-3	-86	-45	-51	-7	5	13	87	-22	-100	44	7.48
2443.94	-15	0	27	78	-4	-83	-42	-55	-6	1	8	88	-18	-97	40	7.54
2443.95	-10	1	31	73	-6	-83	-47	-54	-3	8	14	88	-18	-96	42	7.63
2443.96	-11	6	32	73	2	-84	-50	-48	-5	3	17	86	-25	-96	42	7.70
2443.97	-13	9	30	78	-2	-84	-48	-49	-1	3	5	87	-19	-96	37	7.76
2443.98	-12	7	29	76	-4	-83	-45	-48	-4	4	12	87	-22	-94	43	7.83
2443.99	-13	-1	29	78	-3	-83	-45	-50	-2	-1	16	87	-21	-98	38	7.71
Average	**-12**	**3**	**29**	**75**	**-3**	**-85**	**-45**	**-51**	**-3**	**3**	**12**	**86**	**-20**	**-97**	**41**	**7.67**

	Unit is watered up					Unit Waterup										
	Strain															
Time	1	2	3	4	5	6	7	8	9	10	11	12	12	12	15	Displacem
8585.8	9	-3	-26	-44	-1	40	20	28	2	-15	-6	-35	8	47	18	44.47
8585.81	5	-9	-29	-46	-3	39	20	28	-2	-19	-11	-36	5	42	18	44.47
8585.82	6	-9	-24	-45	-2	39	18	30	-3	-18	-11	-37	6	44	16	44.30
8585.83	7	-2	-22	-45	3	38	19	27	-6	-13	-11	-35	8	43	18	44.17
8585.84	5	-1	-27	-45	-4	36	19	23	2	-19	-8	-35	8	42	16	44.17
8585.85	6	-8	-26	-40	-1	37	21	25	4	-14	-9	-36	8	42	17	44.22
8585.86	4	-8	-20	-45	-1	36	18	28	-7	-16	-10	-33	10	39	17	44.31
8585.87	7	-3	-26	-44	0	38	20	25	-1	-15	-5	-37	4	46	18	44.37
8585.88	5	-2	-28	-43	-1	40	18	26	-4	-13	-9	-37	10	44	22	44.46
8585.89	6	-9	-22	-47	1	42	19	28	-2	-16	-11	-32	7	42	20	44.48
8585.9	9	0	-20	-44	1	40	20	28	-5	-11	-4	-37	8	41	19	44.35
8585.91	9	-7	-28	-43	0	38	18	26	-8	-16	-12	-34	9	44	20	44.18
8585.92	10	-4	-24	-43	0	39	22	25	-3	-21	-9	-33	9	42	16	44.17
8585.93	7	-1	-21	-40	-1	43	23	27	-6	-13	-8	-37	5	43	19	44.22
8585.94	5	-6	-30	-44	-1	37	22	26	1	-18	-13	-34	6	42	18	44.31
8585.95	6	-6	-25	-43	-1	41	20	27	-4	-16	-3	-36	7	44	20	44.38
8585.96	8	-6	-21	-44	1	38	20	30	3	-14	-8	-39	7	44	19	44.43
8585.97	7	3	-23	-42	-3	40	17	28	-2	-15	-13	-36	3	40	16	44.49
8585.98	7	-4	-28	-44	0	38	18	30	-4	-11	-5	-33	7	43	21	44.37
8585.99	6	-5	-24	-44	-3	37	21	29	3	-18	-9	-36	5	39	19	44.20
Average	**7**	**-5**	**-25**	**-44**	**-1**	**39**	**20**	**27**	**-2**	**-16**	**-9**	**-35**	**7**	**43**	**18**	**44.33**

	Unit is watered up					Turbine test runs 1		Unit is started and shuts down, this is from the first start attempt of the test								
	Strain															
Time	1	2	3	4	5	6	7	8	9	10	11	12	12	12	15	Displacem
393.8	-17	0	45	119	5	-121	-65	-88	-8	4	14	137	-16	-135	32	34.54
393.81	-16	3	46	117	0	-123	-63	-89	-11	2	10	135	-16	-132	28	34.56
393.82	-21	5	45	118	5	-124	-64	-89	-3	0	14	137	-12	-131	31	34.64
393.83	-14	-1	43	120	3	-129	-68	-91	-5	6	13	134	-12	-136	29	34.73
393.84	-19	1	52	128	4	-132	-65	-96	-2	2	16	136	-15	-130	26	34.78
393.85	-18	1	55	130	3	-132	-69	-97	-6	4	20	130	-16	-131	34	34.86
393.86	-21	3	51	130	1	-135	-70	-97	-6	6	17	131	-17	-127	30	34.86
393.87	-18	-4	51	135	6	-141	-74	-99	-2	0	15	136	-11	-130	33	34.72
393.88	-18	2	56	135	4	-142	-72	-101	-4	2	17	135	-14	-132	28	34.54
393.89	-22	5	52	135	7	-142	-72	-99	-2	4	18	129	-14	-130	30	34.53
393.9	-17	5	50	136	5	-137	-71	-100	-3	10	18	131	-16	-130	31	34.57
393.91	-23	0	49	137	5	-142	-72	-99	-1	7	20	137	-12	-135	25	34.69
393.92	-17	2	54	132	4	-136	-71	-98	-5	2	12	137	-15	-132	29	34.76
393.93	-18	4	48	133	7	-135	-73	-95	-2	4	13	138	-17	-138	29	34.82
393.94	-16	-3	50	128	4	-133	-70	-93	0	1	22	142	-16	-140	29	34.89
393.95	-18	0	49	123	3	-131	-65	-90	-6	8	13	144	-13	-136	28	34.80
393.96	-17	-3	52	122	3	-129	-65	-89	-5	1	12	146	-16	-140	29	34.60
393.97	-21	1	45	122	4	-130	-66	-90	0	9	18	145	-17	-142	31	34.52
393.98	-13	2	46	121	2	-126	-64	-89	-3	2	12	150	-13	-148	29	34.57
393.99	-18	1	49	116	4	-128	-64	-86	-4	-1	13	150	-16	-147	27	34.65
Average	**-18**	**1**	**49**	**127**	**4**	**-132**	**-68**	**-94**	**-4**	**4**	**15**	**138**	**-15**	**-135**	**29**	**34.68**

	Unit is watered up					Turbine test runs 1		Unit is started and shuts down, this is from the second start attempt of the test								
	Strain															
Time	1	2	3	4	5	6	7	8	9	10	11	12	12	12	15	Displacem
614.2	-17	-5	47	125	6	-130	-65	-95	3	6	21	133	-13	-125	30	34.77
614.21	-21	1	51	127	4	-131	-69	-91	2	10	20	130	-13	-126	31	34.83
614.22	-16	3	46	129	5	-133	-66	-91	-2	6	16	127	-18	-128	30	34.79
614.23	-15	-2	49	132	4	-134	-67	-93	-4	9	20	126	-13	-124	28	34.61
614.24	-20	3	53	134	4	-137	-69	-92	-4	3	14	127	-14	-126	30	34.51
614.25	-17	-2	52	135	6	-138	-67	-96	2	6	22	130	-14	-124	31	34.54
614.26	-20	0	50	134	4	-136	-71	-98	-5	6	14	128	-16	-129	27	34.63
614.27	-20	-1	52	133	7	-137	-71	-98	-1	7	18	131	-15	-134	30	34.71
614.28	-16	3	53	132	8	-133	-73	-97	-11	6	20	137	-10	-135	29	34.79
614.29	-18	3	50	131	-1	-134	-66	-95	1	2	14	137	-14	-135	31	34.85
614.3	-20	-2	50	128	7	-132	-67	-90	-6	4	19	139	-13	-139	31	34.81
614.31	-18	3	46	127	4	-130	-68	-91	-2	6	13	144	-12	-141	29	34.58
614.32	-21	1	43	125	3	-130	-66	-92	-4	2	14	146	-13	-143	27	34.51
614.33	-18	-2	44	123	5	-128	-67	-90	-6	8	16	147	-10	-143	27	34.52
614.34	-13	2	48	122	2	-126	-65	-88	-4	10	16	153	-17	-147	29	34.62
614.35	-17	7	44	120	5	-125	-64	-88	-4	4	16	154	-14	-145	29	34.70
614.36	-19	2	44	119	4	-123	-64	-88	3	5	17	150	-14	-146	30	34.76
614.37	-17	-1	42	121	3	-123	-60	-86	0	2	15	150	-14	-148	29	34.81
614.38	-15	-5	43	116	2	-123	-61	-88	0	7	15	150	-12	-145	31	34.84
614.39	-15	4	43	119	4	-119	-59	-89	0	4	12	147	-15	-142	30	34.60
Average	**-18**	**1**	**48**	**127**	**4**	**-130**	**-66**	**-92**	**-2**	**6**	**17**	**139**	**-14**	**-136**	**29**	**34.69**

	Unit is watered up					Turbine test runs 1		Unit is started and shuts down, this is from the third start attempt of the test								
	Strain															
Time	1	2	3	4	5	6	7	8	9	10	11	12	12	12	15	Displacem
910.8	-16	3	41	121	3	-129	-67	-85	1	8	21	138	-9	-132	31	34.53
910.81	-12	-3	49	129	3	-132	-64	-89	-4	6	16	133	-9	-132	29	34.64
910.82	-17	4	52	126	6	-130	-65	-89	1	2	16	136	-14	-135	27	34.72
910.83	-19	0	44	126	5	-132	-66	-87	-2	8	18	141	-15	-133	29	34.81
910.84	-18	0	50	127	3	-130	-66	-87	0	2	15	138	-16	-133	29	34.82
910.85	-18	3	47	130	6	-130	-64	-92	-4	6	18	141	-12	-134	34	34.62
910.86	-13	-1	52	127	2	-133	-69	-90	-5	10	17	140	-16	-136	30	34.49
910.87	-16	1	47	127	3	-134	-67	-91	-2	4	17	142	-13	-138	25	34.52
910.88	-17	-1	47	132	9	-132	-68	-90	1	7	19	141	-14	-136	33	34.60
910.89	-19	2	55	129	2	-132	-67	-89	-7	3	17	140	-13	-141	28	34.71
910.9	-18	3	49	129	7	-131	-66	-90	-7	7	17	138	-15	-136	34	34.74
910.91	-17	0	44	122	4	-128	-63	-89	-1	2	13	142	-13	-134	28	34.83
910.92	-16	-4	47	123	4	-130	-64	-88	-1	9	16	143	-8	-137	27	34.68
910.93	-6	4	45	123	6	-126	-63	-87	-4	1	15	144	-14	-138	34	34.53
910.94	-16	-1	44	125	5	-128	-63	-91	-8	4	20	144	-13	-143	30	34.51
910.95	-13	0	48	122	4	-126	-61	-87	1	4	15	145	-13	-138	30	34.60
910.96	-18	7	48	123	5	-128	-66	-85	1	5	18	140	-14	-139	27	34.68
910.97	-17	5	41	123	5	-130	-62	-87	-4	7	21	141	-14	-142	30	34.74
910.98	-18	-3	46	122	6	-124	-63	-89	-5	3	14	146	-15	-139	31	34.84
910.99	-12	1	49	120	6	-124	-63	-86	-2	-2	17	143	-15	-140	25	34.73
Average	**-16**	**1**	**47**	**125**	**5**	**-129**	**-65**	**-88**	**-3**	**5**	**17**	**141**	**-13**	**-137**	**30**	**34.67**

	Unit is watered up					Turbine test runs 2		Unit starts then draws back to 18.9% gate, these are the strains after it starts								
	Strain															
Time	1	2	3	4	5	6	7	8	9	10	11	12	12	12	15	Displacem
1110.5	8	29	59	125	24	-92	-32	-57	11	12	26	130	-4	-115	36	36.82
1110.51	10	24	62	127	24	-93	-31	-57	18	11	21	131	-6	-117	31	36.64
1110.52	17	29	64	128	22	-90	-35	-55	21	13	27	132	-5	-113	38	36.57
1110.53	9	26	64	128	20	-95	-36	-61	19	13	23	133	0	-114	34	36.75
1110.54	9	29	58	135	24	-95	-34	-57	17	8	26	126	-6	-116	36	36.86
1110.55	16	23	65	134	22	-93	-37	-60	18	11	26	128	-3	-113	32	36.56
1110.56	10	29	61	131	22	-96	-36	-57	14	14	21	126	-4	-116	41	36.61
1110.57	11	24	63	132	20	-97	-33	-59	14	8	24	129	-2	-113	34	36.81
1110.58	9	26	61	133	23	-97	-35	-55	14	11	25	124	-4	-109	33	36.83
1110.59	12	23	63	135	21	-96	-35	-58	20	13	24	125	-3	-110	33	36.54
1110.6	9	25	61	133	24	-96	-35	-58	19	11	25	124	-6	-109	36	36.69
1110.61	9	17	65	136	26	-99	-37	-63	19	15	25	125	-5	-112	36	36.84
1110.62	10	25	63	134	21	-96	-38	-58	16	10	24	126	-4	-110	37	36.71
1110.63	10	23	65	136	21	-100	-37	-61	13	11	27	128	-4	-114	37	36.55
1110.64	10	21	63	134	22	-99	-35	-61	16	14	21	129	-7	-111	38	36.75
1110.65	7	27	64	138	24	-100	-37	-61	22	13	27	128	-9	-115	35	36.88
1110.66	13	22	65	141	24	-100	-37	-61	16	14	25	126	-3	-112	34	36.58
1110.67	11	27	65	138	22	-99	-33	-60	19	12	23	130	-3	-113	32	36.62
1110.68	6	21	63	136	23	-100	-36	-60	16	8	27	128	-1	-114	35	36.78
1110.69	9	28	66	138	24	-100	-40	-62	22	14	29	131	-6	-114	35	36.88
Average	**10**	**25**	**63**	**134**	**23**	**-97**	**-36**	**-59**	**17**	**12**	**25**	**128**	**-4**	**-113**	**35**	**36.71**

	Unit is watered up					Turbine test runs 2		Unit running - stroking through gate positions								
	Strain															
Time	1	2	3	4	5	6	7	8	9	10	11	12	12	12	15	Displacem
3775.8	13	30	78	163	29	-111	-50	-65	24	13	34	160	-7	-140	40	26.67
3775.81	11	30	78	163	27	-110	-47	-69	21	14	37	160	-6	-138	34	26.56
3775.82	12	34	77	161	30	-112	-47	-69	24	12	30	159	-7	-138	41	26.86
3775.83	9	30	81	162	32	-113	-48	-69	18	22	36	162	-9	-141	42	26.81
3775.84	11	31	84	164	29	-113	-48	-71	19	8	34	161	-5	-141	38	26.69
3775.85	13	32	80	161	29	-112	-47	-69	17	16	29	158	-9	-137	41	26.56
3775.86	7	31	86	162	31	-111	-46	-70	16	10	35	163	-7	-142	35	26.78
3775.87	10	28	80	162	33	-111	-47	-69	21	10	29	162	-7	-140	38	26.83
3775.88	8	27	81	163	27	-114	-46	-67	21	17	36	162	-9	-138	40	26.70
3775.89	12	29	81	165	31	-114	-48	-71	20	10	30	162	-6	-137	40	26.57
3775.9	12	31	82	165	31	-111	-48	-68	22	16	36	162	-2	-139	39	26.77
3775.91	9	28	82	166	29	-114	-46	-70	20	15	29	159	-6	-140	38	26.85
3775.92	11	29	80	165	32	-112	-49	-71	21	18	35	160	-6	-141	41	26.72
3775.93	9	31	86	161	32	-113	-45	-69	23	10	30	157	-9	-135	40	26.54
3775.94	6	29	84	162	30	-114	-48	-72	19	17	35	162	-9	-140	39	26.69
3775.95	9	31	76	163	33	-111	-48	-70	24	8	32	162	-5	-145	40	26.84
3775.96	14	32	79	163	26	-113	-47	-66	27	15	27	158	-10	-135	35	26.76
3775.97	10	35	78	163	31	-112	-49	-65	23	12	37	159	-10	-139	41	26.56
3775.98	10	28	75	164	31	-113	-45	-67	21	16	32	160	-4	-140	38	26.65
Average	**10**	**30**	**81**	**163**	**30**	**-112**	**-47**	**-69**	**21**	**14**	**33**	**160**	**-7**	**-139**	**39**	**26.71**

	Unit is watered up					Turbine test runs 2		Unit running - stroking through gate positions								
	Strain															
Time	1	2	3	4	5	6	7	8	9	10	11	12	12	12	15	Displacem
4347.5	6	24	82	164	30	-113	-51	-64	17	9	31	165	-11	-140	40	22.09
4347.51	10	24	83	163	31	-112	-49	-69	19	12	32	159	-7	-136	36	22.38
4347.52	7	24	81	160	33	-111	-52	-68	21	13	31	161	-7	-139	43	22.39
4347.53	8	28	79	163	28	-110	-48	-65	25	4	33	163	-6	-139	41	22.27
4347.54	13	28	81	160	31	-113	-54	-67	19	15	32	159	-7	-136	41	22.12
4347.55	8	29	80	165	27	-113	-51	-67	19	7	30	164	-11	-137	43	22.19
4347.56	6	26	79	162	30	-114	-51	-68	22	10	35	162	-10	-140	42	22.44
4347.57	10	29	82	164	31	-111	-51	-66	15	13	30	163	-9	-140	40	22.31
4347.58	13	25	86	163	30	-113	-51	-70	19	8	31	164	-8	-138	41	22.16
4347.59	6	29	79	163	29	-115	-49	-71	21	12	34	160	-6	-138	37	22.09
4347.6	11	30	81	160	29	-112	-51	-70	17	8	29	161	-3	-140	39	22.46
4347.61	8	28	80	160	28	-114	-51	-69	16	9	35	159	-5	-138	39	22.34
4347.62	10	30	85	161	28	-113	-50	-65	20	12	30	160	-8	-140	40	22.23
4347.63	12	35	76	160	32	-113	-50	-68	20	11	31	162	-5	-140	40	22.11
4347.64	12	28	77	162	26	-113	-49	-66	22	12	31	163	-9	-139	38	22.32
4347.65	9	27	76	161	28	-112	-53	-65	24	11	31	164	-7	-137	40	22.39
4347.66	6	28	80	161	27	-113	-49	-67	20	7	32	158	-7	-139	40	22.29
4347.67	8	25	78	160	30	-113	-50	-68	22	12	30	160	-6	-138	38	22.12
4347.68	9	25	81	163	30	-111	-47	-66	20	8	30	159	-8	-139	41	22.13
4347.69	8	24	79	160	32	-111	-52	-69	17	8	27	157	-8	-136	42	22.46
Average	**9**	**27**	**80**	**162**	**29**	**-113**	**-50**	**-67**	**20**	**10**	**31**	**161**	**-7**	**-138**	**40**	**22.26**

	Unit is watered up					Turbine test runs 2		Unit running - stroking through gate positions								
	Strain															
Time	1	2	3	4	5	6	7	8	9	10	11	12	12	12	15	Displacem
4499.9	15	29	78	154	32	-103	-45	-59	24	9	31	154	-5	-128	38	19.25
4499.91	14	29	78	155	31	-102	-45	-57	24	11	33	153	-6	-129	41	19.11
4499.92	16	27	81	156	34	-101	-47	-58	24	17	34	151	-6	-126	35	19.01
4499.93	17	32	76	153	33	-100	-47	-58	21	8	31	153	-8	-135	39	19.25
4499.94	13	31	76	152	33	-102	-46	-60	22	15	34	151	-9	-128	44	19.29
4499.95	14	30	74	155	31	-103	-46	-60	20	14	31	154	-4	-127	39	19.19
4499.96	16	31	75	155	30	-105	-45	-60	19	10	32	154	-7	-130	41	19.01
4499.97	14	35	75	156	32	-100	-45	-60	16	15	37	153	-6	-132	41	19.05
4499.98	16	32	76	156	31	-102	-46	-61	21	12	31	156	-3	-129	40	19.35
4499.99	13	35	81	157	34	-103	-46	-60	23	9	31	151	-7	-130	43	19.20
4500	11	35	75	155	34	-102	-45	-64	20	15	36	154	-5	-130	42	19.07
4500.01	17	31	80	154	34	-101	-46	-59	20	14	29	154	-7	-128	43	18.99
4500.02	13	31	79	155	30	-103	-45	-63	19	8	34	152	-3	-130	40	19.30
4500.03	13	32	77	152	30	-103	-47	-60	17	12	35	153	-4	-132	38	19.26
4500.04	13	33	78	155	35	-101	-46	-58	21	15	34	151	-3	-131	41	19.12
4500.05	14	28	77	155	34	-101	-47	-60	24	8	30	151	-3	-132	41	19.00
4500.06	13	28	81	156	35	-101	-47	-60	24	11	37	156	-3	-130	41	19.13
4500.07	17	28	79	157	31	-103	-45	-62	21	11	32	155	-5	-130	42	19.37
4500.08	12	28	80	157	32	-100	-45	-61	22	9	32	149	-6	-130	37	19.19
4500.09	18	26	79	159	32	-101	-44	-57	16	17	36	153	-6	-132	42	19.03
Average	**14**	**31**	**78**	**155**	**32**	**-102**	**-46**	**-60**	**21**	**12**	**33**	**153**	**-5**	**-130**	**40**	**19.16**

	Unit is watered up					Turbine test runs 2		Unit running - stroking through gate positions								
	Strain															
Time	1	2	3	4	5	6	7	8	9	10	11	12	12	12	15	Displacem
4867.7	15	25	72	142	29	-94	-41	-53	23	12	38	136	-7	-120	38	15.30
4867.71	17	25	73	142	29	-93	-43	-52	20	14	32	139	-10	-120	43	15.32
4867.72	11	28	73	141	29	-92	-41	-52	21	16	30	138	-9	-120	41	15.63
4867.73	16	29	72	141	33	-93	-42	-53	22	8	33	142	-3	-119	36	15.55
4867.74	18	28	71	142	30	-92	-43	-50	25	7	35	142	-5	-121	43	15.41
4867.75	16	33	73	142	31	-92	-43	-53	22	9	30	140	-5	-122	42	15.29
4867.76	14	33	73	143	30	-95	-42	-51	21	8	34	143	-5	-123	39	15.50
4867.77	11	37	76	141	34	-93	-43	-49	24	14	31	140	-4	-124	43	15.59
4867.78	13	33	71	142	30	-92	-40	-53	22	15	29	139	-6	-121	36	15.47
4867.79	16	33	68	141	32	-95	-44	-51	17	13	31	142	-7	-121	44	15.31
4867.8	14	29	74	142	34	-93	-41	-51	21	4	32	140	-5	-122	40	15.34
4867.81	13	33	68	139	30	-93	-41	-51	19	5	39	141	-8	-119	40	15.66
4867.82	13	33	68	143	31	-92	-41	-52	21	6	40	139	-6	-120	38	15.53
4867.83	18	30	65	140	32	-94	-43	-52	18	10	29	139	-7	-123	40	15.39
4867.84	13	29	69	139	31	-91	-44	-50	20	8	31	142	-8	-122	42	15.27
4867.85	12	30	67	143	33	-94	-41	-55	17	2	36	142	-10	-120	39	15.56
4867.86	14	26	68	139	29	-92	-40	-52	20	13	35	137	-6	-120	38	15.57
4867.87	13	29	67	138	33	-90	-43	-52	20	13	31	141	-4	-123	40	15.45
4867.88	16	27	67	143	35	-93	-44	-55	21	12	33	138	-2	-119	41	15.28
4867.89	13	32	69	141	31	-94	-42	-52	20	6	32	138	-7	-122	41	15.42
Average	**14**	**30**	**70**	**141**	**31**	**-93**	**-42**	**-52**	**21**	**10**	**33**	**140**	**-6**	**-121**	**40**	**15.44**

	Unit is watered up					Turbine test runs 2		Unit running - stroking through gate positions								
	Strain															
Time	1	2	3	4	5	6	7	8	9	10	11	12	12	12	15	Displacem
4736.2	20	30	63	126	28	-78	-39	-44	15	8	28	121	-12	-105	38	10.98
4736.21	22	34	68	125	29	-76	-34	-44	19	7	28	125	-9	-106	42	10.91
4736.22	18	27	64	124	26	-80	-38	-43	19	8	30	123	-10	-107	37	11.21
4736.23	20	30	66	126	27	-77	-40	-45	17	1	28	121	-8	-110	41	11.19
4736.24	22	30	68	127	28	-80	-32	-43	19	9	34	123	-9	-112	42	11.05
4736.25	13	29	67	123	27	-82	-38	-42	21	9	25	123	-11	-107	39	10.88
4736.26	14	26	68	124	28	-78	-34	-41	20	6	32	125	-8	-106	42	11.00
4736.27	21	28	65	126	28	-80	-36	-41	21	8	29	122	-6	-108	40	11.26
4736.28	21	30	65	128	31	-76	-38	-43	18	6	31	122	-7	-111	41	11.10
4736.29	21	28	70	127	28	-78	-36	-42	22	10	29	122	-12	-107	39	10.94
4736.3	21	30	66	124	28	-80	-36	-47	20	5	30	122	-13	-106	40	10.92
4736.31	17	28	65	123	28	-78	-37	-49	21	9	25	123	-8	-110	40	11.22
4736.32	18	28	67	127	27	-78	-39	-43	20	12	36	124	-9	-109	38	11.15
4736.33	21	31	65	127	33	-76	-36	-45	21	9	27	123	-6	-103	39	11.02
4736.34	17	27	66	124	29	-78	-35	-43	22	8	33	123	-8	-104	40	10.87
4736.35	15	36	65	123	26	-78	-38	-42	24	8	25	122	-10	-107	38	11.07
4736.36	18	33	66	123	27	-77	-37	-41	23	9	30	119	-9	-110	42	11.20
4736.37	16	30	63	126	26	-78	-38	-44	24	9	29	120	-9	-108	40	11.11
4736.38	18	31	64	124	27	-77	-34	-43	20	16	30	124	-11	-112	42	10.91
4736.39	19	31	62	127	27	-77	-37	-40	21	4	27	124	-7	-106	38	10.90
Average	**19**	**30**	**66**	**125**	**28**	**-78**	**-37**	**-43**	**20**	**8**	**29**	**123**	**-9**	**-108**	**40**	**11.04**

	Unit is watered up					Turbine test runs 2	Unit running - stroking through gate positions									
	Strain															
Time	1	2	3	4	5	6	7	8	9	10	11	12	12	12	15	Displacem
5260	17	31	63	112	26	-68	-31	-38	21	7	31	113	-9	-95	39	8.44
5260.01	17	30	56	114	27	-69	-32	-38	22	9	35	112	-11	-95	39	8.33
5260.02	20	31	56	113	26	-70	-32	-37	21	13	29	109	-8	-102	39	8.16
5260.03	18	28	64	113	26	-67	-30	-35	22	12	30	111	-8	-93	44	8.23
5260.04	21	31	60	114	26	-67	-30	-40	16	8	29	112	-9	-95	40	8.51
5260.05	20	30	61	114	26	-69	-33	-38	18	7	35	115	-8	-95	40	8.38
5260.06	20	30	61	116	26	-68	-30	-39	20	14	36	112	-11	-98	42	8.21
5260.07	16	30	60	114	27	-69	-32	-37	21	12	29	114	-6	-95	42	8.14
5260.08	20	35	61	113	22	-68	-32	-36	21	10	29	111	-10	-96	41	8.48
5260.09	15	28	61	118	27	-69	-33	-40	22	6	28	107	-9	-99	40	8.41
5260.1	21	27	58	115	25	-68	-30	-39	21	5	32	110	-10	-96	41	8.27
5260.11	20	30	64	114	26	-67	-35	-39	20	14	33	111	-7	-101	41	8.14
5260.12	21	31	61	116	27	-70	-32	-41	19	12	33	110	-11	-96	39	8.36
5260.13	20	28	61	114	25	-68	-33	-38	17	13	29	111	-10	-96	42	8.46
5260.14	15	31	62	115	25	-67	-34	-40	22	7	26	113	-12	-96	38	8.33
5260.15	17	24	61	117	25	-70	-34	-40	17	13	33	112	-11	-95	40	8.16
5260.16	19	28	64	117	23	-67	-33	-38	20	11	33	114	-10	-94	39	8.20
5260.17	19	36	62	115	29	-70	-32	-41	17	17	34	115	-9	-97	42	8.52
5260.18	20	31	59	114	27	-69	-33	-40	16	9	29	109	-6	-96	42	8.37
5260.19	21	30	63	113	26	-69	-34	-42	19	8	29	110	-6	-96	42	8.21
Average	**19**	**30**	**61**	**114**	**26**	**-68**	**-32**	**-39**	**20**	**10**	**31**	**112**	**-9**	**-96**	**41**	**8.32**

	Unit is online					Turbine test runs 2	Unit running - unit is online to grid									
	Strain															
Time	1	2	3	4	5	6	7	8	9	10	11	12	12	12	15	Displacem
19500	23	37	77	143	36	-85	-35	-46	23	-42	37	142	2	-112	41	16.62
19500.01	19	30	75	145	38	-86	-38	-47	22	-51	39	139	-1	-114	41	16.62
19500.02	19	35	79	146	37	-83	-39	-46	24	-46	44	144	2	-111	43	16.80
19500.03	18	34	72	146	38	-88	-39	-49	26	-41	40	143	-1	-112	37	16.97
19500.04	23	34	79	146	36	-86	-39	-50	25	-46	47	142	-3	-114	42	16.95
19500.05	15	34	73	148	38	-84	-36	-47	22	-44	45	143	0	-111	40	16.85
19500.06	18	35	69	145	39	-88	-36	-45	26	-45	42	141	-5	-111	42	16.80
19500.07	18	37	77	143	37	-86	-40	-46	31	-44	38	141	2	-112	42	16.71
19500.08	17	35	72	143	38	-86	-39	-45	26	-46	43	139	-1	-113	40	16.63
19500.09	24	31	73	146	38	-87	-39	-48	24	-42	41	142	0	-113	41	16.63
19500.1	15	43	74	147	40	-86	-37	-48	26	-46	40	144	-2	-117	39	16.69
19500.11	15	34	72	148	37	-86	-38	-50	23	-43	45	143	-2	-110	38	16.91
19500.12	21	34	75	141	38	-87	-37	-48	24	-44	42	142	1	-111	41	16.97
19500.13	21	38	76	148	39	-86	-40	-46	27	-48	39	141	-1	-112	42	16.88
19500.14	17	32	73	146	36	-86	-37	-45	25	-49	39	143	2	-115	39	16.83
19500.15	21	32	79	145	36	-87	-38	-44	25	-43	43	145	0	-113	40	16.75
19500.16	17	35	72	147	35	-89	-40	-47	27	-46	37	143	4	-110	41	16.65
19500.17	19	31	73	144	40	-84	-40	-45	28	-44	47	144	1	-113	42	16.62
19500.18	16	36	75	146	38	-86	-38	-51	25	-41	42	140	3	-112	43	16.63
19500.19	22	35	72	145	39	-86	-42	-43	25	-43	36	141	-2	-111	39	16.90
Average	**19**	**35**	**74**	**145**	**38**	**-86**	**-38**	**-47**	**25**	**-45**	**41**	**142**	**0**	**-112**	**41**	**16.77**

	Unit is online				Normal Operation	Unit running - unit is online to grid, this test is the highest loading scenaroio recorded during this test										
	Strain															
Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Displacem
20322.7	22	41	85	168	45	-90	-37	-54	30	-85	53	167	5	-120	21	19.06
20322.71	20	45	91	166	41	-90	-36	-52	26	-81	51	172	8	-120	22	19.06
20322.72	21	45	86	171	44	-92	-33	-56	29	-80	52	170	7	-122	21	19.10
20322.73	23	41	88	169	45	-92	-33	-57	30	-81	51	165	6	-119	20	19.05
20322.74	21	36	88	169	47	-90	-32	-54	32	-75	58	170	5	-116	22	19.07
20322.75	22	41	90	169	45	-92	-35	-55	29	-77	56	170	2	-122	23	19.10
20322.76	22	37	90	167	46	-92	-36	-55	30	-84	53	165	8	-117	21	19.09
20322.77	21	43	87	169	42	-92	-37	-54	32	-82	52	171	4	-121	22	19.12
20322.78	24	40	90	168	47	-92	-35	-54	31	-82	52	167	9	-122	19	19.19
20322.79	24	39	86	166	47	-92	-34	-57	30	-83	50	169	9	-121	21	19.22
20322.8	18	41	89	167	48	-90	-35	-53	32	-80	53	169	2	-119	20	19.31
20322.81	18	43	86	170	48	-91	-36	-50	31	-76	49	170	1	-120	21	19.33
20322.82	19	38	94	168	46	-91	-33	-55	31	-72	58	167	4	-123	20	19.39
20322.83	26	44	84	170	43	-90	-33	-56	28	-79	55	168	10	-120	21	19.40
20322.84	22	41	90	171	47	-91	-31	-53	28	-81	55	169	6	-121	22	19.41
20322.85	23	44	86	168	45	-93	-35	-53	31	-82	50	167	7	-122	23	19.46
20322.86	22	36	86	169	47	-91	-34	-51	23	-82	55	168	7	-121	20	19.41
20322.87	23	43	87	169	47	-90	-33	-50	25	-79	51	169	5	-119	23	19.41
20322.88	20	41	89	172	41	-92	-36	-54	29	-80	47	168	6	-120	21	19.36
20322.89	21	40	85	168	47	-93	-38	-51	34	-80	51	169	9	-123	22	19.35
Average	**22**	**41**	**88**	**169**	**45**	**-91**	**-35**	**-54**	**30**	**-80**	**53**	**168**	**6**	**-120**	**21**	**19.25**

	Unit is online			Normal Operation 2		Unit running - unit is online to grid, this test is the highest loading scenaroio recorded during the first part of the te										
	Strain															
Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Displacem
23185.6	25	44	89	178	46	-94	-34	-53	34	-87	60	180	12	-124	8	22.61
23185.61	22	42	93	178	48	-95	-35	-53	36	-92	58	177	9	-123	9	22.63
23185.62	23	44	94	176	46	-96	-39	-55	27	-88	58	180	8	-120	7	22.61
23185.63	25	39	90	176	48	-94	-36	-53	34	-91	61	178	7	-122	5	22.59
23185.64	27	43	96	176	50	-95	-35	-59	31	-91	57	181	9	-120	4	22.61
23185.65	21	43	90	175	46	-96	-38	-53	36	-93	59	178	8	-125	10	22.61
23185.66	22	38	96	178	49	-92	-34	-57	29	-97	62	179	8	-122	12	22.62
23185.67	23	43	90	178	44	-96	-32	-54	35	-91	64	179	5	-120	5	22.59
23185.68	21	41	91	177	49	-94	-35	-55	35	-93	60	180	8	-122	9	22.56
23185.69	20	47	92	178	50	-94	-36	-56	29	-90	59	179	11	-122	11	22.58
23185.7	16	39	90	177	47	-96	-37	-54	31	-89	59	178	6	-124	9	22.59
23185.71	18	45	92	178	45	-94	-36	-57	37	-88	62	179	10	-120	11	22.59
23185.72	20	39	89	178	46	-96	-37	-56	29	-85	63	182	13	-124	7	22.55
23185.73	24	44	93	175	48	-96	-34	-55	30	-91	65	178	8	-121	9	22.59
23185.74	22	42	89	178	50	-94	-38	-55	38	-91	62	182	7	-124	10	22.56
23185.75	21	39	91	177	46	-92	-36	-56	38	-87	64	181	7	-124	9	22.57
23185.76	20	45	94	178	44	-97	-31	-57	31	-86	67	179	6	-121	10	22.60
23185.77	23	41	92	177	49	-95	-38	-55	34	-90	63	177	9	-121	12	22.58
23185.78	24	43	91	176	47	-92	-35	-55	33	-88	64	181	11	-120	8	22.58
23185.79	21	39	92	175	45	-95	-35	-56	33	-89	64	179	8	-127	9	22.55
Average	**22**	**42**	**92**	**177**	**47**	**-95**	**-36**	**-55**	**33**	**-90**	**62**	**179**	**9**	**-122**	**9**	**22.59**

	Unit is online					Normal Operation		Unit running - unit is online to grid								
	Strain															
Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Displacem
25438	22	34	71	130	42	-69	-30	-35	28	-85	44	138	11	-90	17	13.08
25438.01	24	36	74	133	43	-66	-30	-35	29	-87	44	140	8	-91	16	13.07
25438.02	25	37	69	134	41	-67	-28	-32	24	-86	45	135	10	-91	18	13.11
25438.03	24	34	76	134	42	-61	-26	-35	28	-89	48	139	13	-90	17	13.14
25438.04	23	38	71	131	38	-64	-30	-39	27	-85	43	137	6	-85	16	13.09
25438.05	24	35	71	133	39	-64	-27	-37	28	-83	48	137	6	-89	20	13.11
25438.06	25	43	73	134	38	-66	-30	-38	28	-82	51	140	11	-89	16	13.15
25438.07	26	37	71	136	37	-66	-28	-33	32	-86	49	136	6	-92	19	13.15
25438.08	24	32	76	134	39	-65	-27	-35	28	-83	49	141	6	-92	15	13.16
25438.09	24	38	68	133	39	-63	-27	-34	28	-84	47	138	6	-91	17	13.17
25438.1	26	35	71	136	42	-66	-27	-34	29	-80	51	139	9	-90	16	13.22
25438.11	24	41	71	135	42	-64	-27	-35	23	-82	49	137	8	-90	15	13.21
25438.12	20	35	76	136	40	-63	-29	-36	26	-77	51	140	7	-88	14	13.19
25438.13	21	41	70	133	39	-67	-27	-40	25	-81	50	138	9	-91	16	13.20
25438.14	21	36	72	129	38	-66	-30	-34	27	-84	49	142	5	-95	17	13.17
25438.15	23	38	73	135	41	-70	-28	-36	34	-84	45	136	10	-94	18	13.20
25438.16	23	35	74	137	39	-65	-28	-32	27	-82	45	141	15	-91	16	13.20
25438.17	22	38	76	135	39	-67	-26	-34	22	-82	45	137	12	-92	16	13.21
25438.18	19	38	69	135	42	-67	-27	-37	28	-85	42	139	5	-90	15	13.23
25438.19	24	42	75	135	43	-64	-29	-38	24	-89	44	142	12	-95	17	13.21
Average	**23**	**37**	**72**	**134**	**40**	**-66**	**-28**	**-36**	**27**	**-84**	**47**	**139**	**9**	**-91**	**17**	**13.16**

	Unit is online					Normal Operation 2		Unit running - unit is online to grid								
	Strain															
Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Displacem
29847	30	46	85	170	47	-86	-27	-46	35	-111	61	172	16	-111	10	24.69
29847.01	27	45	92	170	46	-88	-25	-47	37	-105	53	172	15	-114	9	24.69
29847.02	20	45	86	171	46	-88	-23	-48	33	-105	57	173	13	-115	7	24.64
29847.03	24	40	91	171	46	-87	-28	-50	33	-102	61	173	15	-115	11	24.64
29847.04	26	45	92	170	45	-88	-28	-47	35	-105	59	174	15	-116	9	24.60
29847.05	23	42	89	169	48	-86	-25	-49	33	-103	53	171	14	-114	8	24.57
29847.06	22	46	92	171	44	-90	-25	-51	33	-104	54	171	12	-115	9	24.52
29847.07	21	41	86	170	49	-89	-26	-49	36	-103	58	173	16	-115	7	24.54
29847.08	25	40	90	172	46	-85	-24	-50	31	-106	58	175	11	-115	12	24.53
29847.09	23	42	87	169	46	-89	-26	-49	32	-107	59	170	12	-116	6	24.49
29847.1	29	39	91	170	48	-87	-25	-49	35	-108	57	172	15	-113	9	24.50
29847.11	25	44	90	170	46	-88	-27	-48	35	-106	59	171	10	-115	9	24.56
29847.12	23	44	92	170	46	-88	-25	-54	30	-111	53	169	10	-111	5	24.54
29847.13	27	49	90	171	46	-89	-27	-47	34	-109	54	173	13	-116	7	24.51
29847.14	24	42	85	172	45	-90	-26	-50	35	-107	53	170	8	-116	8	24.56
29847.15	27	46	87	170	51	-86	-26	-54	38	-105	55	170	13	-117	8	24.59
29847.16	24	40	91	167	48	-88	-28	-53	37	-104	59	171	15	-115	8	24.70
29847.17	23	47	91	172	47	-89	-28	-47	30	-105	55	173	12	-116	8	24.75
29847.18	30	40	87	171	48	-88	-28	-47	37	-109	52	171	14	-114	7	24.78
29847.19	27	40	88	172	48	-90	-26	-46	37	-105	54	172	12	-114	7	24.85
Average	**25**	**43**	**89**	**170**	**47**	**-88**	**-26**	**-49**	**34**	**-106**	**56**	**172**	**13**	**-115**	**8**	**24.61**

	Unit is online					Normal Operation 2		Unit running - unit is online to grid							
	Strain														
Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Displacem
460.7	25	45	87	159	48	-82	-32	-51	35	-84	54	162	7	-110	5	16.69
460.71	21	41	88	161	46	-80	-31	-47	31	-84	53	164	10	-109	7	16.67
460.72	28	44	88	162	45	-82	-27	-46	40	-83	54	159	9	-106	7	16.71
460.73	23	44	85	164	48	-80	-27	-46	36	-85	52	159	5	-108	7	16.74
460.74	24	40	88	162	46	-82	-31	-46	32	-82	53	159	5	-107	8	16.72
460.75	30	42	82	160	47	-80	-30	-47	31	-82	56	160	8	-108	5	16.74
460.76	28	38	88	165	48	-81	-28	-45	36	-85	52	155	10	-106	7	16.77
460.77	25	49	84	161	45	-81	-33	-43	36	-79	54	162	8	-108	5	16.71
460.78	27	39	86	162	46	-79	-31	-45	31	-85	54	161	9	-110	8	16.67
460.79	26	44	87	161	46	-78	-30	-43	36	-80	56	162	12	-107	6	16.57
460.8	27	38	85	163	47	-81	-28	-50	32	-79	51	160	11	-107	6	16.54
460.81	20	43	87	160	45	-83	-31	-45	34	-77	57	162	8	-102	5	16.50
460.82	25	39	88	165	49	-85	-30	-47	30	-81	52	163	9	-112	9	16.40
460.83	22	46	84	162	47	-82	-27	-49	34	-77	55	160	11	-109	6	16.38
460.84	22	43	85	163	49	-84	-29	-49	24	-78	52	162	4	-110	9	16.37
460.85	22	46	90	165	48	-81	-27	-49	34	-78	54	164	7	-108	8	16.37
460.86	24	39	91	162	49	-85	-28	-46	33	-77	55	161	9	-109	7	16.38
460.87	26	43	85	167	49	-82	-29	-48	32	-76	56	162	13	-114	6	16.37
460.88	26	40	86	162	50	-82	-30	-48	36	-75	55	162	12	-107	7	16.38
460.89	23	44	82	162	47	-80	-31	-44	34	-75	56	161	4	-112	6	16.40
Average	**25**	**42**	**86**	**162**	**47**	**-82**	**-29**	**-47**	**33**	**-80**	**54**	**161**	**9**	**-109**	**7**	**16.55**

Screenshots from Somat Infield

Test: Normal Operation

During this test the turbine is generating power and connected to the power grid. Strain 3 and 7 are strain gauges at the crack location. Strain 6 is measuring bending in the shear lever and is the location of the highest strain in the control system. The displacement plot is recording the stroke of the servo hydraulic that controls the wicket gate position.

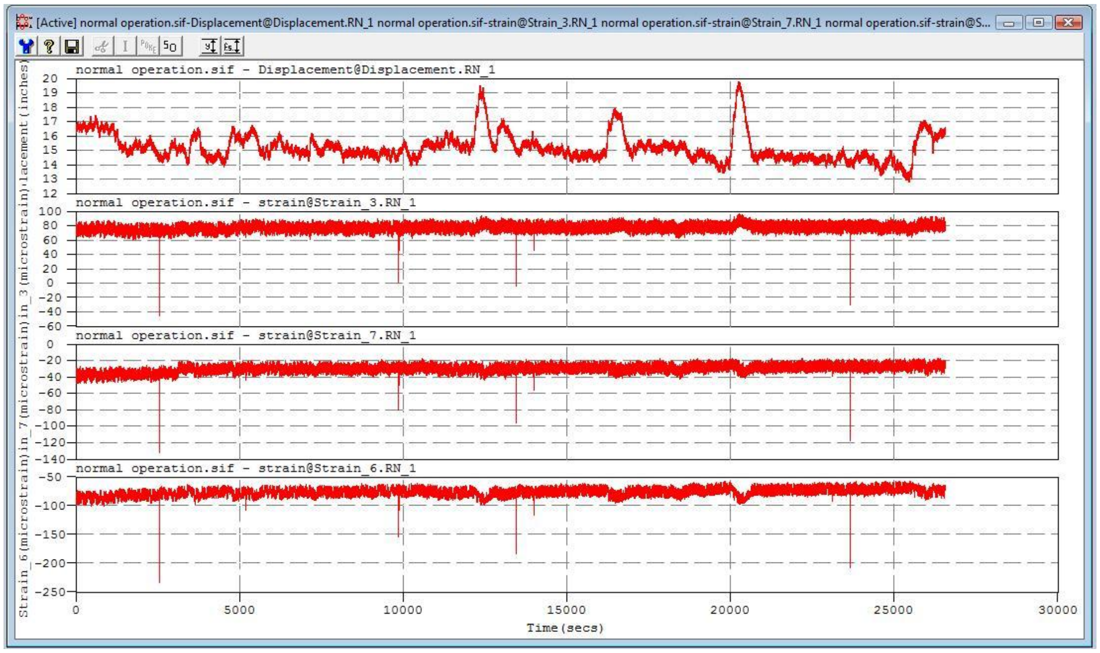


Figure 22. Normal Operation Strains

Test: Turbine Test Runs 1

During this test the turbine attempts to start several times. Each peak in the timeline of the plots is a failed attempt of the turbine to self excite its electromagnets.

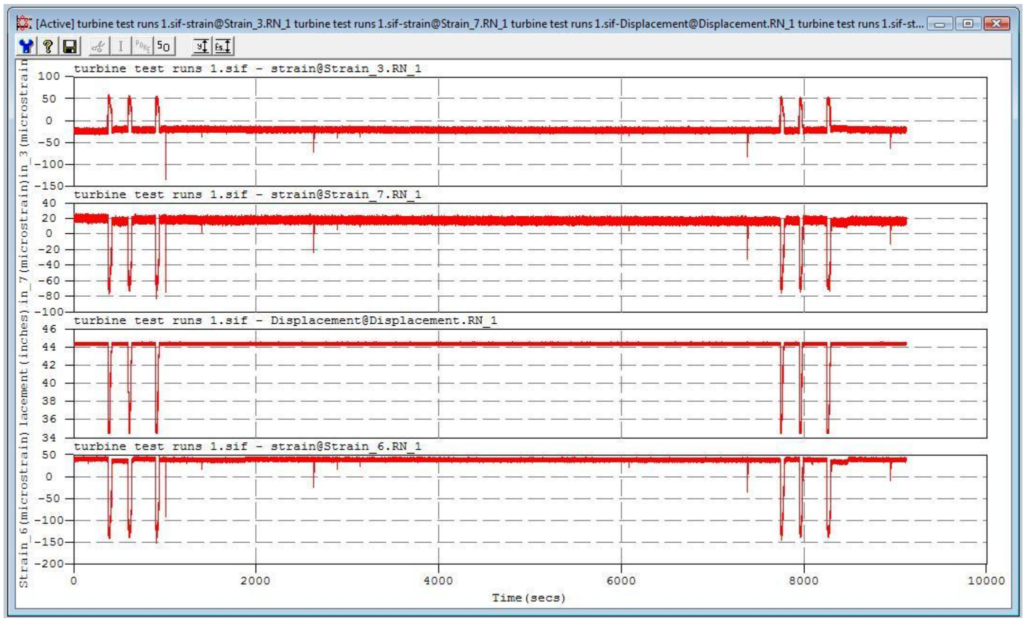


Figure 23. Turbine test run 1

Test: Turbine Test Run 2

During this test the turbine successfully starts. Once started, the unit is stroked from 19% to 90% gate opening; this is shown near the 5000 second marker in the displacement plot.

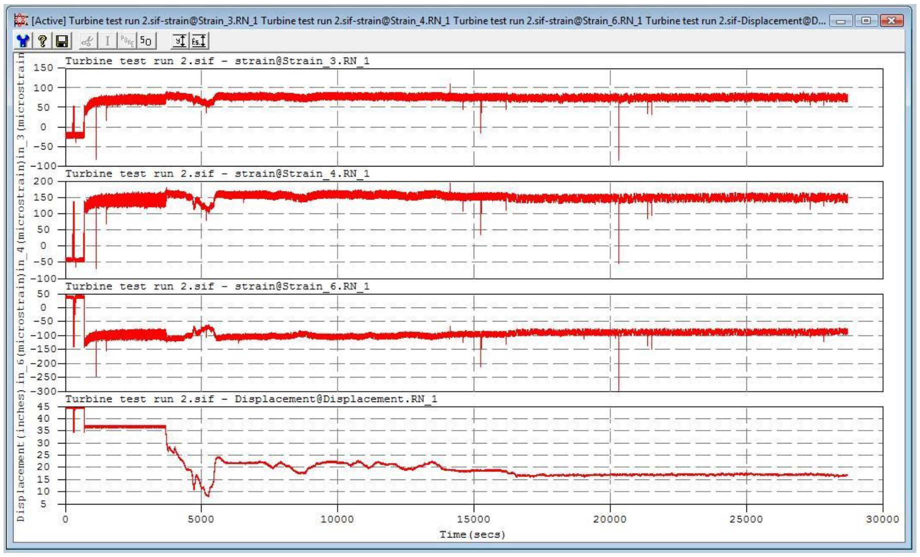


Figure 24. Turbine test run 2

Appendix C. Hand Calculations

Note that all stresses are measured in psi, and all strains are microstrains.

From Hooke's Law the stress in the material is directly related to the strain (ε).

$$\sigma = E\varepsilon$$

The lever components are made of ASTM A27 steel with an elastic modulus (E) of 29x10^{-6}psi. The data recorded by the Somat data acquisition system is automatically corrected for the gauge factor, temperature and other considerations. Because of this the data can be directly used to calculate the material stress.

The highest strain recorded during the test for the crack location was at 54% gate with a recorded value of 92x10^{6}. From this the strain can be calculated.

$$\sigma = E\varepsilon = (29 \times 10^{-6}) \times (92 \times 10^{6}) = 2668psi$$

To compare the calculated strain the FEA model the proper input force must be used in the FEA. From the measured strain in the shear lever the bending force can be calculated.

For pure bending the stress is related to the input loading by:

$$\sigma = \frac{My}{I}$$

Where M is the bending moment, y is the distance from the neutral axis and I is the moment of inertia of the lever. At the center location where the strain gauges are located the lever has a moment of inertia of 1111in^4 and the distance from the neutral axis is 8.71in. To solve for the force the bending moment can be broken down to the input force multiplied by the lever arm distance. For the input from the connecting link to the shear pin location on the shear lever the distance is 28in (D). The bending equation can be rearranged to solve for force:

$$M = \frac{\sigma I}{y} = FD \; \rightarrow F = \frac{E\varepsilon I}{Dy}$$

For the shear lever at 54% gate opening the lever experiences both axial loading and bending. At this gate position the shear lever experiences an axial strain of 47 microstrain as recorded by strain 5. However this is measured at a location of the lever arm where the cross sectional area is smaller. To account for this the strain must be corrected to an equivalent axial strain at the location of bending. By taking a ratio of the areas a correction factor can be determined.

$$\frac{36.18in.}{41.54in.} = 0.87$$

Applying this correction factor to the measured axial strain results in the equivalent axial strain at the center of the lever.

$$47 * 0.87 = 40.9$$

Since the lever is in bending and axial loading this load must be taken into account before the input force can be determined as we are concerned only with the pure bending force in this lever. For the tension side of bending this must be subtracted and for the compression side it must be added. At 54% gate the bending strains are -95 on the compression side and 177 on the tension side (strain 4 and 6).

$$95 + 40.9 = 135.9$$

(note: the absolute value of -95 is used for comparison to the tension side)

$$177 - 40.9 = 136.1$$

The average of these strains is 136 microstrain. This will be used to calculate the pure bending input force which will be used in the FEA analysis. Now the bending strain, elastic modulus, and lever geometry can be used to solve for the input force.

$$F = \frac{E\varepsilon I}{Dy} = \frac{(29 \times 10^{-6})(92 \times 10^{6})(1111)}{(28)(8.71)} = 17{,}996lbF$$

This value was used as the maximum load the shear lever experiences and will be used in the comparison of the actual loading to the FEA model.