UNIVERSITY
OF MANITOBA

THE DESIGN OF A MULTIPART WICKET GATE FOR

WUSKWATIM GENERATING STATION

MECH 4860: Engineering Design
Final Design Report
Team # 13
Louie's Lightning Bugs

Sponsoring Company: Manitoba Hydro
Project Advisor: Dr. Meera Singh
Date of Submission: December 6th, 2010

Department of Mechanical and Manufacturing Engineering

I, Sukhwant Sidhu have read and understood the following design report and agree with the content within the document provided by Team 13.

December 5th, 2010

Sukhwant Sidhu, P.Eng
Mechanical Engineer, Power Generation Systems

Date

December 6th, 2010

S.S. Sidhu, P.Eng
Power Generation Systems
Mechanical Engineering Department
Manitoba Hydro
17th Floor 360 Portage Ave
Winnipeg, Manitoba

Dear Mr. Sidhu:

Team 13 of the MECH 4680Mechanical Engineering Design coursewould like to submit the design report entitled*The Design of a Multipart Wicket Gate for Wuskwatim Generating Station.* This report will be submitted on December 6th, 2010.

The purpose of this design report is to explain the design generated by Team 13 for a possible solution for a multipart wicket gate that can be assembled and disassembled without removal of the head cover. This report is complete with 3D CAD models and drawings explaining the design.

The report begins with an introduction to the problem which identifies the customer needs, target specifications and project objectives. Next, the details of the design are given, complete with 3D figures and drawings, a removal and installation procedure and a detailed cost analysis.

If you have any questions or concerns, please feel free to contact myself, Britta Borchers, Team manager.

Sincerely,

Britta Borchers on behalf of:

Colin Jones
Jason Reimer
Kingsley Woods

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Glossary of Terms

Allowable Stress – The maximum stress value any component of the wicket gate can be subjected to, as specified by Manitoba Hydro.

AutoCad Inventor – The type of Computer Aided Design (CAD) software used to generate the models, drawings and finite element analysis used in this report.

Finite Element Analysis (FEA) – A type of analysis used to calculate stresses on a geometrically complex component under loading. A CAD program separates the component body into small elements and calculates the stresses in each element.

Runner – Also known as a turbine, it is the bladed assembly that rotates when subjected to the flow of water. The rotation of the runner drives electricity generation.

Scroll Case – The area surrounding the wicket gates that channels the water over the runner.

Stress Concentration – An area on a part over which the stress caused by loading is amplified. This amplification is caused by geometrical features such as sharp corners.

Von Mises Stress– A value based on the principal stresses at a point which can be used to check for yielding on a part. Von Mises stress is also known as equivalent stress.

Abstract

The purpose of this report is to present a solution to Manitoba Hydro's request for a multipart wicket gate that can be installed and removed from Wuskwatim Generating Station without requiring major disassembly of the generating equipment. The team has designed a multipart wicket gate that addresses the requirements of the project. This report includes a discussion of the design, a method of installation and removal, drawings of the designed wicket gate assembly and a finite element analysis.

The current wicket gate is one solid part, and significant disassembly of generating equipment must occur before the gate can be removed and refurbished. Disassembly of the generating station takes several months and results in substantial costs to Manitoba Hydro due to loss of revenue. Therefore, Manitoba Hydro has requested a multipart wicket gate be designed in order to greatly reduce generator downtime.

The final design is made up of three major components: the top stem section, the gate body, and the bottom stem section. These three sections can be bolted together inside the scroll case, which eliminates the need for removal of any generating equipment. The top and bottom stem sections mate with the gate body in such a way that the torque required to rotate the gate can be transmitted to the body through the mating surfaces as well as the bolts.

Due to the large stress concentrations present in the corners of the stem-to-gate mating surfaces, it is recommended that large fillets be present at those corners and that a high strength material be used for the top stem section. Preliminary finite element analysis showed maximum Von Mises stresses below the allowable stress for some, but not all of the loading conditions. In addition to performing the finite element analysis, the team was asked to produce a detailed installation procedure for the multipart wicket gate. The team recommends that a detailed review of the installation procedure, as well as further finite element analysis, be performed before manufacture and implementation of the multipart gate.

1. Introduction

Manitoba Hydro is a world leader in the production of hydroelectric energy; as such, it is committed to continually improving the performance of its generating units and maintenance practices. In a hydroelectric generating station as seen in Figure 1, water flows from the forebay (the left of the figure) through the intake structure which directs the flow through the wicket gates.The water then spins the runner and exits through the draft tube at the bottom. The area that the team is mainly concerned with is the wicket gates, highlighted in green.
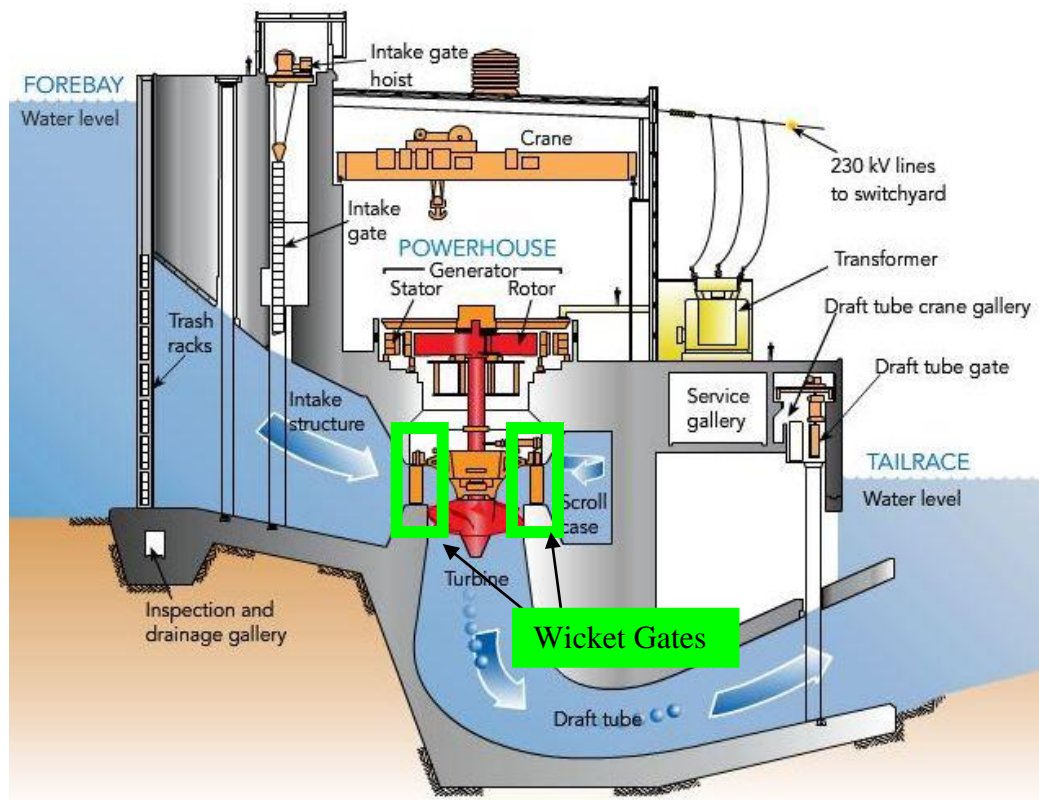
Figure 1: Turbine Cross Section [1]

Inspection and refurbishment of the wicket gates and wicket gate bushings are part of Manitoba Hydro's maintenance program, which occur every 15 - 20 years or as needed.The team, comprised of mechanical engineering students, was asked by Manitoba Hydro to re-design the wicket gate for a cost effective alternative during non-scheduled maintenance.The following sections explain the purpose of the project and what the teamplans to accomplish.

1.1 *The Problem*

In order to perform refurbishment on the wicket gates, the turbine unit must be shut down for at least six to eight weeks. Each day that the turbine is not generating electricity it costs Manitoba Hydro approximately $40,000 - $50,000. In addition to this cost from lost generation, the unit disassembly and reassembly work results in another $750,000 - $1,000,000 inlabour costs. This high cost justifies the need to find an alternative solution to improve the maintenance procedure of the wicket gates.

The current procedure to remove the wicket gates during refurbishment is to disassemble the head cover. The head cover is a major structural component and its removal is the primary reason for the extended down time on a turbine unit. Therefore, the team was asked by Manitoba Hydro to design a multipart wicket gate that can be uninstalled without requiring major disassembly of the turbine.

1.2 *Project Objectives*

The project objectives for the team and outcomes of the final project are as follows. The team will design a wicket gate that can be dissembled and removed from the installed position without removal of the turbine head cover. The design will include an innovative method for assembly of the wicket gate that will meet the standards Manitoba Hydro requires. The team will also perform a stress analysis on the final design using the **finite element analysis** (FEA) software included in **AutoCAD Inventor**. Finally, the team will strive to ensure the safety of the technicians by using safe work practises in the installation and removal procedures.

2. Details of Design

The multipart wicket gate is comprised of three major components: the gate body, the top stem segment, and the bottom stem segment. These three segments were designed so that the gate body could be unbolted from the top and bottom stem segments while the head cover is in place. After the gate body has been unbolted and removed, the top and bottom stem segments can be uninstalled and serviced. Once the gate stems are removed, the wicket gate bushings in outer head cover and bottom ring can be replaced. Further details of the design have been included.

2.1 *Features of Design*

The following sections discuss each part individually and describe how each part helps fulfill the design requirements of the gate as a whole.

2.1.1 Body

The functionality of the newly designed wicket gate body is identical to the old design in that it directs and controls the flow of water coming through the **scroll case** over the **runner**. The hydrodynamic profile of the gate is no different than the profile currently used in the field. The overall dimensions are also unchanged from the current model. The design constraints specified by Manitoba Hydro regarding the wicket gate body required that the dimensions and profile of the gate be unchanged and those constraints have been met.

However, to fulfill the purpose of this project, sections of the gate on the bottom and top of the body have been cut out, as seen in Figure 2. In order to change the gate from a single piece into a multiple-piece assembly, the cutouts were added where the top and bottom stems will be fastened. The cutouts on the top and bottom stems are exact mirrors of each other, in order to simplify manufacturing and installation.
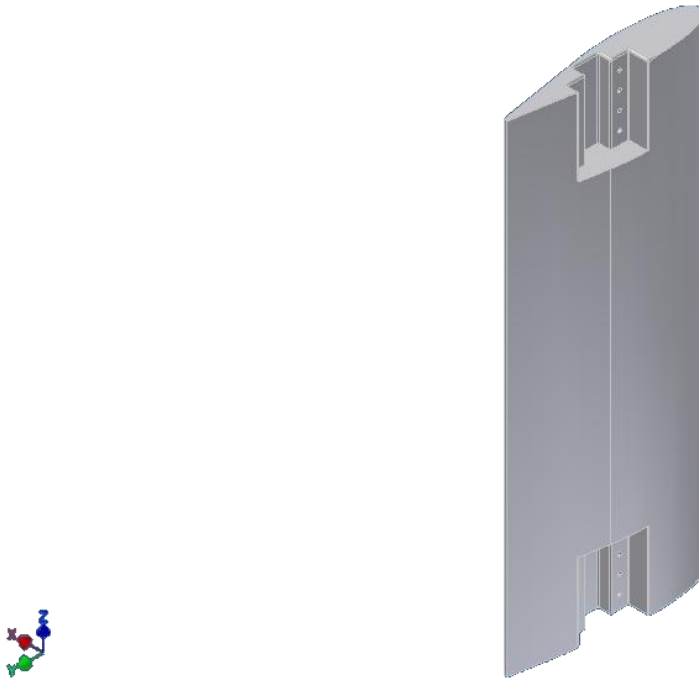
Figure 2: Stem Sectioned Wicket Gate Body

The cutout section is designed to be as small as possible to keep the hydrodynamic profile disturbance to a minimum, and yet large enough to transmit the torque transferred from the top stem over a sufficient area. Each cutaway section has eight threaded holes drilled into the body where bolts will fasten the top and bottom stems to the gate. A top view of the cutaway section reveals a T-shape which is designed to act as a key slot for the stem sections. All corners of the cutaway are filleted to decrease **stress concentrations** as much as possible.A detailed drawing of the wicket gate body cutout section is available in Appendix A.1.

2.1.2 Top and Bottom Stem Sections

The top stem section of the assembly is now a separate component of the wicket gate, as shown in Figures 3 and 4. This design contrasts the current design where the stem and gate body are welded. The section of the top stem which protrudes from the top of the gate body is unchanged from the original design, as specified by Manitoba Hydro. Only the section of the top stem section which mates with the gate body is new. The functionality of the top stem will be

identical to its current usage, which is to transmit torque from the servomotors to the gate to control the flow of water over the runner.
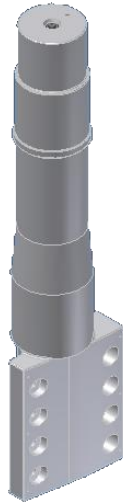
Figure 3: Front View: Top Stem Section   **Figure 4: Back View: Top Stem Section**

The section attached to the bottom of the top stem is in a T-shape, and fits directly into the cutaway section of the wicket gate body. The top stem section is a separate component; this allows the top stem to be installed first by attaching it to the servomotor fixture. Once the top stem has been installed, the gate body can be brought in directly from the side and fastened to the stem. This feature was designed due to the impossibility of fastening the parts together using any vertical motion. The T-shape, as discussed earlier, is designed to transmit the torque from the servomotors into the gate body without slippage.

There are eight holes drilled through the flanges of the top stem section. These holes allow bolts to go through the flange and thread into the gate. Countersunk holes will be drilled into the outward facing side of the stem section, so that the hex bolt heads will not protrude out from the surface of the gate. In addition, six small threaded holes will be drilled into the flanges of the section, where the screws holding the cover plate will be placed. These holes will be

drilled in a normal direction to a tangent planeon the curve of the hydrodynamic profile, as opposed to the bolt holes which are drilled horizontally into the surface of the part.

Due to the extreme torsion applied to the top stem, large fillets are required between the shaft and horizontal surface of the stem section. Additionally, large fillets will be applied to all sharp corners where stress concentrations occur. The FEA carried out under the specified loading conditions shows regions of high stress at some of the corners of the top stem section and are displayed in Appendix C.1.

In response to sealing requirements, the outside dimensions of the stem section are slightly smaller than the cutout dimensions of the gate body. This gap allows a rubber gasket seal to be installed around the mating sections of the top and bottom stem, while still allowing the top and bottom stems to fit inside the cutout. It was assumed that 1 mm of clearance around the part would be sufficient space for an appropriate sealant.A detailed drawing of the top stem section is included in Appendix A.2 and A.3.

The bottom stem section design is an approximate mirrored image of the top stem section, with the exception of the protruding shaft. Please see Figures 5 and 6. However, this shaft is no different than the shaft currently in use. The T-shape of the section above the shaft has the same specifications as the top stem section except that smaller fillets were applied to the corners. This is because less torque is transmitted through the bottom shaft in comparison to the top shaft. All bolt and screw holes are placed at the same locations as in the top stem section.A detailed drawing of the bottom stem section is included in Appendix A.4 and A.5.
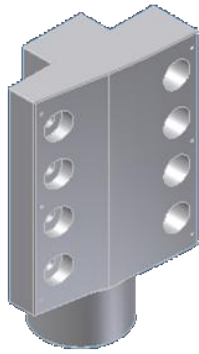
Figure 5: Front View: Bottom Stem Section   **Figure 6: Back View: Bottom Stem Section**

2.1.3 Cover Plate

The cover plate's function is to help maintain the hydrodynamic profile of the gate. Once the gate and stem sections are fastened together, the cover plates will be fastened to the gate using stainless steel machine screws. The plate has six holes which are countersunk so that the surface of the plate will be seamless when the screws are in place, offering minimal resistance to the flow of water. Stainless steel was the material selected for the plate and fasteners in order to reduce corrosion and fouling as much as possible. The cover plate may also offer sealing benefits if a gasket is applied underneath it before attachment. A detailed drawing of the stainless cover plate is included in Appendix A.6.
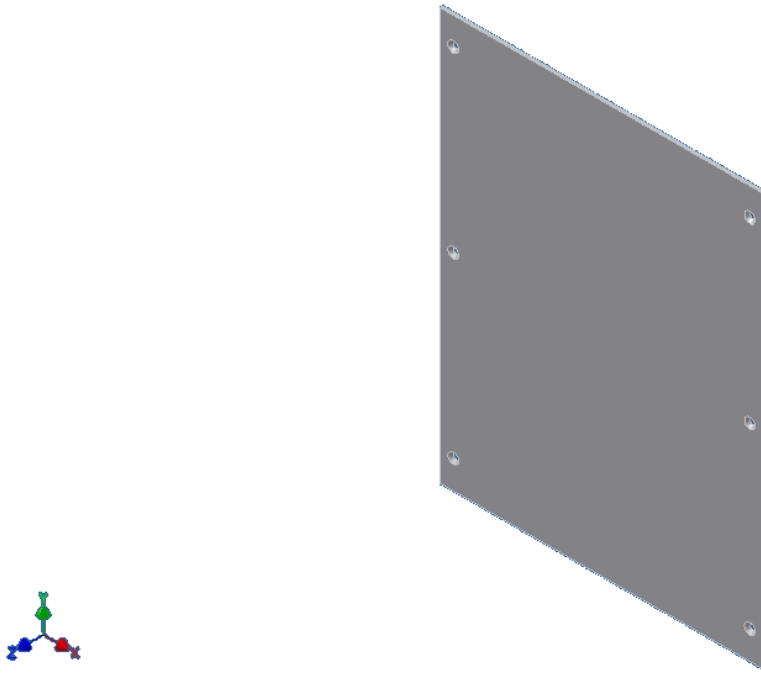
Figure 7: Stainless Steel Cover Plate

2.1.4 Hex Bolts

High strength stainless steel hex bolts will be used to fasten the top and bottom stem sections to the main wicket gate body. The required size of the bolts has been calculated and can be seen in Appendix B. These bolts must be strong enough to hold the gate in place and help transmit torque and fluid pressure between the stems and body. Although the shape of the interface between the stem sections and gate body has been designed to transfer force adequately, the bolts will be under significant stresses and so must be made out of high strength material. Again, because corrosion is a factor, stainless steel is used to keep fouling to a minimum.

2.1.5 Sealing Gasket

The presence of a rubber gasket or O-ring type of sealant was assumed throughout the design process, as referenced earlier in the top stem section description. The sealing of the wicket gate connection points was requested by Manitoba Hydro and so has been taken into consideration. However, no gasket specifications will be put forward due to time constraints.

2.1.6 Summary of Design

The new wicket gate presented in this report is used in exactly the same way as the current gate, so none of the parts discussed actually perform any new task, as such. The reason for the redesign of the gate is to change it from a one-piece weldment into a multipart bolt-together assembly. Therefore, each part in the new assembly has a function in making the gate modular, not in adding new abilities to the gate.

The top and bottom stems have been redesigned to fit into their existing places in the dam as required, while being able to be bolted to the wicket gate body. The intent of the redesign was that the torque transferred from the servomotors, and the hydraulic pressure applied to the gate body could be handled by the top and bottom stems without failure. That way, the strength of the gate assembly will not be compromised while being able to be disassembled and removed from the dam without long downtimes, as per Manitoba Hydro's request.

The gate body and cover plates have been redesigned to direct the flow of water over the same hydrodynamic surface as is presently used in the field. Manitoba Hydro requires that the profile of the gate not be changed. Therefore, the gate and stems have been designed so that when assembled, the overall shape of the gate is identical to the current model. The cover plate is used to cover the bolt holes in the stem sections and create a seamless profile over the face of the gate.

The wicket gate assembly does not have any new functionality other than the ability to be disassembled. It fulfills its design requirements by directing the flow of water over the turbine runner while possessing the ability to be removed relatively easily from the generating station.

2.2 *Drawings*

Detailed drawings of the design can be found in Appendix A.1 through to A.6.

2.3 *Operation*

The wicket gate directs the necessary tangential flow of the water onto the turbines to absorb most of the momentum from the water flow to drive the turbine. This section will present the procedures for the installation of the multipart wicket gate at Wuskwatim generating station. The safety of the employees and the contractors are the highest priority in this project. This is a new product to be implemented into a hydro generating station, so the following procedures will be a primary draft presented to the client, Manitoba Hydro.

1. De-water the unit and have local clearances in place to prevent watering up.
2. Attach Hilti anchors on the ceiling of the scroll case:
   a. Drill holes for Hilti anchors as per latest edition of Appendix D in the Building Code Requirements for Structural Concrete (ACI-318). Drill three holes for every five feet of length (from the scroll case access door to the wicket gate location).
   b. Install Hilti anchors into the pre-drilled holes using adhesive as per latest edition of Appendix D in the Building Code Requirements for Structural Concrete (ACI-318).
   c. Attach a 2ft x 2ft steel plate with 3/4" thickness to each Hilti anchor with one located in each corner.These plates will have pre-existing bolts that are counterbored into the steel plate to attach the monorail system.
3. Weld 2ft x 2ft with 3/4" thickness steel plates on to the monorail. These steel plates will have holes that are aligned with the counterbore bolts. The field maintenance crew will have these plates installed in the field for proper fit. Install monorail with 3 ton hoist on to the steel plates.
4. Weld a hook on the bottom of the head cover to the right of where the wicket gate will be placed.
5. Weld four lifting lugs to body of wicket gate (Position of lifting lugs to be determined by center of gravity).
6. Remove the scroll case access door panel.
7. Place the top and bottom stems outside of the scroll case door using the powerhouse crane.

8. Attach come-along to monorail.

9. Attach come-along to top stem.

10. Swing the top stem into the scroll case.

11. Using monorail, transport the top stem to the desired location.

12. Attach come-along to bottom stem sitting outside scroll case door.

13. Swing the bottom stem into the scroll case.

14. Using monorail, transport the top stem to the desired location.

15. Install bottom stem of the wicket gate:

    a. Attach come-along inside turbine pit.

    b. Extend the chain through the head cover to the scroll case using the wicket gate stem hole.

    c. Attach the bottom stem to come-along.

    d. Place in desired location.

    e. Disconnect come-along.

16. Install top stem of the wicket gate:

    a. Attach the top stem to come-along.

    b. Lift the top stem into place.

    c. Secure to wicket gate linkages.

17. Measure the distance between the top and bottom stems using laser measuring equipment. If needed shim the bottom stem.

18. Place the multipart wicket gate body in the horizontal position on its side outside of the scroll case access door using the powerhouse crane.

19. Attach come-along to monorail.

20. Attach come-along to lifting lugs on the body of wicket gate.

21. Swing the wicket gate into the scroll case.

22. Move the wicket gate to desired location.

23. Detach wicket gate from monorail.

24. Attach come-along to top of body section.

25. Lift the wicket gate to a vertical position.

26. Attach come-along to hook on head cover, feed through Hilti anchor (located on the ceiling of the scroll case) and then attach to multipart wicket gate.

27. Lift up wicket gate using come-along.

28. Swing the wicket gate into place.

29. Align the top stem to fit in the top section of the multipart wicket gate.

30. Align the bottom stem to fit in the bottom section of the multipart wicket gate.

31. Attach the top stem to the body of the multipart wicket gate.

32. Attach the bottom stem to the body of the multipart wicket gate. If needed make adjustments on the bottom stem's bushings.

33. Remove come-along attachments.

34. Remove come-along in turbine pit attached to top stem.

35. Dismantle monorail.

The process for removal is opposite to the installation. The multipart wicket gate is a new feature to be installed on the Wuskwatim generating station and the installation procedures will become more refined as the multipart wicket gate is used more frequently. The maintenance crews will provide the necessary feedback to improve the turnaround time and help reduce the overall maintenance cost.

2.4 *Overall Cost*

Manitoba Hydro is a producer and distributor of hydroelectric power. The company does not manufacture the wicket gates for its hydro generating stations, but provides a request for proposals to various vendors. The vendor that currently manufactures the required wicket gates is GE Hydro Asia (GEHA) in China [2]. The associated costs to develop the new design of the multipart wicket gate in the project will be assumed to be absorbed by the vendor.

The team will compare the time-frames of the current refurbishment practice and the proposed refurbishment of the wicket gates. The wicket gates refurbishment schedule is over a 15 year period. The income is taken over a 15 year period of the proposed Wuskwatim Generating Station. A summary of the wicket gate refurbishment analysis can be found in Table I. A detailed analysis can be found in Appendix C.3.

TABLE I: WICKET GATE REFURBISHMENT ANALYSIS

Wicket Gate Refurbishment			
Source	**Type**	**Current Refurbishment**	**Proposed Refurbishment**
Income	Revenue	$246,375,000	$246,375,000
	Total Revenue	$246,375,000	$246,375,000
Expenses	Loss Revenue	$2,800,000	$1,050,000
	Labour Materials	$1,000,000	$378,000
	Total Expenses	$3,800,000	$1,428,000
Benefit to Cost Ratio		64.84	172.53

The benefit to cost ratio found in Table I enhances the decision to develop the new multipart wicket gate for the Wuskwatim generating station.

3. Conclusion

The team recommends further analysis of the multipart wicket gate design before manufacture and implementation by Manitoba Hydro. The preliminary FEA results showed stresses present in the top stem section and gate body that are slightly above allowable stresses under the regular and fatigue loading conditions. Further iterations and higher element resolution in the analyses would be required before concrete recommendations can be made on the viability of the design.

Installation of the gates is feasible but difficult due to the large size and weight of the assembly parts and the small size of the doorway into the scroll case. While the installation procedure is not a prohibiting factor in implementation of this design, it will require substantial manpower and time. However, compared to the downtime currently required for disassembly of the head cover and other generating equipment, the installation of the multipart wicket gates will be much simpler and less expensive.

The stem sectioned multipart wicket gate meets Manitoba Hydro's functional requirements in that it can be disassembled and removed from the generating station without significant disassembly of other generating equipment. As specified, no other components of the generating equipment were changed, and the overall performance of the wicket gate to direct fluid flow has not been compromised. However, high stresses in the top stem section and gate body due to the torque applied by the servomotors are cause for concern. Further FEA, testing and design iterations must be completed before manufacture of these gates can proceed. In addition, streamlining of the installation procedure should be applied in order to gain the highest possible cost savings for Manitoba Hydro.

4. References

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[4] R. L. Mott, *Machine Elements in Mechanical Design*, 4[th]ed. Upper Saddle River, NJ:
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   http://www.roymech.co.uk/Useful_Tables/Screws/Hex_Screws.htm [November 21, 2010].

[8] "Concept Selection" class notes for MECH 4860, Department of Mechanical Engineering,
   University of Manitoba, 2010.

Appendix A –Multipart Wicket Gate Drawings

PARTS LIST			
ITEM	QTY	PART NUMBER	DESCRIPTION
1	1	wicket.gate.access.panel.cutaway	
2	1	wicket_gate_top_stem_panel	
3	16	BOLT_M24	
4	1	wicket_gate_bottom_stem_panel	
5	2	stainless_cover_plate	
6	12	stainless_mach_screw_5x18	

DRAWN Jason Reimer 11/20/2010
CHECKED
QA
MFG
APPROVED

TITLE
A.1 Wicket Gate Assembly Exploded View

SIZE A

DWG NO wicket.gate.access.panel.asmb_explode

REV

SCALE

SHEET 1 OF 1

ISOMETRIC VIEW

REAR VIEW

SIDE VIEW

FRONT VIEW

BOTTOM VIEW

50.00
Ø24.00 X 8 THRU ALL
Ø60.00 X 8

80.00
180.00
225.50
280.00
380.00

R9.00
R9.00

30.00
225.00
420.00

SHAFT DESIGN IDENTICAL TO CURRENT DESIGN

R5.88
R4.00

Profile follows gate profile offset by 3.175 mm

SEE SHEET 2 FOR BOTTOM VIEW DETAIL

108.26
350.00
63.40

DRAWN Jason Reimer
CHECKED
QA
MFG
APPROVED

11/20/2010

TITLE
A.2 Wicket Gate Top Stem Sheet 1

SIZE A

DWG NO
wicket_gate_top_stem_panel

REV

SCALE

SHEET 1 OF 2

BOTTOM VIEW

R3.00

R6.00

R4.85
R6.00

R6.00

R6.00

R4.85
R6.00

60.00
50.00

58.03

54.76

141.00

104.50

60.00
50.00

70.50

49.75

27.58

17.40

B

A

Ø5.00 ▼ 18.00
∨ Ø 5.65 X 90.0°

11.94

M5x0.8 - 6H

DETAIL B
SCALE 1 : 1

Ø5.00 ▼ 18.00
∨ Ø 5.65 X 90.0°

M5x0.8 - 6H

12.74

DETAIL A
SCALE 1 : 1

TITLE

A.3Wicket Gate Top Stem Sheet 2

SIZE
A

DWG NO
wicket_gate_top_stem_panel

REV

SCALE

SHEET 2 of 2

DRAWN
Jason Reimer   11/20/2010
CHECKED
QA
MFG
APPROVED

ISOMETRIC VIEW

REAR VIEW

Ø24.00 X 8 THRU ALL
Ø60.00 X 8

50.00

70.00

170.00

270.00

370.00

SIDE VIEW

R3.00

R3.00

30.00

225.00

420.00

FRONT VIEW

R3.00

450.00

BOTTOM VIEW

Profile follows gate profile offset by 3.175 mm

108.26

350.00

63.40

SEE SHEET 2 FOR BOTTOM VIEW DETAIL

TITLE A.4Wicket Gate Bottom Stem Sheet 1

DWG NO wicket_gate_bottom_stem_panel

REV

SIZE A

SCALE

SHEET 1 OF 2

DRAWN Jason Reimer 11/20/2010
CHECKED
QA
MFG
APPROVED

BOTTOM VIEW

R3.00

R3.00

R3.00

R3.00

R3.00

R3.00

141.00

104.50

70.50

49.75

27.58

16.80

60.00

50.00

58.03

54.76

60.00

50.00

11.94

M5x0.8 - 6H

⌀5.00 ▽ 18.00
⌵ ⌀ 5.65 X 90.0°

⌀5.00 ▽ 18.00
⌵ ⌀ 5.65 X 90.0°

12.74

M5x0.8 - 6H

DETAIL B
SCALE 1 : 1

DETAIL A
SCALE 1 : 1

A.5Wicket Gate Bottom Stem Sheet 2

DRAWN Jason Reimer   11/20/2010
CHECKED
QA
MFG
APPROVED

TITLE

SIZE
A

DWG NO
wicket_gate_bottom_stem_panel

REV

SCALE

SHEET 2 OF 2

SIDE VIEW

3.18

DETAIL A
SCALE 1/1

5.65

12.00

90.0°

FRONT VIEW

420.00

225.00

30.00

353.50

451.00

⌀5.65 ⊽ 3.18 X 8
⌵ ⌀ 12.00 X 90.0°

A.6 Stainless Steel Cover Sheet

TITLE	
DRAWN Jason Reimer	11/20/2010
CHECKED	
QA	
MFG	
APPROVED	

SIZE A	DWG NO stainless_cover_plate	REV
SCALE		SHEET 1 OF 1

Appendix B – Bolt Design

B.1 Bolt Design

B.1 Bolt Design

The design of the wicket gates requires that the top and bottom stem segments of the wicket gate be secured to the wicket gate body. This is best accomplished by using threaded bolts that drive through the flange on the stem segment and into the body of the gate. The following calculations were used to determine the dimensions required for the bolt diameter and effective thread depth. R. L. Mott's text: *Machine Elements in Mechanical Design* was used as a reference for many of the following equations [4]. An M24 threaded bolt with a 2mm pitch has been selected.

B.1.1 *Step 1: Determining the Maximum Force*

Based on the FEA Load Conditions document provided by Mr. Sidhu [3], a figure for the maximum force exerted by the servomotors and hydraulic pressure was calculated from Extreme Loading (Runaway Condition) – Wicket Gate Closed scenario.
The hydraulic force was determined to be

$$Hydraulic\ Force\ (F_{H)} = Pressure * Area$$

Where the pressure is the hydraulic pressure at a depth of 21.4m, and the area is the rectangular cross sectional area of the wicket gate body.

$$Hydraulic\ Force = (210\ 000\ Pa) * (2.772\ m * 1.11667\ m)$$

$$Hydraulic\ Force\ (F_H) = 650\ 035\ N = 651\ kN$$

The force exerted on the wicket gate by the torque was determined to be

$$Torque\ Force\ (F_T) = \frac{Torque}{Distance}$$

Where the torque is the torque exerted by the servomotors, and distance is the distance from the centre of the stem to the center of the bolt hole location.

$$Torque\ Force = \frac{20\ 767.6\ Nm}{0.125\ m}$$

$$Torque\ Force\ (F_T) = 166\ 140.8\ N = 170\ kN$$

Under the runaway conditions, the maximum force on the bolts is the sum of the torque force and the hydraulic force.

$$F_{max} = F_H + F_T$$

$$F_{max} = 651\ kN + 170\ kN$$

$$F_{max} = 821\ kN$$

For ease of performing calculations with the aid of the textbook [4] the maximum force exerted on the gate will be converted to the imperial system of measurement. This value will be used to determine the bolt size required in the imperial system. This bolt size will then be converted back into the metric system.

One kN equals 224.809 lbf. Therefore, the maximum force on the bolts is

$$F_{max} = 821\ kN * 224.809\ \frac{lbs.force}{kN}$$

$$F_{max} = 184\ 568.189\ lbs.force$$

$$F_{max} = 185\ 000\ lbs.force$$

Multiplying the maximum force by a factor of safety equal to two, and dividing by the number of bolts in the top stem yields the maximum force per bolt. The top stem contains eight bolts and will be the stem responsible for transmitting the torque to the wicket gate body and the bottom stem.

$$F_{max/bolt} = \frac{F_{max} * SF}{\#\ of\ bolts}$$

$$F_{max/bolt} = \frac{185\ 000 * 2}{8}$$

$$F_{max/bolt} = 46\ 250\ lbs.force$$

B.1.2 *Step 2: Determining the Bolt Dimensions*

The bolt material was chosen to meet two criteria: it must be very strong to support the large forces exerted on the bolts, and it must be stainless steel to protect against any corrosion that might occur while the gate is in operation.

For these two reasons 410-HT martensitic stainless steel – hardened and tempered bolts were chosen [5]. This material has an ultimate tensile strength and yield strength of:

$$\sigma_{uts} = 180 \; ksi$$

$$\sigma_{yield} = 135 \; ksi$$

The proof strength of the bolt is defined to be approximately 90% of the yield strength of the bolt [4].

$$\sigma_{proof} = 0.90 * \sigma_{yield}$$

$$\sigma_{proof} = 0.90 * 135 \; ksi$$

$$\sigma_{proof} = 121.5 \; ksi$$

The **allowable stress** on each bolt is defined by 75% of the proof strength.

$$\sigma_{allowable} = 0.75 * \sigma_{proof}$$

$$\sigma_{allowable} = 0.75 * 121.5 \; ksi$$

$$\sigma_{allowable} = 91.125 \; ksi$$

Dividing the allowable stress by the maximum force per bolt will yield the minimum cross sectional area of the bolt.

$$Area = \frac{F_{max \,/bolt}}{\sigma_{allowable}}$$

$$Area = \frac{46\,250 \; lbs.\,force}{91\,125 \; psi}$$

$$Area = 0.507\,544 \; in^2$$

Referring to Table 18-4B [4], a 7/8 inch sized bolt has a cross sectional area of 0.509 in^2. This exceeds the minimum cross sectional area calculated above. This bolt will now be converted to the metric system; however, the dimensions for the above imperial system bolt will be used to determine the effective thread length and shear forces exerted on the bolt.

Converting the minimum cross sectional area determined from Table 18-4B into the metric system yields a cross sectional area of:

$$Area = (25.4)^2 \frac{mm^2}{in^2} * 0.507\ 5\ in^2$$

$$Area = 327.42\ mm^2$$

Consulting Table 18-5 [4], a bolt with a 24mm major diameter and fine threads has a cross sectional area of 384 mm^2 and a pitch of 2 mm. It is this size bolt that should be used to secure the top and bottom stem segments to the wicket gate.

B.1.3 *Step 3: Determining the Effective Thread Depth*

The material of the wicket gate body is weaker than the bolt material. To determine the effective thread depth Equation 18-12 was used [4].

$$L_e = \frac{\sigma_{utB}\ (2 * A_{tB})}{S_{utN} * \pi * OD_{Bmin}\ [0.5 + 0.57735 * n * (OD_{Bmin} - PD_{Nmax})]}$$

Where the variables in the equation are defined as:
L_e = The effective thread depth
σ_{utB} = The ultimate tensile strength of the bolt = 180 000 psi
A_{tB} = The cross sectional area of the bolt = 0.509 in^2
S_{utN} = The ultimate tensile strength of the wicket gate based on A36 Steel = 58 000 psi
OD_{Bmin} = The minimum major diameter of the bolt = 0.8631 in.
n = The number of threads per inch = 14
PD_{Nmax} = The maximum pitch diameter of the wicket gate threads = 0.8356 in.

Using these values it is now possible to determine the minimum required thread depth of the bolt.

$$L_e = \frac{180\ 000\ (2 * 0.509)}{58\ 000 * \pi * 0.8631[0.5 + 0.57735 * 14 * (0.8631 - 0.8356)]}$$

$$L_e = 1.613\ in$$

The effective thread length is easily incorporated into the wicket gate design. It is necessary to converting this value into the metric system for ease of manufacturing. The resulting metric thread depth is 41mm. Therefore, the recommended depth of the bolt hole is 45mm, slightly larger than the thread length to provide room for additional bolt material.

B.1.4 *Step 4: The Shear Force on the Bolt*

The bolts on the bottom stem will secure the weight of the entire wicket gate assembly. Because of this, it is critical to calculate the shear force acting on the bolts which may cause them to fail. The yield stress in shear for 410-HT martensitic stainless steel could not be found in the literature [5]. However, the shear stress for many stainless steels is typically on the same order of magnitude as the yield stress (135 ksi). Therefore, the value of 100 ksi will be used as the shear stress for 410-HT martensitic stainless steel.

The equation which governs the shear force for fasteners is [6].

$$\tau = \frac{F}{A}$$

Where τ is the shear force on the bolt, F is the weight of the wicket gate acting on each bolt, and A is the cross sectional area of the bolt.

$$F = 1\ 800\ kg * 9.81\ \frac{m}{s^2}$$

$$F = 17\ 658\ N$$

$$F = \frac{17\ 658\ N * 0.2248\ \frac{lbs.force}{N}}{8\ bolts}$$

$$F = 496.18\ \frac{lbs.force}{bolt}$$

$$F = 497 \ \frac{lbs.force}{bolt}$$

The shear force acting each bolt is

$$\tau = \frac{497 \ \frac{lbs.force}{bolt}}{0.509 \ in^2}$$

$$\tau = 976.42 \ \frac{psi}{bolt}$$

$$\tau = 977 \ psi$$

This value is well below the estimated value for the shear strength of 410-HT martensitic stainless steel; therefore, shear failure of the bolts is unlikely to occur.

B.1.5 *Bolt Summary*

The recommended bolt is a 24mm 410-HT martensitic stainless steel bolt. The dimensions of the bolt are summarized in Table B-1 and a schematic of a bolt and thread with the labelled dimensions is provided in Figures B-1 and B-2 [7].

TABLE B-I: BOLT SPECIFICATIONS [7]

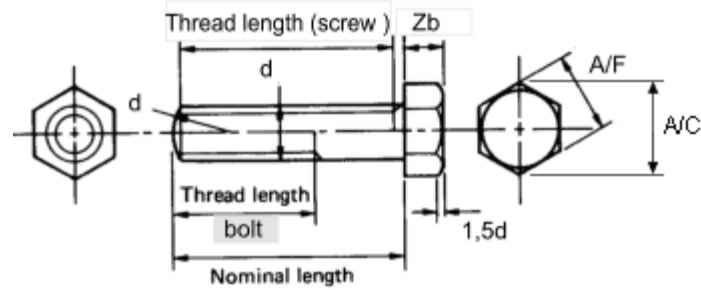| Nominal Size	Thread Pitch	Major Diam. (mm) d	Minor Diam. (mm) d3	Pitch Diam. (mm) d2	Bolt Head Thickness (mm) Zb	Flats max/min (mm) A/F	Corner (mm) A/C
M24	3	23.952 - 23.577	20.701 - 19.955	22.003 - 21.803	15.215	36.00 - 35.58	41.6

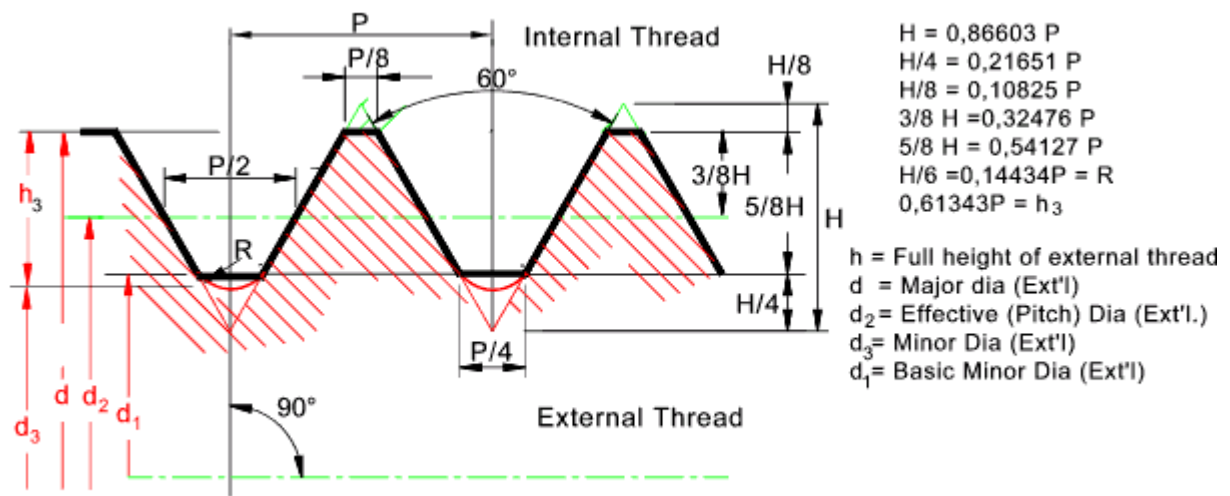**Figure B-1: Bolt Sketch [7]**

Figure B-2: Thread Schematic [7]

Appendix C – Analysis of Chosen Design

C.1 Design Analysis
C.1.1 *FEA Analysis*
C.1.2 *FEA Loading Constraints*
      C.1.2.1 FEA Load Condition 1
      C.1.2.2 FEA Load Condition 2a
      C.1.2.3 FEA Load Condition 2b
      C.1.2.4 FEA Load Condition 3a
      C.1.2.5 FEA Load Condition 3b
C.2 Assembly and Manufacturing Principles
C.3 Detailed Cost Analysis

C.1 Design Analysis

To analyze the structural integrity of the multipart wicket gate assembly, Manitoba Hydro requested the team perform a FEA simulation. Manitoba Hydro did not specify which FEA software to use, so the team chose the Inventor stress analysis feature since all the drawings for the multipart wicket gate were prepared using Inventor 2010 build version 140223002, 223. This appendix is a summary of the methods used to perform the FEA simulations and provides a brief discussion of the results.

C.1.1 *FEA Analysis*

To analyze the performance of the wicket gate assembly, Manitoba Hydro provided five loading conditions the wicket gate must satisfy before being placed into service. Please note that all FEA simulations are initial analyses only and their purpose is to provide the end designer with an indication of the stress distribution throughout the wicket gate assembly. Before discussing these simulations, several analysis parameters were selected. A brief list of these parameters is provided in Table C-I. Many of these parameters were simply left as the default settings found in AUTOCAD Inventor 2010.

TABLE C-I: GENERAL FEA SETTINGS IN INVENTOR

General Objective and Settings:	
Design Objective	**Single Point**
Simulation Type	Static
Detect and Eliminate Rigid Body Modes	Yes
Avg. Element Size (fraction of mode diameter)	0.1
Min. Element Size (fraction of avg. Size)	0.2
Grading Factor	1.5
Max. Turn Angle	60 deg
Create Curved Mesh Elements	No
Ignore Small Geometry	No

The relevant properties for an FEA model which is based on a linear elastic response are the Young's Modulus and Poisson's Ratio. The values in Table C-II were chosen since they represent most steels.

TABLE C-II: GENERAL MATERIAL PROPERTIES

Material Specifications	
Young's Modulus	200 GPa
Poisson's Ratio	0.287 ul

Images of the base FEA model showing mesh size is provided in Figures C-2 through C-7. The mesh size is listed above as average element size (as a fraction of mode diameter) equal to 0.1 and the minimum element size (as a fraction of average size) equal to 0.2. The number of 10-noded tetrahedral elements determined by Inventor is 96, 861 and the corresponding number of degrees of freedom is 454, 172.

Before discussing the results of the FEA loading conditions, an exploded view of the entire wicket gate assembly is provided in Figure C-1.
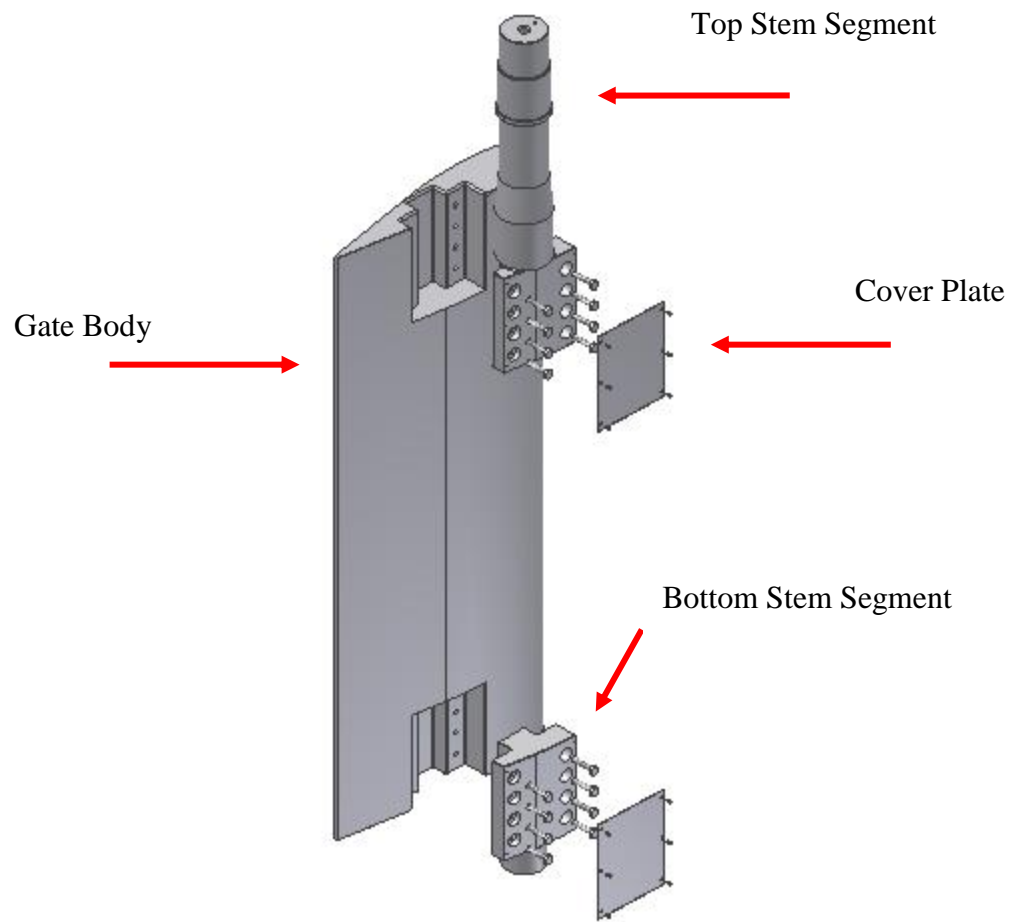
Top Stem Segment

Cover Plate

Gate Body

Bottom Stem Segment

Figure C-1: Exploded View Of The Gate Assembly

An illustration of the various model components with the finite element mesh in place is also
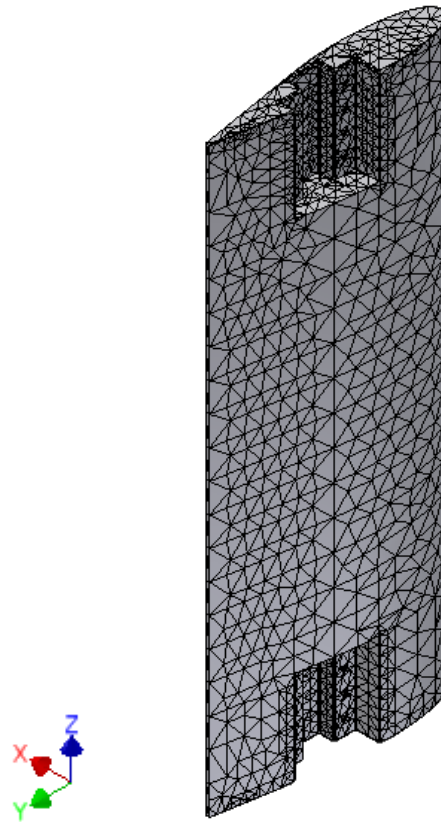provided in Figure C-2 to C-7

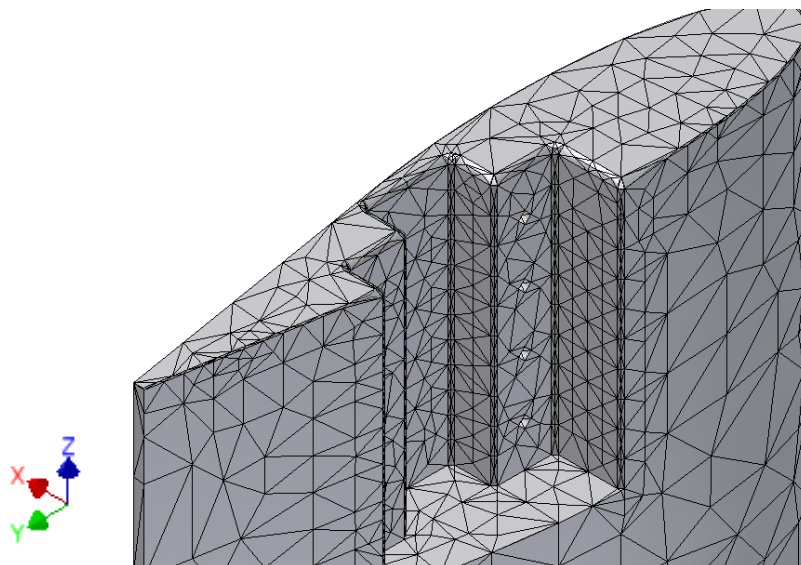**Figure C-2: Gate Body With The Finite Element Mesh In Place**

Figure C-3: A Close Up Of The Gate Body's Top Stem Insert With The Finite Element Mesh In Place
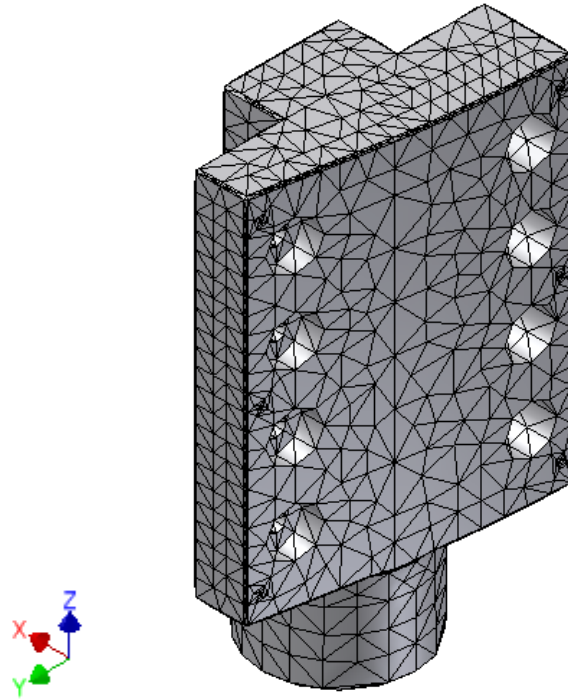
Figure C-4: Front Face Of The Bottom Stem With The Finite Element Mesh In Place
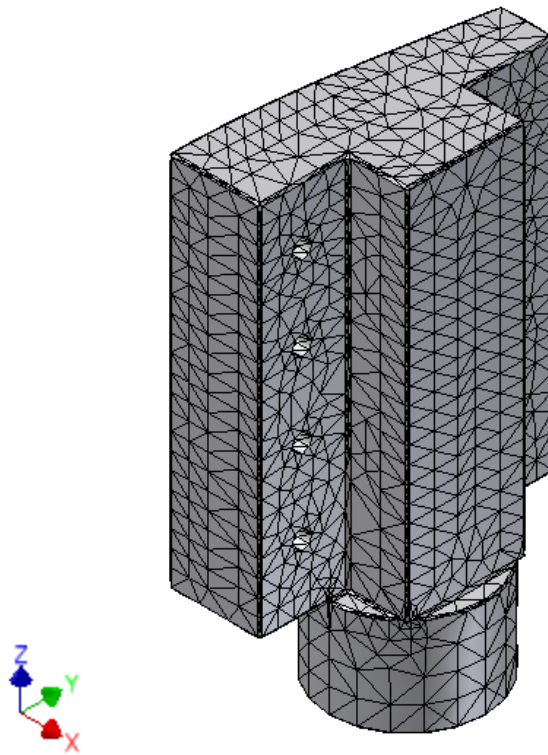

Figure C-5: Mating Face Of The Bottom Stem With The Finite Element Mesh In Place
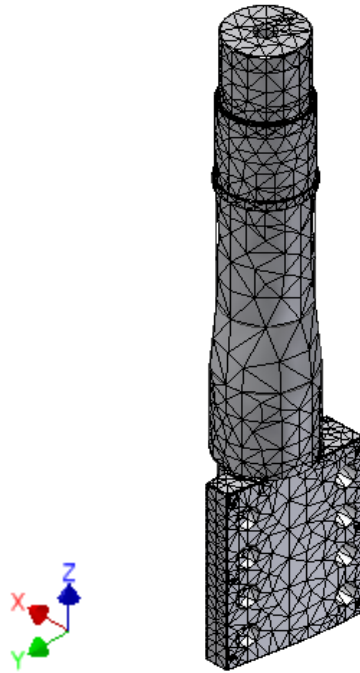
Figure C-6: Front Face Of The Top Stem With The Finite Element Mesh In Place
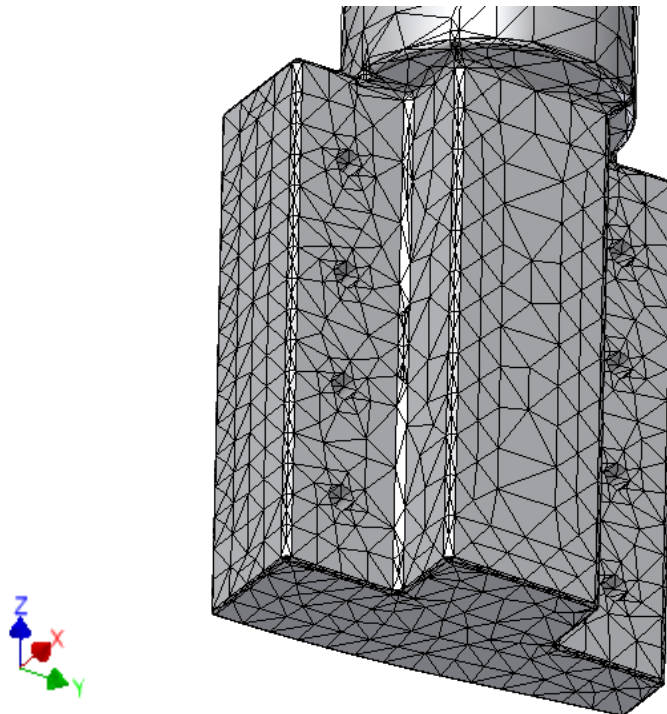

Figure C-7: Close Up Of The Mating Face Of The Top Stem With The Finite Element Mesh In Place

The results of the FEA analysis have been compiled in Table C-III. It lists each loading condition, the maximum stress allowed based on Manitoba Hydro's requirements, and the resulting **Von Mises** induced in the wicket gate assembly. Note that in some cases, the resulting Von Mises stress is greater than the allowable stress indicating that further design is required.

TABLE C-III: FEA RESULTS SUMMARY

| | | | Resulting | |
| | | | Von Mises Stress (MPa) | |
	Loading Condition	Allowable Stress (MPa)	Top Stem	Body
1	Extreme Loading (Runaway) - Wicket Gates Closed	160	120	130
2a	Regular Operating Condition - Wicket Gates Closed	80	120	130
2b	Regular Operating Condition - Wicket Gates Open	80	210	60
3a	Fatigue Condition - Wicket Gates Closed	140	70	20
3b	Fatigue Condition - Wicket Gates Open	140	270	170

A detailed discussion of each loading scenario, complete with figures is provided below.

C.1.2 *FEA Loading Constraints*

In order to simulate existing physical conditions on the wicket gate, several portions of the assembly needed to be constrained in Inventor. Two pin constraints were applied to the top stem and are highlighted in blue in Figure C-8 and C-9. An additional pin constraint was applied to the bottom stem and is highlighted in blue in Figure C-10. Pin constraints allow rotation about the component's axis, but prevent translation in any direction. Furthermore, one face constraint was applied to the wicket gate body which restricts both translation and rotation and is highlighted in blue in Figure C-11. The face constraint applied is somewhat conservative since in reality, the gate would not be fixed on this face; rather, it is permitted to rotate and this motion is only hindered by the flow of water. These constraints have been applied to the wicket gate assembly for all loading conditions.
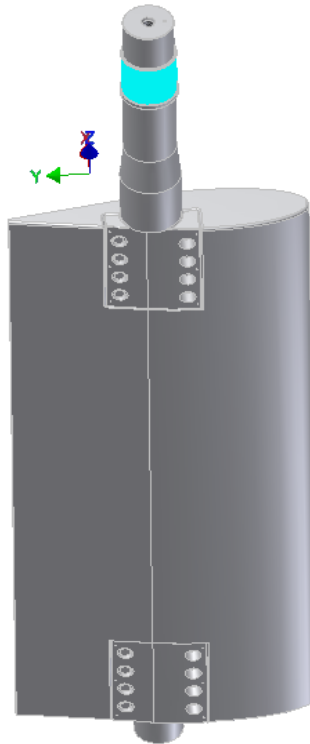
Figure C-8: Pin Constraint #1 On The Top Stem Is Highlighted In Blue
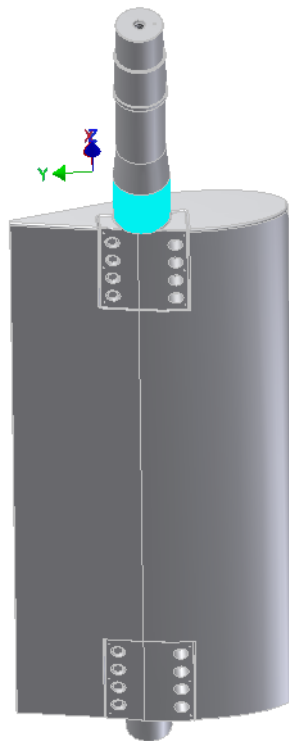

Figure C-9: Pin Constraint #2 On The Top Stem Highlighted In Blue
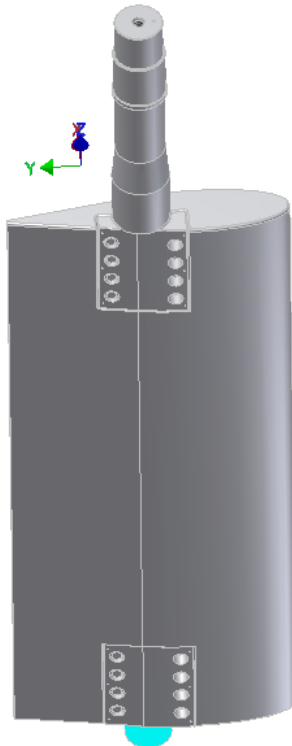
Figure C-10: Pin Constraint Applied To The Bottom Stem Highlighted In Blue
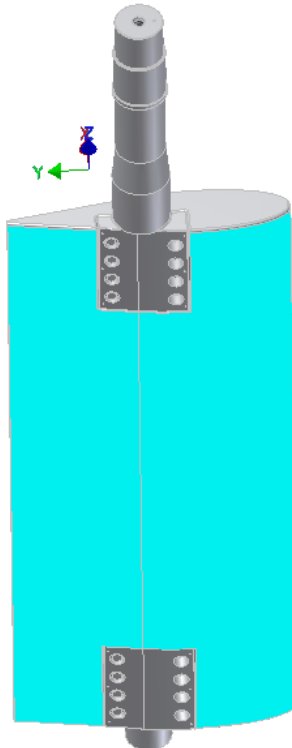
Figure C-11: Face Constraint Applied To The Gate Body Highlighted In Blue

C.1.2.1 <u>FEA Load Condition 1: Extreme Loading</u> (Runaway Condition) – Wicket Gate Closed

This loading condition is the most extreme condition where the maximum forces act upon the gate.

- Stress Evaluated at 2/3 yield equal to 166.67 MPa
- Apply torque of 20.7675 kNm
- Apply hydraulic pressure of 210 kPa

The torque was applied to the top stem while the hydraulic pressure was applied to the gate body. The locations of the loads applied to the assemblyare indicated by the yellow arrows in Figure C-12.
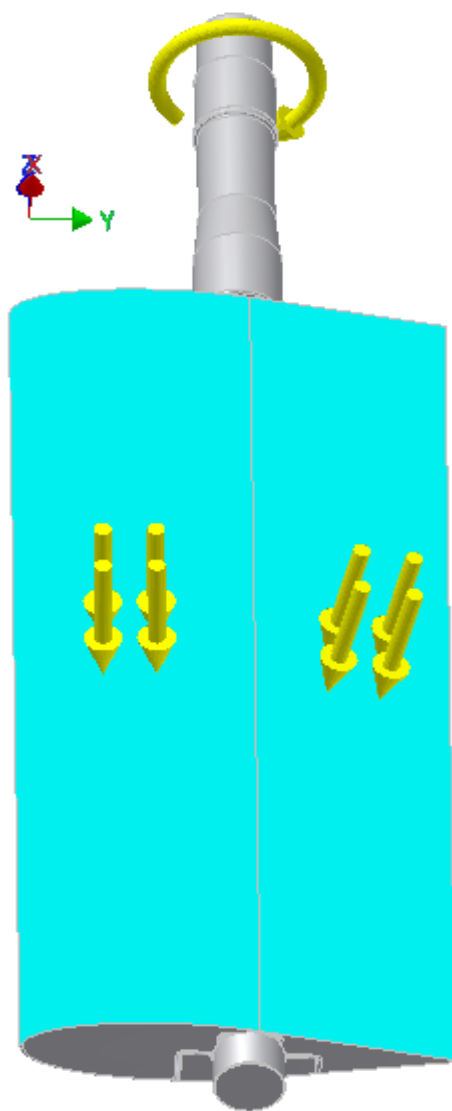
Figure C-12: The Loads Applied To The Wicket Gate Indicated By Yellow Arrows

The maximum stress under loading condition one on the gate body is located on the top section of the gate body where the top stem and gate body are clamped together and is indicated below by the red arrow in Figure C-13. According to the Inventor Stress Analysis simulation, the resulting Von Mises stress has a value of 130MPa.

Figure C-13: Preliminary Results For The Contour Plot Of The Gate Body Under Loading Condition 1. The Location Of The Maximum Stress Is Indicated By The Red Arrow
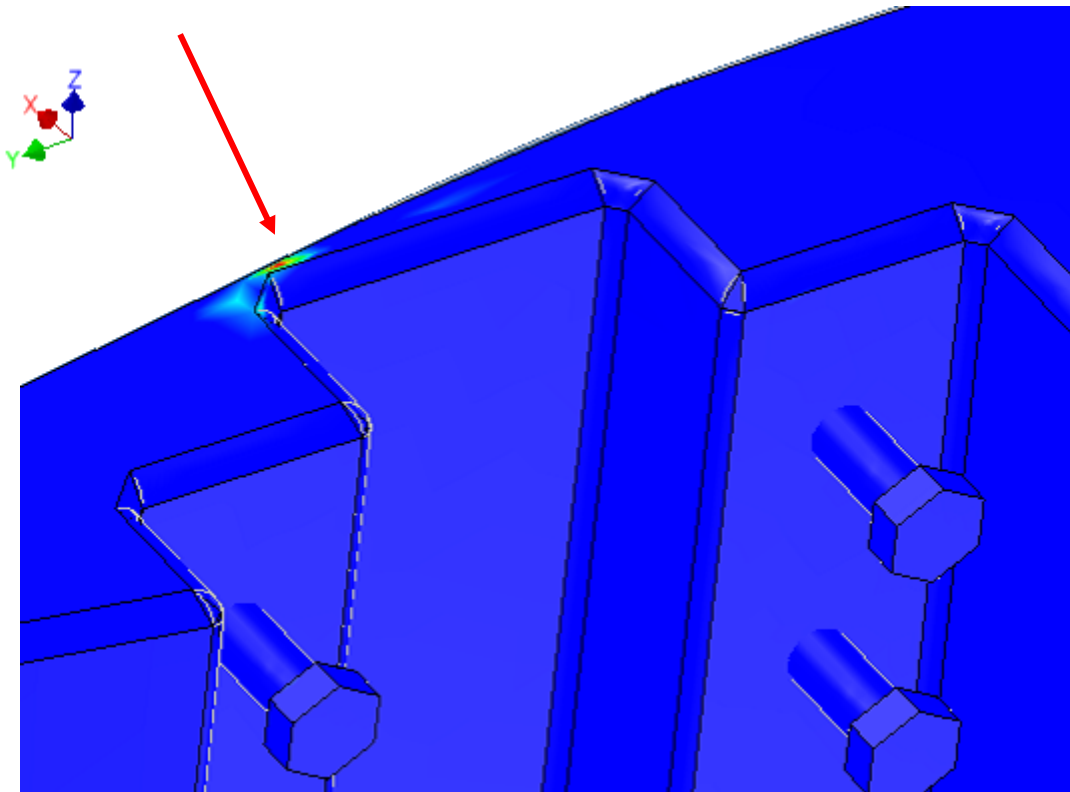
The maximum stress under loading condition one on the top stem section is indicated by the red arrow in Figure C-14. It occurs on the fillet between the circular cross section of the stem and the square cross section of the clamping plate. According to the Inventor Stress Analysis simulation, the highest stress level has a value of 120MPa.
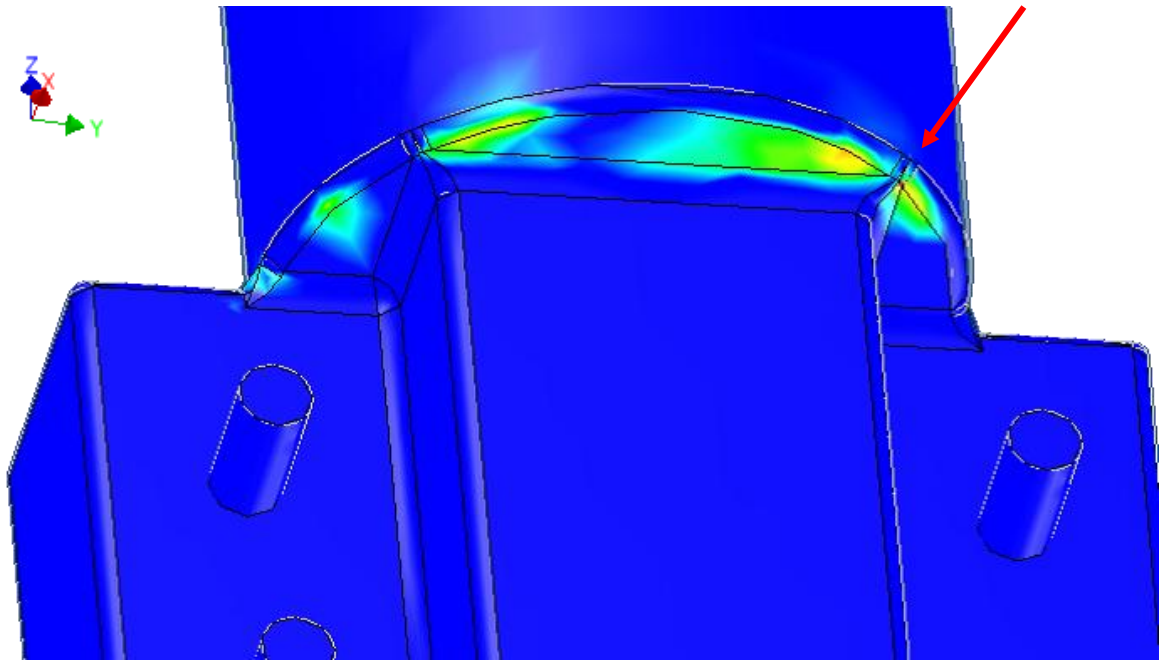
Figure C-14: Preliminary Results For The Contour Plot Of The Top Stem Under Loading Condition 1. The Location Of The Maximum Stress Is Indicated By The Red Arrow

The bottom stem segment did experience stress during this analysis, but the maximum stress obtained on this component was extremely small; therefore it has been neglected from this discussion.

This simulation has identified that stress concentrations exist at the narrowest section of the gate body and the fillet radii of the top stem segment. The maximum resulting stresses occurring in the wicket gate assembly for all future simulations will be located in the vicinity of the stress concentrations found in this simulation. Although the maximum stress at these locations does fall below the criteria for this simulation, these locations warrant further investigation and design before a final product is manufactured and placed in service.

C.2.1.2 <u>FEA Load Condition 2A: Regular Operating Condition</u> – Wicket Gate Closed

This load condition exactly matches load condition 1: Extreme Loading (Runaway Condition) – Wicket Gate Closed; therefore, the team did not run the simulation again. The major difference is the allowable stress is 1/3 the yield stress condition. The stresses in the areas indicated in Figures C-13 and C-14 exceed this limit.

- Stress evaluated at 1/3 yield stress equal to 83.33 MPa
- Apply torque of 20.7675 kNm
- Apply hydraulic pressure of 210 kPa

C.2.1.3 <u>FEA Load Condition 2B: Regular Operating Condition</u> – Wicket Gate Open

Under normal operating conditions with the wicket gates open, a torque of 33.3159 kNm must be applied to maintain their position.

- Stress evaluated at 1/3 yield stress equal to 83.33 MPa
- Apply torque of 33.3159 kNm
- Do not apply hydraulic pressure

The loads were applied to the gate as illustrated in Figure C-15. Note the removal of the hydraulic load.

Figure C-15: Torque Applied To The Assembly Is Indicated By The Yellow Arrow

The maximum stress on the gate body is located on the narrow section of the gate and is indicated by the red arrow in Figure C-16. The stress at this location has a magnitude of 60 MPa. There is also significant stress located on the upper bolt that transmits most of the torque from the top stem to the gate body. The values of the stress at both of these locations fall below the 83.88 MPa criteria listed above.

Figure C-16: Preliminary Results For The Contour Plot Of The Gate Body Under Loading Condition 2b.The Location Of The Maximum Stress Is Indicated By The Red Arrow

The maximum stress located on the top stem segment has a magnitude of 210MPa. Its location is highlighted below with a red arrow in Figure C-17. Again, it is located on the fillet radii where the circular cross section transfers to a square cross section. This value exceeds the 83.33 MPa requirement set above.

Figure C-17: Preliminary Results For The Contour Plot Of The Top Stem Under Loading Condition 2b. The Location Of The Maximum Stress Is Indicated By The Red Arrow

C.1.2.4 <u>FEA Load Condition 3A: Fatigue Condition</u> – **Wicket Gates Closed**

The stress of 142.59 MPa is the allowable fatigue stress at 80,000 cycles. Manitoba Hydro provided this value and eliminated the need for the team to perform any fatigue analysis methods such as the Modified Goodman Method. The loads were applied to the gate as illustrated in Figure C-12.

- Stress evaluated at 80,000 cycles and 142.59 MPa
- Apply a torque of 4.39666 kNm
- Apply hydraulic pressure of 210 kPa

The maximum stress located on the gate body is highlighted by the red arrow in Figure C-18and has a value of 20MPa. This value is well below the allowable fatigue stress value of 142.59 MPa.
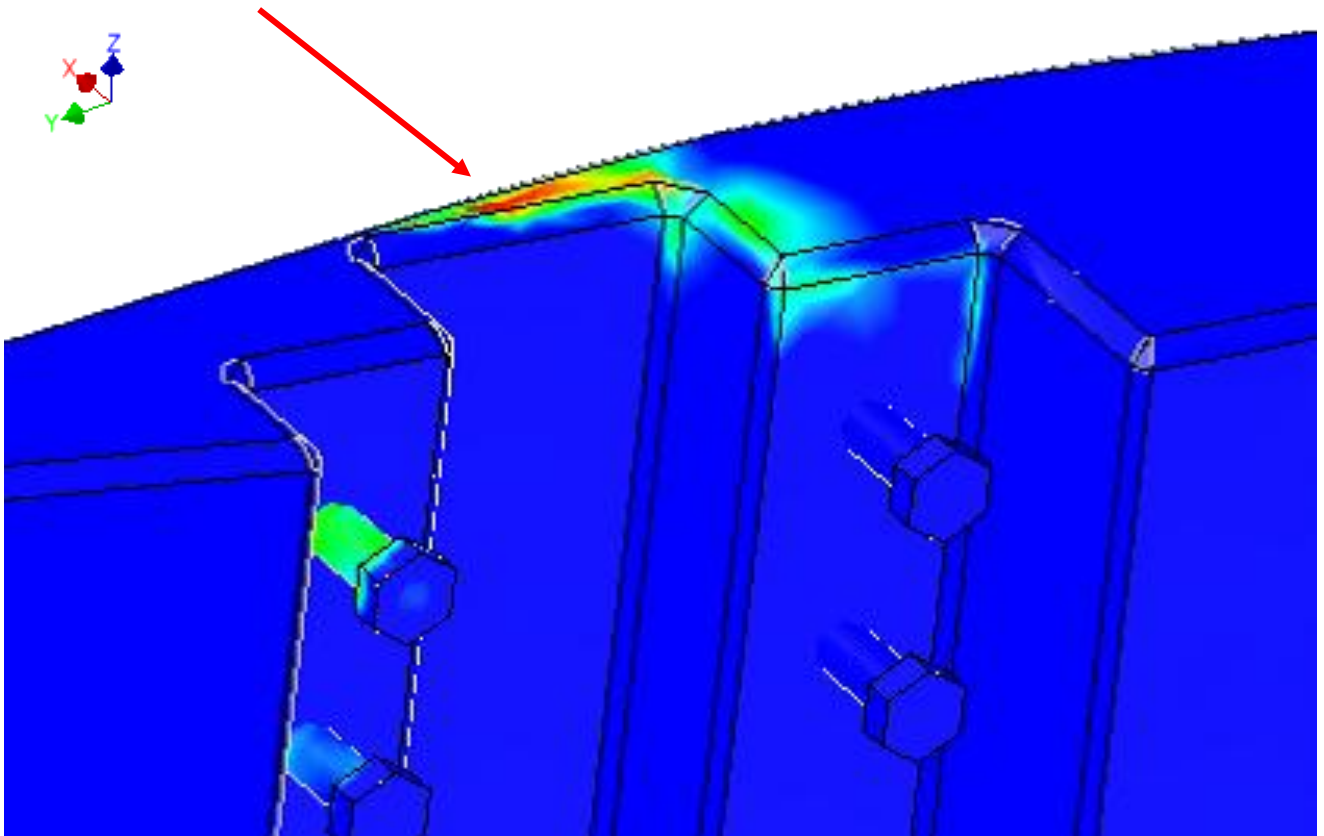

Figure C-18: Preliminary Results For The Contour Plot Of The Gate Body Under Loading Condition 3a. The Location Of The Maximum Stress Is Indicated By The Red Arrow

The maximum value for the stress located on the top stem is highlighted by the red arrow in Figure C-19and has a value of 70MPa. Again, this value is well below the allowable fatigue stress of 142.59 MPa.
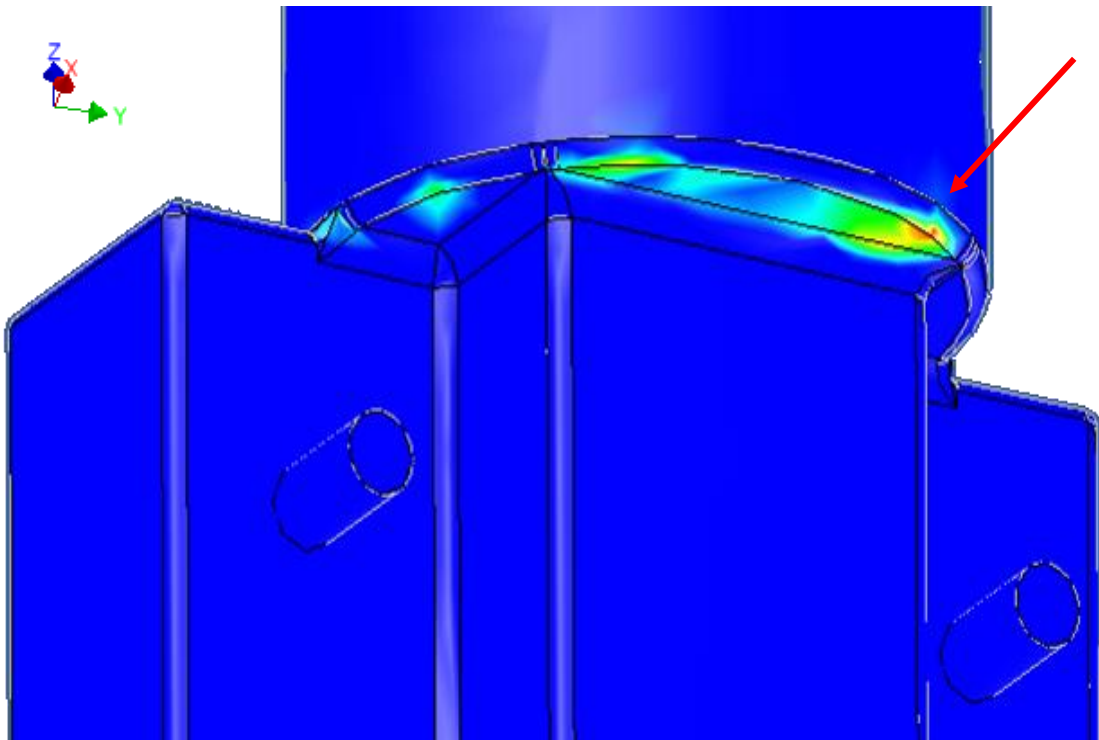

Figure C-19: Preliminary Results For The Contour Plot Of The Top Stem Under Loading Condition 3a. The Location Of The Maximum Stress Is Indicated By The Red Arrow

C.1.2.5 <u>FEA Loading Conditions 3B: Fatigue Condition</u> – Wicket Gates Open

As with condition 3a, the wicket gate is subject to 80,000 cycles, however the torque and pressure have changed in this simulation.

- Stress evaluated at 80,000 cycles and 142.59 MPa
- Apply a torque of 43.0975kNm
- Do not apply the hydraulic pressure

The loads were applied to the wicket gate in accordance with Figure C-15.

The maximum value of the stress on the gate body is highlighted by the red arrow in Figure
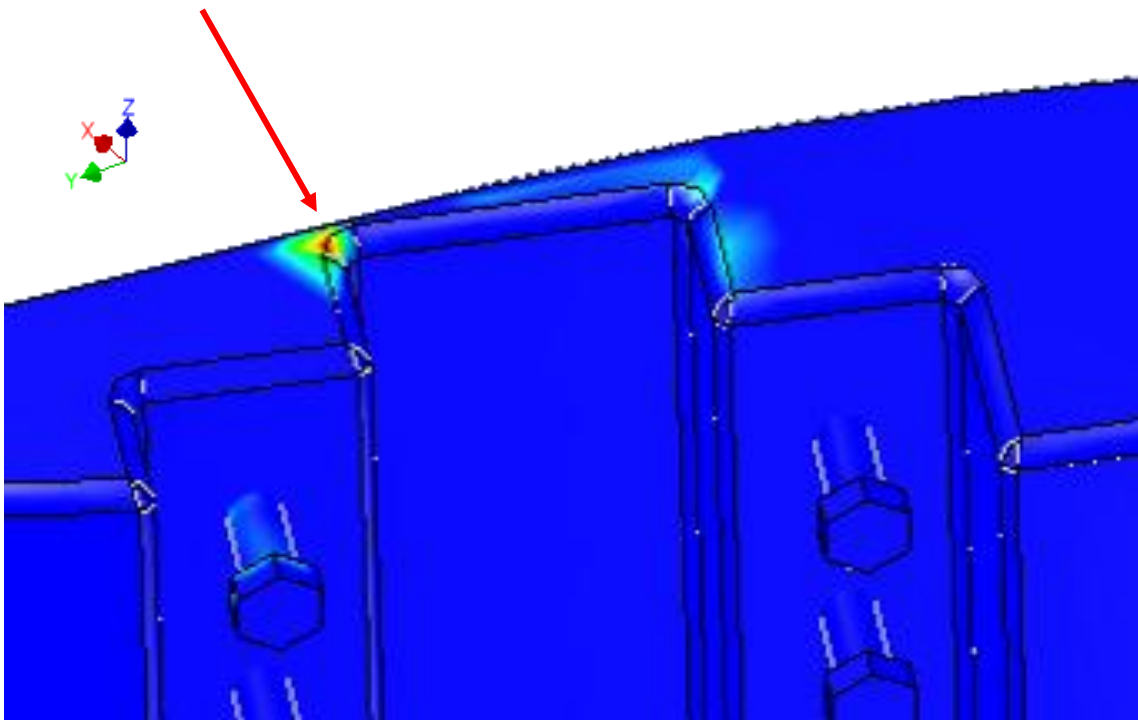C-20 and has a corresponding value of 170MPa.
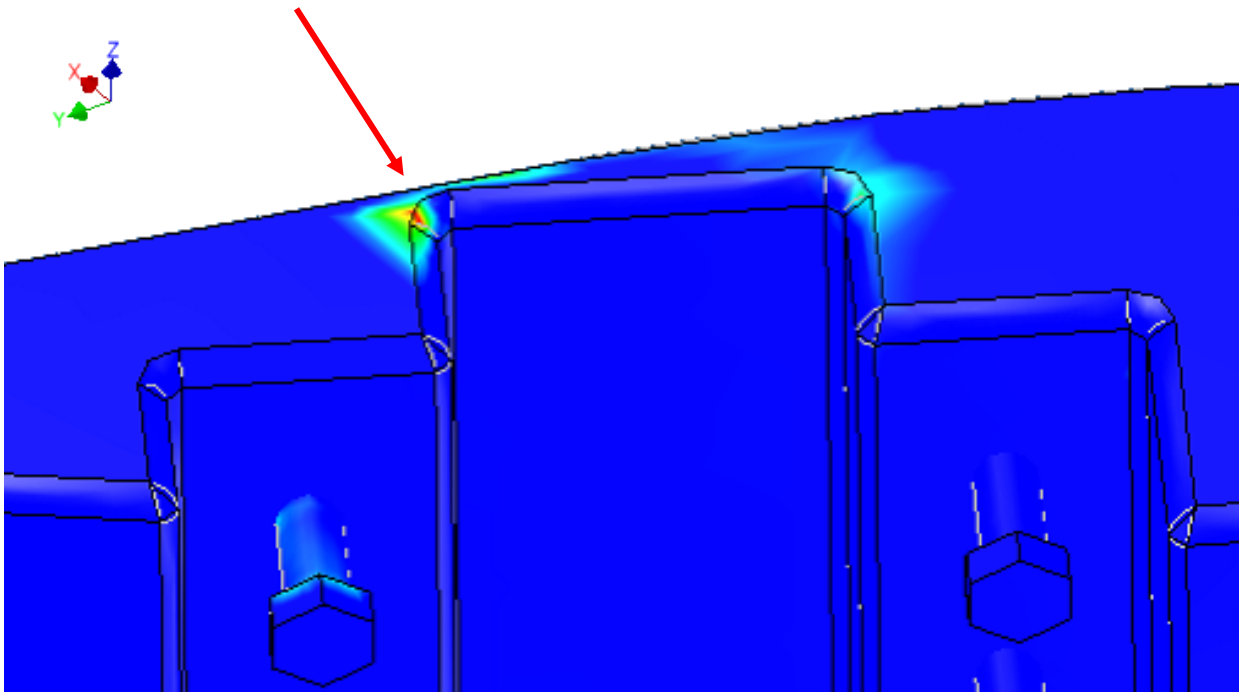
**Figure C-20: Preliminary Results for the Contour Plot of the Gate Body Under Loading
Condition 3b. The Location of the Maximum Stress Is Indicated By the Red Arrow**

The maximum value of the stress on the top stem is highlighted in by the red arrow in Figure C-21 and has a value of 270MPa. Both of the maximum stresses on the gate body and top stem exceed the allowable fatigue stress of 142.59 MPa.
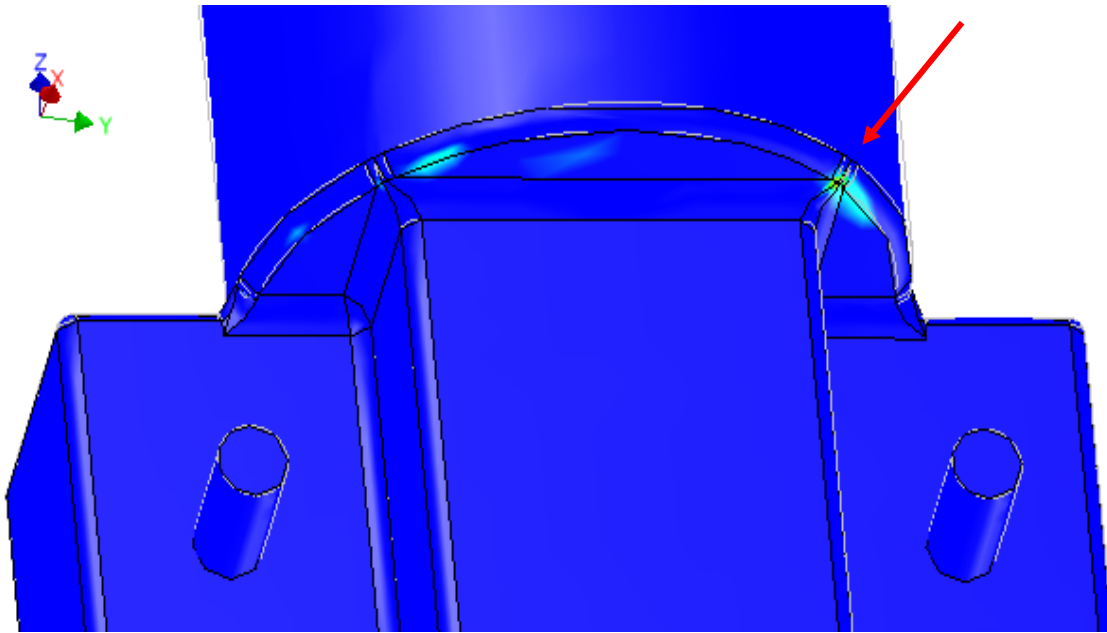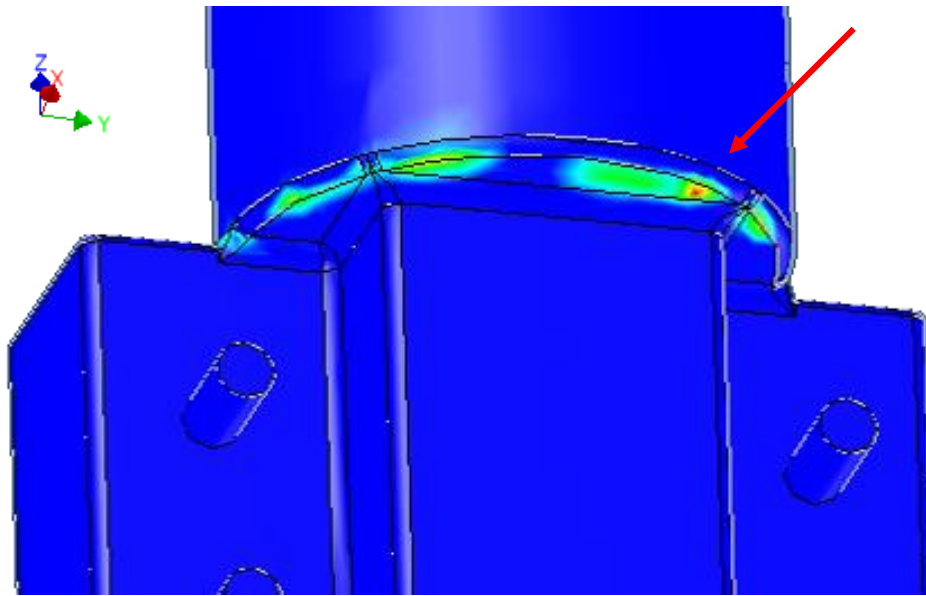

Figure C-21: Preliminary Results For The Contour Plot Of The Top Stem Under Loading Condition 3a. The Location Of The Maximum Stress Is Indicated By The Red Arrow

The results of the FEA simulations indicate that the wicket gate assembly meets several criteria outlined by Manitoba Hydro, but requires some modification before being capable of meeting all of the requirements. All of the stress concentrations can be found on the narrow section of the gate body and the filleted transition from the circular cross section of the top stem to the square face of the top stem. These areas require additional design consideration before being placed into service.

C.2 Assembly and Manufacturing Principles

The final design presented in this report is unique in that it is the first multipart wicket gate within any Manitoba Hydro generating station. This led to challenges when developing the installation and removal procedures. Theoretically the assembly of the multipart wicket gate is simple, yet when coupled with fact that the head cover is in place, challenges arise.

The first step the team took to creating the assembly procedures was to review the drawings provided by Manitoba Hydro. This was done to find where the wicket gate could be brought into the unit without removal of the head cover. A brainstorming session then took place as to what the options were. Options explored included:

a. The first option was to remove the wicket gate through the draft tube and float it down to the tailrace. This process would be reversed to install the new wicket gate. This option was not explored in detail since the runner of the turbine would be in place, and would be a significant obstacle to overcome when lowering and raising the wicket gate to the desired location.

b. The second option was to lower and raise the wicket gate through the intake gates. Once the gate was in the intake structure, the gate would then just need to be moved horizontally to the installed area. The team considers this to be a viable back-up option.

c. The third option was to use the scroll case access door to bring the wicket gate in or out of the unit. This is the closest of the options to the final installed position and therefore the most favourable.

With these options in mind the team met with Chad Hayes, a mechanic from Manitoba Hydro who has practical working knowledge of the units. From his experience working in the Limestone, Long Spruce and Kelsey generating stations, Mr. Hayes was able to describe to the team the physical constraints within the unit and the physical limitations of the staff that would be involved in installing and removing the wicket gate.

Using this background research the team then devised an installation and removal procedure based off the third option. The team strove to make the installation of a multipart wicket gate as easy as possible. This included installing multiple hooks on the head cover and the use of come-alongs as lifting devices.

Manufacturing the multipart wicket gate design is anticipated to be no more challenging than to manufacture the current single piece wicket gate. The only significant difference is that each component of the multipart wicket gate should be manufactured separately. Finish machining should take place on all mating surfaces and threaded holes to ensure that the bolts can be properly inserted and the gate can be assembled.

C.3 Detailed Cost Analysis

Minimizing the cost associated with the downtime of the generator is the fundamental reason Manitoba Hydro requires a multipart wicket gate. The current cost of refurbishment is approximately $3,800,000. By implementing the multipart wicket gate, the team estimates this cost will be reduced to $1,430,000. Calculations supporting these estimates are provided below.

The refurbishment of the hydro generation stations results in a loss of revenue between $40,000 to $50,000 per day for an eight week period. The associated labour cost of the refurbishment is between $750,000 and $1,000,000 for the eight week period. The refurbishment takes place every 15 years to maintain continued hydroelectric generation. The worst case scenario was used as the baseline for the budget for a scheduled refurbishment.

Current Refurbishment Schedule:

$$Average\ Loss\ Revenue\ per\ Day = \$50,000$$

$$Loss\ Revenue\ for\ Refurbishment = \frac{\$50,000}{day} * \frac{7\ days}{1\ week} * 8\ weeks = \$2,800,000$$

$$Average\ Labour\ and\ Material\ Costs\ for\ Refurbishment\ = \$1{,}000{,}000$$

$$Average\ Labour\ and\ Material\ Cost\ per\ Day = \frac{\$1{,}000{,}000}{56\ days} = \$17857$$

$$Average\ Labour\ and\ Material\ Cost\ per\ Day = \$18{,}000$$

$$Total\ Refurbishment\ Cost = \$2{,}800{,}000 + \$1{,}000{,}000 = \$3{,}800{,}000$$

The total cost for a scheduled refurbishment is approximately $3,800,000.

Proposed Refurbishment Schedule:

The list of assumptions will aid in the calculation of the approximate cost of the proposed refurbishment schedule:

- One day to dewater the hydroelectric station.
- Five days to erect supports and safety provisions.
- 10 days to change out 24 wicket gates and wicket gate bushings.
- Four days to remove supports and safety provisions.
- One day to start up hydroelectric station.
- The average daily loss revenue and cost of labour and material will remain the same.

This timeframe results in a 3 week schedule for a refurbishment. As technicians become more familiar with the installation procedures and develop improvements, the time frame will reduce and the result will be a quicker turnaround. The three week timeframe will be used for calculations.

$$Loss\ Revenue\ for\ Refurbishment = \frac{\$50{,}000}{day} * \frac{7\ days}{1\ week} * 3\ weeks = \$1{,}050{,}000$$

$$Labour\ Cost\ and\ Materials = \frac{\$18,000}{day} * \frac{7\ days}{1\ week} * 3\ weeks = \$378,000$$

$$Total\ Refurbishment\ Cost = \$,1050,000 + \$378,000 = \$1,428,000$$

The total cost of proposed scheduled refurbishment is approximately \$1,430,000.

Change in Refurbishment Costs:

The comparison in proposed saving is:

$$\%\ Change = \frac{\$3,800,000 - \$1,430,000}{\$3,800,000} * 100\% = 62.4\ \%$$

The proposed schedule refurbishment of the wicket gates results in savings of 62.4% from the current refurbishment schedule.

Benefit to Cost Ratio:

If we use a conservative \$45,000 per day of revenue generation over 15 years, we get:

$$Projected\ Revenue = \frac{\$45,000}{day} * \frac{365\ days}{1\ year} * 15\ years = \$246,375,000$$

One drawback of this cost analysis is that the present value of future revenue is not taken into account since the team was not provided with an accurate interest rate that could be used to calculate these present values. For this reason, the benefit to cost ratio uses only today's dollars. The comparison of the benefit to cost ratio is:

Benefit to Cost Ratio of the Current Refurbishment Schedule:

$$B/C_1 = \frac{\$24,637,500}{\$3,800,000} = 64.84$$

Benefit to Cost Ratio of the Proposed Refurbishment Schedule:

$$B/C_1 = \frac{\$24,637,500}{\$1,430,000} = 172.53$$

The increased benefit-to-cost ratio of the proposed refurbishment schedule illustrates that the development of a multipart wicket gate capable of reducing generator downtime is an excellent opportunity to improve profitability.

Appendix D – Concept Generation

D.1 Concepts Considered

The concepts developed throughout the design process were eventually refined into three major ideas: the stem sectioned wicket gate, the four piece wicket gate, and the three piece wicket gate. In order to decide on one final design to pursue, several concept screening matrices were developed to rank each idea according to its merits and shortcomings. These processes and their results are detailed below.

D.1.1 *Stem Sectioned Wicket Gate*

The stem section wicket gate design keeps the majority of the gate as one solid piece of steel, thereby preventing the need for large amounts of sealant. The gate also maintains a significant portion of the gate's hydrodynamic profile. The design is illustrated in Figure D-1 below, where the top and bottom stems are cast as separate components of the gate. These components are designed to fit snugly within the gate itself and are secured by numerous bolts that are driven through a flange and into the body of the gate.
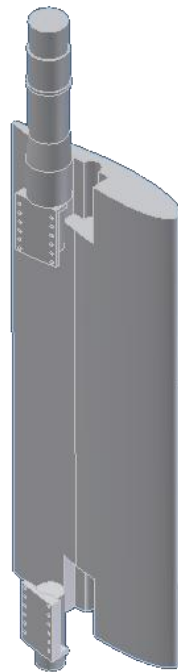
.

Figure D-1: Stem Sectioned Wicket Gate

To install the stem section design, the operators raise the top stem section and insert the top stem through the head cover and secure it to the servomotors. The bottom section can then be inserted into its corresponding hole. Bushings and shims can be inserted into the bottom of this hole to ensure that the distance between the top and bottom stems is precisely the height of the wicket gate body.

The key to this design is the fact that the bottom section is capable of being manoeuvred and positioned by one person without mechanical assistance. Furthermore, the top stem section's weight is supported by the servomotor connections.

A crane is then used to hoist the main body of the gate into place. Because the operators have shimmed the bottom bushing to the precise height, the gate fits snugly to the top and bottom sections. Bolts are driven through aligning holes in the sections, and the gate to provide a strong joint.

Each section would have a rubber gasket on the joining face to ensure a water tight seal between the section and the gate. A stainless steel cover plate would then be secured over the bolt faces to ensure the hydrodynamic profile is maintained and the bolts are not directly exposed to water. Another factor the design accounts for is that the bolted faces of the top and bottom sectionsface inwards, and are therefore not exposed to water when the gate is in the closed position. This avoids high pressure water from forcing its way into any crevice and corroding the gate.

D.1.2 *Four Piece Wicket Gate*

The four piece wicket gate design involves dividing the gate symmetrically from top to bottom as illustrated in Figure D-2 below. One vertical section of the gate would have the same hydrodynamic profile as the original gate, while the other section of the gate would need to incorporate threaded holes that the operator could use to secure the two halves together. These

two vertical faces combined with a top and bottom stem make up the four pieces of this wicket gate design.

Figure D-2: Four Piece Wicket Gate

The bottom stem would need to be installed in the appropriate wicket gate hole. One side of the gate would need to be raised with a crane and secured to the bottom stem. Once this section is secured, the bottom stem and half-gate section would be secure, and a crane would not be required to keep this section upright. The top stem would then need to be raised and secured to the first half-gate. Finally, the last face would need to be raised with a crane, placed into position and bolts driven into the threaded holes, thereby securing the structure in place.

The major challenge this design poses is that the top and bottom stems are separate pieces that must be mechanically joined to the wicket gate. The servomotors that turn the wicket gate apply a great deal of torque to these stems, with the tendency to shear them. Furthermore, the large forces exerted on the wicket gate by the flow of water would also tend to shear the top

and bottom stems. These stems and the means by which they are affixed to the gates would need to be extremely robust.

An additional challenge of this four piece design is that the hydrodynamic profile of one of the faces would be compromised by the many threaded holes required to join the two gate faces together. Large amounts of sealant and epoxy would be required to seal these holes and protect them against water damage. Furthermore, the two segments would have a gap running between them on both sides of the gate. This gap would also need to be filled with epoxy to ensure a watertight seal.

D.1.3 *Three Piece Wicket Gate*

The three piece wicket gate involves dividing the gate horizontally across the gate body into three segments. As Figure D-3 illustrates, the top section contains the top stem, the middle section contains the joining mechanism, while the bottom segment contains the bottom stem. The middle section containing the joining mechanism is critical to the operation of the three piece design. Its functionality and technical challenges will be discussed below.
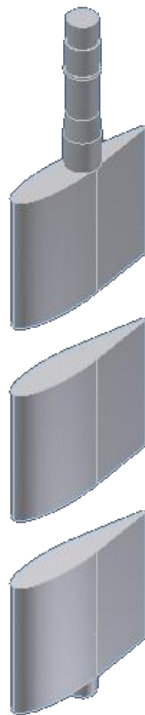

Figure D-3: Three Piece Wicket Gate

Our group had developed a preliminary sketch of the middle section containing four "deadbolts" that would extend from the top and bottom faces of the middle section and lock into the top and bottom gates on either side. These deadbolts would be operated by the use of an externally mounted key that could be turned to extend or retract the deadbolts.

To install this wicket gate design, the operators would need to place the bottom section of the gate into the corresponding hole. The top section would then need to be raised with the use of a crane and held in place. This crane is housed in the chamber above the wicket gate, called the turbine pit. The top section would need to be hoisted into position and secured to the servomotors.At this stage of assembly, the middle section of the gate would need to be raised and placed between the top and bottom gate. The operator would then use the externally mounted key to extend the deadbolts into both the top and bottom sections. This would complete the installation procedure.

This design posts several challenges which our group decided would make the three piece gate unfeasible. One challenge is the fact that high tolerances must be maintained between each section of the gate. Each wicket gate must seal to its neighbour with no greater than 0.12mm clearance between them. This same tolerance would therefore need to be built into the three sections of the gate as each section mates with the other sections within the same gate. Holding the top and middle sections of the gate while they are correctly aligned would be extremely challenging, especially considering the clearance on either side of the middle section would be no greater than 0.06mm. Subtle temperature changes could cause each section to expand or contract, making it impossible to fit the sections together.

A second challenge would be to seal the horizontal joints between the three sections. These joints would run the entire length of the perimeter, including the side that faces high pressure water when the gates are in the closed position. One risk is that water could leak into the middle section and begin corroding the gears and deadbolts that hold the gate together, possibly resulting in catastrophic failure.

The risk of leakage is significantly increased in the three piece design since the horizontal joints on one gate would contact the horizontal joints on its identical neighbouring gate. The sealing system must prevent water from leaking between the gates while in the closed position. It would be a significant technical challenge to find an epoxy capable of sealing the joints on one gate while maintaining the water tight tolerances between two neighbouring gates.

The difficulty in assembling the three piece design combined with the technical challenge of sealing each gate makes the three piece design a clever idea, but by no means a viable solution to Manitoba Hydro's problem.

D.2 Selection Criteria and Analysis

To help aid the team in making the right design decision, matrices were used to visually indicate which design was more feasible and met more of the required criteria opposed to others. The selection criteria was decided on as a team, based on the needs of the client. The following sections contain our concept screening and concept selection matrices.

D.2.1 *Concept Screening Matrix*

Table D-I shows our concept screening matrix. A concept screening matrix is used to help eliminate one or more designs from advancing to further development. A quick evaluation of the selection criteria is done by assessing the design a -, +, or 0. These values represent negative, positive, or neutral aspects of the design. Then the total number of negatives is subtracted from the total number of positives to give you the net result [8].

TABLE D-I: CONCEPT SCREENING MATRIX

Selection Criteria		Concept Variants		
		Three Piece Gate	Four Piece Gate	Stem Segment Gate
Ease of Handling		-	-	0
Ease of Installation		-	0	+
Portability		+	+	+
Ease of Manufacturing		-	+	+
Working within Tolerances		-	0	+
Weight/Size of the Pieces		+	0	0
Minimal Sealant Required		-	-	0
Fits within Existing Space		0	0	0
Maintains Hydrodynamic Profile		0	-	+
	Pluses	2	2	5
	Same	2	4	4
	Minuses	5	3	0
	Net	-3	-1	5
	Rank	3	2	1
	Continue?	No	Yes	Yes

The concept screening matrix provides a clear indication that the stem segment gate design and the four piece wicket gate are more favourable than the three piece gate. These designs are relatively easier to manufacture and install and therefore, warranted further investigation.

D.2.2 *Concept Scoring Matrix*

Table D-II shows our concept scoring matrix. A concept scoring matrix rates designs on a scale of 1 to 5 for the given selection criteria. The advantage to the concept scoring matrix is that the selection criteria are weighted in order of importance. This allows the user to visually see the criteria which are more important and, therefore, which design meets the needs best [8].

TABLE D-II: CONCEPT SCORING MATRIX

Selection Criteria		Four Piece Gate		Stem Segment Gate	
		Concepts			
	Weight	Rating	Weighted Score	Rating	Weighted Score
Ease of Handling	5%	4	0.2	3	0.15
Ease of Installation	25%	4	1	5	1.25
Portability	15%	3	0.45	4	0.6
Ease of Manufacturing	5%	3	0.15	5	0.25
Working within Tolerances	20%	2	0.4	5	1
Weight/Size of the Pieces	5%	1	0.05	3	0.15
Minimal Sealant Required	10%	2	0.2	4	0.4
Fits within Existing Space	5%	5	0.25	5	0.25
Maintains Hydrodynamic Profile	10%	4	0.4	5	0.5
Rating: 1=low, 5=high	Total Score	3.1		4.55	

The weight of each of the selection criteria was determined by analysing the problem statement of the design project. The goal of the project is to create a multipart wicket gate that can be installed and uninstalled without dismantling the entire generating assembly. The wicket gate must maintain its aerodynamic profile and must prevent leakage. Criteria such as "Ease of Installation" and "Working within Tolerances" were given more weight simply because the designs that best met these criteria should be chosen. The stem segment gate is quickly identified as the most promising design idea due to the fact that it works within existing tolerances, is relatively easy to install and maintains the gate's hydrodynamic profile.