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# Analysis and Recommendation of Core Annealing Furnace Designs

Final Design Report

MECH4860 - Engineering Design

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Everyone at Carte for putting up with our incessant questions and emails

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# Table of Contents

## List of Figures

## List of Tables

# Executive Summary

The batch-process electric bell annealing furnace currently used by Carte International Inc. ("the Client") is outdated and is believed to be operating at below acceptable efficiency. The authors of this report (collectively "the Authors") have been contracted to assess the condition of the current furnace and recommend a course of action including the recommendation of a new replacement furnace. A Failure Modes and Effects Analysis (FMEA) identified seven key failure risks in the current system. These failure modes are identified as: core oxidation, foreign contamination, failure to achieve soak temperature or time, overheating of cores, non-uniform temperature distributions, thermal shock, and general safety. Further work was performed to collate available data on the construction, history, maintenance, and operation of the existing furnace to assist future analysis by the Client. Finally, an experimental analysis was planned and arranged for the Client to test for the presence of non-uniformity in operating temperature distributions within the current furnace. Due to long lead-times on equipment acquisition this experiment could not be performed in time for this report; however, it will be carried out by the Authors in the coming weeks.

In parallel, theoretical work was undertaken to establish a cohesive set of client needs and metrics which were used to adjudicate various proposed replacement systems. Five (5) quotes were obtained from various suppliers consisting of variations on two key furnace designs: a new (replacement) bell furnace, or a switch to a single-piece workflow rolling hearth furnace. Each was compared against the generated client needs.

The final analysis indicated that based on currently available data a switch to single-piece workflow is not cost effective due to the large capital cost and space requirements of rolling hearth furnaces.

Replacing the existing furnace with an updated, high efficiency bell furnace is recommended.

However, it was also found that current operations and growth projections are directly on the boundary between batch-optimal and single-piece-optimal conditions. Should production or growth projections be revised upwards, single-piece workflow systems would become preferable. As such, a full description of a recommended rolling hearth design is also included as an alternate proposal that can be pursued should further data become available, or current data be revised, that countermands the above conclusions.

# 1.0 Introduction

The Client has requested that work be undertaken regarding the transformer core annealing furnace at their Winnipeg, Manitoba facility. The Client is a local manufacturer producing small- to medium-sized transformers; a sub assembly area of their manufacturing plant produces transformer cores out of Grain Oriented Electrical Steel (GOES). GOES is cut and deformed from sheets and then annealed to remove strains and restore magnetic properties. Currently these cores are annealed using a batch-type electric bell annealing furnace. However, this unit is outdated and the Client feels that it may no longer be operating at peak efficiency. It has been refurbished many times but concerns have been expressed that continued maintenance is no longer keeping pace with the rate of degradation.

Of central importance in this report is a suspicion by the Client that the current furnace's advanced age is hindering its ability to maintain even temperature distributions during operation, which may in turn be affecting the quality of the cores produced. When the Client sells a transformer that underperforms they pay fees to their customers to compensate. Improving the temperature distribution in the annealing furnace could reduce fees paid by the Client and as such they have requested an analysis to determine whether the temperature distribution is uneven or if temperatures are exceeding maximum acceptable values.

The Client has allocated up to CAD $800,000 for an appropriate solution. The Authors have been asked to assess the condition of the current furnace and to recommend a potential solution in the form of a replacement design. This report represents the final results of these efforts.

The first stage of this project involved research and analysis of the current annealing furnace. The work that was undertaken in this regard is discussed in Section 2.0; this includes a description of the furnace and its constituent parts (Section 2.1), a history of major repairs and retrofits carried out (Section 2.2), a discussion of the general annealing process for bell furnaces and specifics on the process currently used by the Client (Section 2.3), a Failure Modes and Effects Analysis (FMEA) examining key vulnerabilities of the current furnace and areas of recommended improvement (Section 2.4), and a presentation of the proposed experimental design (Section 2.5).

Section 3.0 presents the results from stage two, which involved the recommendation of replacement design. Two designs are proposed. The first (optimal) design is the one that is felt to represent the most balanced solution given currently available information. A detailed description of this design and its operation is given in Section 3.1. The second (alternate) design is a proposal that, while not as effective under current assumptions as the optimal design, could readily become the preferable should production or growth prove more aggressive than currently predicted. The alternate design is detailed in Section 3.2.

Further details and background on the selection of Client needs and metrics, other considered designs, cost analysis, and design selection can be found in Appendix A; an overview of relevant codes and standards is provided in Appendix B.

Before any discussion of results or analysis can occur it is necessary to outline the scope of the project that was undertaken as well as the specific objectives and deliverables that must be produced. Additionally, a very brief summary of the Client needs that were developed throughout the project is provided.

## 1.1 Project Scope

The scope of this project covers assessment and data collation of the current furnace, procedure development and equipment procurement for an experimental analysis, acquisition of furnace proposals from external suppliers, and recommendation of an optimal design. Time and resources permitting the Authors will attempt to perform the proposed experiment for the Client and analyze the results. However, due to lead-time concerns no guarantees are made regarding this particular issue.

Work is also performed regarding the determination of Client needs and the comparison of available operating data on obtained quotes to those needs and metrics for the purposes of recommending an optimal design. Time and technical constraints have meant that the dominant data source in this project for the performance of proposed systems have been the suppliers themselves. As such, some constraints do exist on the data that was obtainable within the available timeframe. In all cases the most complete, detailed, and reliable data was pursued from the source of highest authority. Wherever this was not possible, due diligence and the best available methods were used to fill in whatever gaps may be present. Any data that was obtained using these alternate methods has been clearly indicated as such and, wherever possible, discussion of possible sources of error or the impacts of inaccurate assumptions has been performed.

A cost analysis was carried out for the various considered designs and was made as accurate and detailed as feasible. The unavailability of detailed cost information regarding the current system rendered a financial analysis of current methods unfeasible and no comparative analysis could be performed between the proposed designs and current practise.

Finally, the design, mathematical or numerical analysis, or construction of an annealing furnace is beyond the abilities of the Authors and firmly outside the scope of this project. All technical analysis is derived from discussion with the Client and suppliers or external sources. Any analysis beyond this is limited to such experimental work as can be completed within the available time constraints.

## 1.2 Project Objectives and Deliverables

The objectives of this project, as determined through internal discussion and client consultation are:

1. Develop a procedure and procure equipment for an experimental analysis with the objective of assessing the validity of concerns regarding the presence of thermal pockets and uneven temperature distributions within the existing annealing furnace.
2. Assess the needs of the Client, analyze present and anticipated issues, and establish formal specifications to fulfill the former and alleviate the latter.
3. Obtain quotes and proposals for various furnace systems from suppliers, compare the operating parameters and abilities of these to the criterion developed in Objective 2, and use the resulting data to recommend an optimal solution.
4. Present the results of Objectives 1, 2, and 3 to the Client in a formal report, no later than December 2, 2013.

In addition to achieving the objectives outlined above, several key deliverables must also be produced and communicated to the client for the project to be considered complete. These deliverables, as included in this report, the attached appendices, or communicated externally to the client are:

1. A formal experimental design, outlining required hardware, procedure, and objectives.
2. A full design report, outlining work completed, areas requiring further analysis, and final conclusions.
3. A complete set of quotes and proposals for various furnace designs from suitable suppliers.

## 1.3 Client Needs

Table I and II summarize the final Client needs and their associated metrics, respectively. These were developed in an iterative and organic fashion through consultation with the Client, external research, and internal discussion. Details on this development process can be found in Appendix A.

These needs and metrics collectively formed the criterion against which the proposed designs are compared in Appendix A. Prior to the discussion of solutions, a firm grasp of current conditions must be ensured. Therefore, a thorough discussion of the current annealing system is carried out in Section 2.0.

## TABLE I: CLIENT NEEDS

| Number | Need | Description |
|---|---|---|
| **1.0** | **Design Anneals Cores** | **This category assesses the ability of the design to anneal cores in general, or to obviate the need for annealing** |
| **1.1** | Design accommodates maximum core dimensions | The final design must be able to handle the largest core dimensions produced by the Client. |
| **1.2** | Design achieves annealing temperature | The final design must be capable of reaching the required annealing temperature for the materials used. |
| **2.0** | **Design is Compatible** | **This category assesses the compatibility of the design with existing infrastructure and methodology** |
| **2.1** | Design fits in available footprint | The final design must fit within the allowable floor space in the factory. |
| **2.2** | Design fits existing workflow | The final design must mesh with existing or desired productions methods. |
| **3.0** | **Design is Controllable** | **This category assesses the ability of the design to accept input from operators and to display outputs to them** |
| **3.1** | Design allows operator input/output | The final design must communicate status and other data to operator, and should ideally allow modifications to operational parameters. |
| **4.0** | **Design is Reliable** | **This category assesses how reliable the design is in general** |
| **4.1** | Design has long operational life | The final design should have an acceptable predicted operational life before replacement. |
| **4.2** | Design requires minimal downtime | The percentage of time the final design is in use/available for use should be as high as possible. |
| **5.0** | **Design is Safe** | **This category assesses the ability of the design to operate safely and to be controllable in case of an emergency** |
| **5.1** | Design protects operator from heat | The final design must not expose operator to unsafe temperatures at any time. |
| **5.2** | Design uses gasses safely | If the final design utilizes gasses, it must prevent dangerous gas discharges or ignitions. |
| **5.3** | Design allows emergency shutdown | The final design must allow for the system to be immediately shut off in an emergency. |
| **6.0** | **Design is Efficient** | **This category assesses how efficiently the design operates** |
| **6.1** | Design can accommodate expected work volume | The final design must be capable of processing the work flow maintained by the client. |
| **6.2** | Design processes cores quickly | The final design must anneal cores to an acceptable standard in the shortest time possible, or obviate the need for annealing. |
| **6.3** | Design delivers uniform temperature distribution | The final design must operate with minimal internal temperature gradients, or obviate the need for heat treatment. |
| **7.0** | **Design is Economical** | **This category assesses the economic feasibility of the design** |
| **7.1** | Design has capital cost within budget | The final design should require a capital investment less than or equal to the available capital budget. |
| **7.2** | Design has minimal operating costs | The final design should be as inexpensive to operate as possible. |
| **7.3** | Design has acceptable buyback period | The design should "pay for itself" within a reasonable period of time, and much less than the expected operational life. |

TABLE II: CLIENT METRICS

| Number | Metric Description | Units | Optimal Value | Marginal Value |
|---|---|---|---|---|
| **1.1** | Maximum dimensions that design can accept | [Inches] | 35 5/8" x 16" x 8 1/2" [1] | N/A |
| **1.2** | Maximum temperature that design can reach | [F] | 1550[2] | 1475[2] |
| **2.1** | Approximate floor area required for design | [$ft^2$] | 750 [3] | 2000 [3] |
| **2.2** | Design meshes with existing/desired workflow | [Binary] | Yes | No |
| **3.1** | Design allows controller input/offers data output | [Binary] | Yes | Yes |
| **4.1** | Expected operational life of design | [Years] | 60 | 30 |
| **4.2** | Estimated planned downtime per year | [Days/Year] | 10 [4] | 14 [5] |
| **5.1** | Average temperature at operator station | [F] | Ambient | 80 [6] |
| **5.2** | Design follows relevant gas safety standards | [Binary] | Yes | Yes |
| **5.3** | Design incorporates an emergency shutdown feature | [Binary] | Yes | Yes |
| **6.1** | Maximum production capacity of design | [Lbs/Hour processed] | 2500 [4] | 2000 [7] |
| **6.2** | Average total processing time for each core | [Hours] | 14 [4] | 24 [4] |
| **6.3** | Maximum temperature difference after 1 hour | [F] | 0 | +/- 9 [8] |
| **7.1** | Estimated capital cost of design | [$Cdn] | <$800,000 | $800,000 [9] |
| **7.2** | Estimated hourly operating costs | [$Cdn/hour] | $45/hour [4] | $60/Hour [5] |
| **7.3** | Estimated buyback period of design | [Years] | 15 [4] | 20 |

## 2.0 Analysis of Current Furnace

One of the desired outcomes of this project for the Client was a greater understanding of the operations, condition, and abilities of the current furnace. That desire informed much of the following discussion. The current equipment is detailed in Section 2.1, while a history of major retrofits, redesigns, and overhauls carried out on the equipment is provided in Section 2.2, and the core annealing process is discussed in Section 2.3. The results of the FMEA that was performed is given in Section 2.4, and the proposed experimental design is presented in Section 2.5.

For context, the current floor plan of the core assembly area is shown below in Figure 1. Currently, this area consists of the core preparation area, charge loading zone, gas systems, and the furnace area. The gas systems area is beyond the floor plan but it is to the left of the orange lines. The green lines show the track for the crane which is used in loading the charges and changing the components of the annealing furnace.

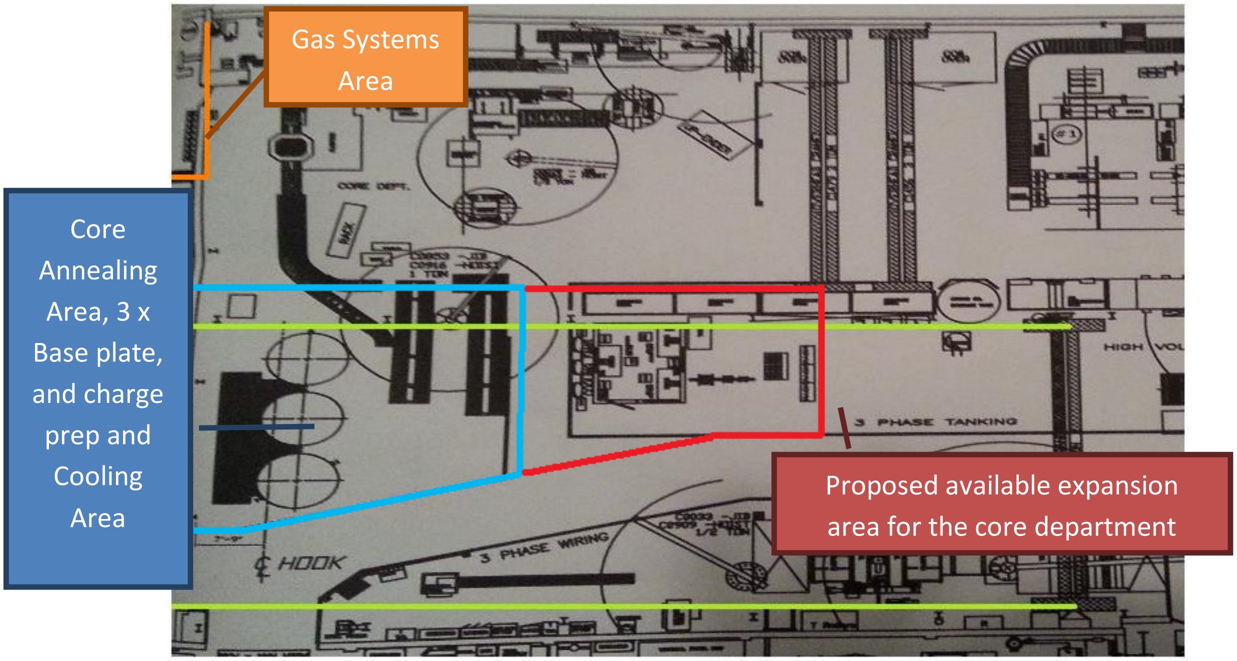


Figure 1: Annealing department floor plan [10]. Courtesy of Carte International Inc.

The current annealing area comprises approximately 750 ft$^2$ with a proposed expansion potentially increasing the available area up to 2000ft$^2$. The core annealing area receives newly fabricated cores, loads them onto plates, moves the plates to the bases, and anneals them by using three bases, two retorts, an annealing furnace and a cooling tower. Section 2.1 will review critical components in the core annealing department to facilitate further discussion in the following sections.

## 2.1 Overview of Current Equipment

The electric bell furnace currently used by the Client was manufactured by Westinghouse Ltd.; the precise age of this furnace is unknown, however, the instruction manual has been dated to 1948. The Client originally purchased the furnace second hand in 1975; at the time of purchase it was noted as being in excellent condition [11]. This section reviews the components that together make up the full annealing system. These components include bases, the retort, loading plates, transformer cores, packaging materials, furnace, controller system, gas system, and cooling tower. Figure 2 shows many of the elements of the annealing system.

The Annealing furnace is rated to 240KW and delivers heat through 5 layers of heating coils inside

Guide rails secure the furnace

The “charge”, refers to the loading plates, cores, lifting pods and core packaging materials

The Retort fits within on top and into the base to create a seal for the controlled atmosphere within the annealing chamber

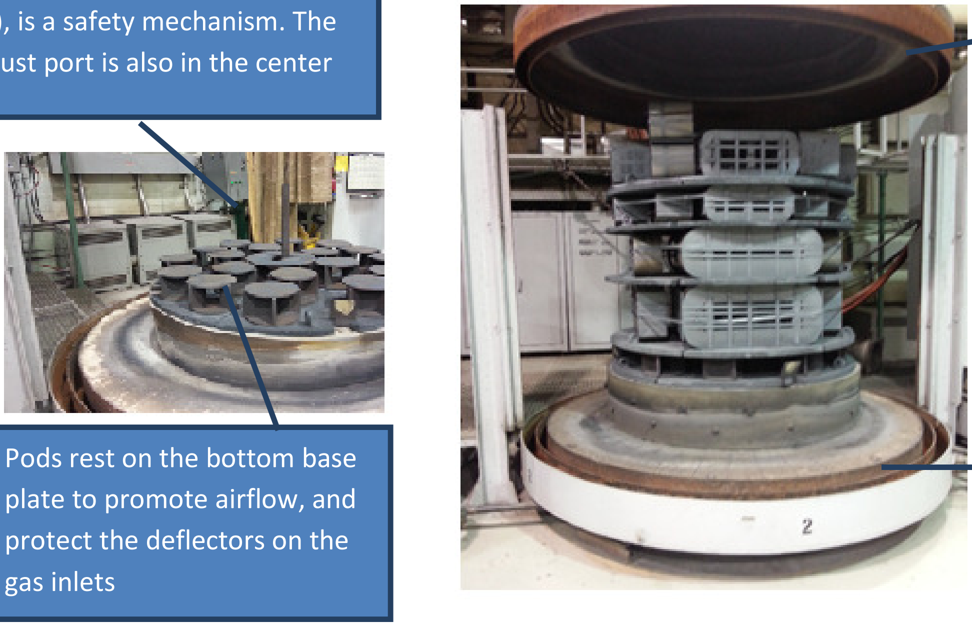
The base supports the charge and forms the lower part of the seal with the retort. The gas system runs through the based and controls the atmosphere within the chamber for annealing conditions

Figure 2: Furnace being removed from base three

### 2.1.1 The Base (Hearth) and Retort

There are three circular bases (or hearths) and two retorts. The bases and retorts fit together to create a controlled atmosphere within the annealing chamber. The main features and functions of the base and retort are illustrated in Figures 3 and 4.

The circular bases support the charges, the retort bell, and the cooling tower or the furnace as required and consist of lower and upper platforms. The lower platform creates a seal with the retort by filling the outermost ring with water while the retort is seated; the upper platform contains three gas inlets, each covered by a deflector, and one main gas exhaust offset by 6” from the center. From the center of the upper base the thermocouple pipe protrudes 26” and the thermocouples read temperatures within the chamber to activate the emergency shutdown if temperatures exceed safe limits. The base also has guide rails which are used to guide the furnace or cooling tower and secure them.



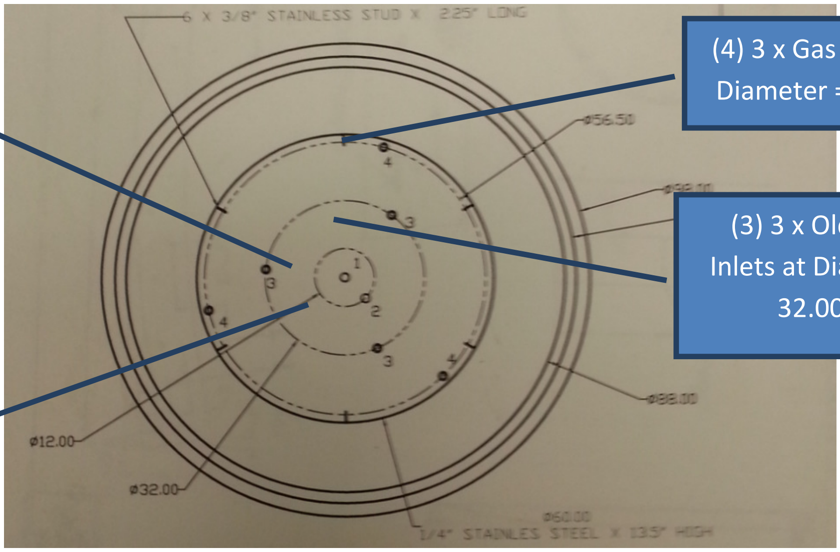
The thermocouple (26” up from base), is a safety mechanism. The exhaust port is also in the center

Pods rest on the bottom base plate to promote airflow, and protect the deflectors on the gas inlets

The retort mates with the lower base

The lower base outer ring fills with water to create a seal when the retort is seated

Figure 3: Base with pods and charge



(1) Thermocouple and pipe, sensor for safety mechanism, not for controlling heating coils.

(2) Exhaust Pipe at 12” Diameter

(4) 3 x Gas Inlets at Diameter = 56.50”

(3) 3 x Old Gas Inlets at Diameter 32.00”

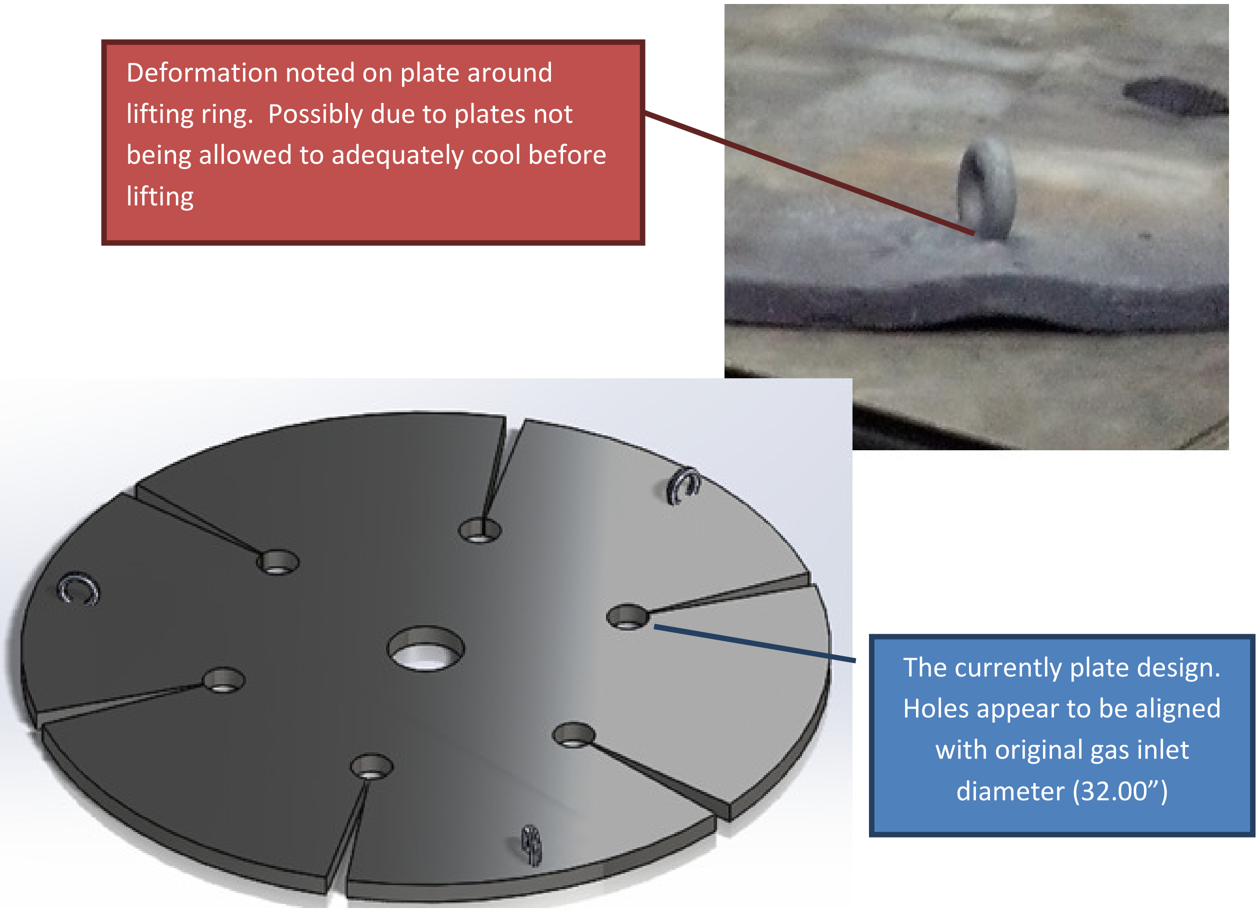
Figure 4: Top view of base. Courtesy of Carte International Inc.

There is an arrangement of structural steel pods, shown in Figure 3, which stay on the upper base, mounted on a single loading plate, and act as support for the charge. In addition, the pods and bottom plate are designed to promote gas flow and allow the atmosphere to flow directly around the inlets and exhaust. The pods and single loading plate take up roughly 10” of the available charge height in the chamber.

### 2.1.2 Charge Elements – Loading Plates, Cores, Packing Straps and Steel

The loading plates are used to support cores so they can be transported to the annealing bases and back to the core charge preparation area once annealing is complete. The loading plates are designed to support loads up to 19000lbs per plate and are lifted by three rings [12]. Figure 5 shows the plate design as well as a plate with deformation around the lifting rings. The plates are made of 44W steel (considered of medium carbon content) and are 1 ½" thick [12].

New plates are ordered every two to three years to replace any plates which are showing significant flaking or deformations. The designed safe lifting weight of the plates is based on room temperatures; however, plates are currently being moved from the base before they are fully cooled. This could explain the significant deformations in the plates and the high frequency of required replacement. The costs from frequent replacement of plates are summarized in Section 2.2.



Deformation noted on plate around lifting ring. Possibly due to plates not being allowed to adequately cool before lifting

The currently plate design. Holes appear to be aligned with original gas inlet diameter (32.00")

Figure 5: Deformed eyelet and base plate model

As plates with loaded cores are stacked upon one another there is a risk of damage or deformation to the cores. To prevent this, the cores must be prepped prior to loading. Stainless steel plates and pipes are used to fill the inner gap of the cores to provide strength and to resist deformation while the cores are under compression during the annealing process. The stainless steel plates and pipes come with an oily finish that should be removed before being used with cores. Cores are spaced on the plate at least 1” apart and arranged so as to balance both their weight and height. The steel inserts and plates are strapped onto the cores and the entire load on a plate may be strapped together for stability as the charge plate is moved.

It takes approximately two to three hours to prepare enough cores to fill a loading plate. A full change can take four to five stacks of plates and cores (depending on core heights) and only once the entire charge is ready can any cores be annealed. It can take eight to ten hours to prep a complete charge. The prepped plates are moved to the bases by the main overhead crane using an attachment with three smaller lifting hooks. Loading the plates and fitting the overhead bell takes roughly 15 minutes. It is possible that the charge prep introduces elements not intended to be within the annealing furnace and may have negative impacts on the quality of the cores. This is discussed further in Section 2.3

### 2.1.3 Heating Bell

The heating bell is the component of the furnace that provides the actual heat to the system. It is refractory lined and uses five layers of hanging coil elements lining the furnace to radiate heat to the retort. Thermocouples are situated at the top and bottom of the inside of the annealing bell to sense temperatures. The controlling system using the data from these thermocouples to toggle individual coils as needed to deliver an approximately uniform temperature distribution. The furnace is rated to 240 KW delivered to two zones. The top two coils comprise zone one and can receive up to 90 KW while the lower three coils make up zone two which can receive up to 150 KW of power.

Figure 6 illustrates the major components of the annealing furnace. On the outside the electrical cabling is shown leaving the furnace. The guide rail shown beside the furnace is used for securing the heating bell and a ladder is used by operators to reach the top of the furnace to connect the crane hook to the furnace. The furnace is removed by the house crane at a slow speed to avoid shocking the retort with cooler air. The retort is also delicate at higher temperatures and the guide rails help keep the retort safe while lifting the furnace. When placing the furnace on a retort the retort is cool but a second operator is required to use a 2x4 to help rotate the furnace to line up the guide rails.

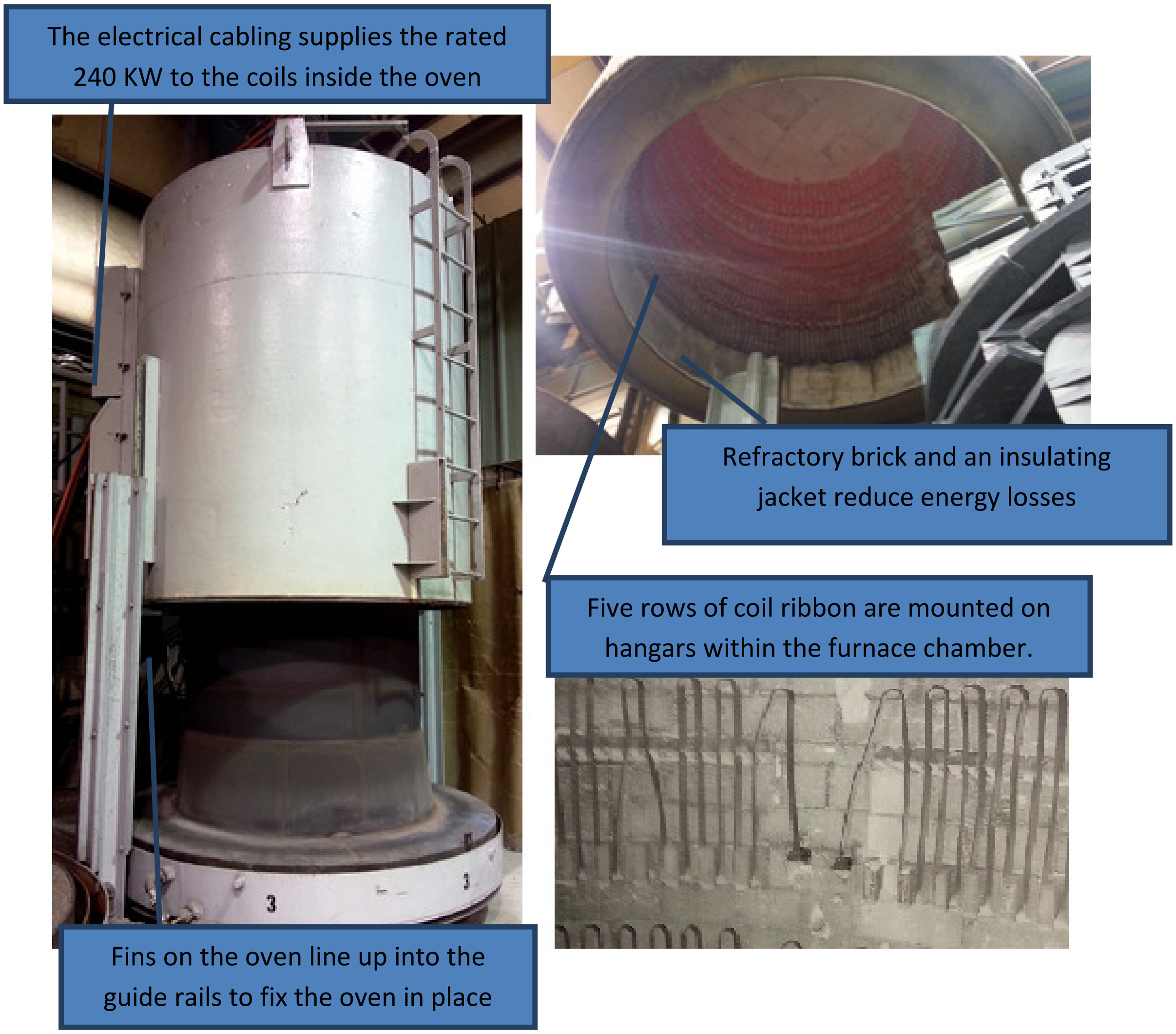


Figure 6: Furnace, retort, and element coil details [13]. Courtesy of Carte International Inc.

Figure 6 above also illustrates the interior features of the furnace. The interior of the furnace is lined with refractory bricks (~5" thick), porcelain hangers and five levels of heating coils. The refractory bricks are surrounded by an insulating jacket (~2" thick) and the protective exterior coating. Annually the furnace is shut down for two weeks to perform preventative maintenance. Hangars and coils are often replaced and new thermocouples are also installed and calibrated. The calibration of the thermocouples is contracted out to an external service [13]. The cabling for the furnace was completely redone in 2008 and electrical components of the controller system were updated in 1985 [14]. Before the updates to the controller system there were lengthy downtimes due to short circuiting of components [15].

### 2.1.4 Cooling tower

After annealing is complete the heating bell is removed and the cooling bell is placed over the hot charge. The cooling tower fits on top of the base and uses a fan to blow air around the retort to help cool the charge. Figure 7 shows an external view of the cooling tower in use. The currently prescribed cooling cycle from the soak temperature down to furnace removal temperature is suspected to be faster than desirable for optimal core performance which is discussed further in Section 2.3.2.

The cooling tower is placed on a charge after the retort is removed and brings the charge from ~600F to room temperature. The cooling tower is an insulated housing with a blower to move air around the charge. In the summer the cooling tower uses from inside the building and ducting is added to take the cooling air from the outside in the winter.

The cooling tower is modified to draw cold air from outside during the winter

The tri-hook attachment to the building crane is used for moving the plates, retort, and the cooling tower

Figure 7: Cooling tower external view

### 2.1.5 Gas Systems

The Client flows N2 and H2 within the annealing chamber to create a protective atmosphere during the annealing process. It is necessary to remove all oxygen prior to annealing in order to prevent the cores from oxidizing, and to control the dew point - limiting the water vapour within the annealing chamber. The sealed annealing chamber created by the base and the retort requires initial purging by the gas system for two hours to remove all oxygen and any other airborne contaminants before the heating cycle commences. The gas system continues to deliver gas throughout the heating cycle as fully described in Section 2.3.3.

Most of the N2 requirement is met by a Nitrogen generator [16]. However, when all three bases are in operation supplemental gas must be drawn from a bulk N2 tank. The nitrogen generator uses electrical power to generate gas, though the power drawn by this generator is not measured by the Client. The gas system follows the prescribed flow rates of N2 and H2 as discussed in Section 2.3.3 and operators only have to initiate the purge; the adjustment to add 2% H2 above 700F and the final shut off are automated with the heating cycle.

The flow from the four inlets offer combined flow rate of 5.5 LPM (litres per minute). The flow was increased from 3.5 LPM to 5.5 LPM to increase convection within the annealing chamber [17]. The inlets have been moved to the outer diameter edges of the upper base (D = 56.60”) and the exhaust port is near the center (D = 12”). It was considered that gas flowing in at room temperature would require a larger exit port once the gas has increased in volume from heating within the chamber. The exhaust port area needs to be 1.87 times the total area of the inlets to accommodate for the increase in volume of the gases from increasing from room temperature to peak temperatures [17]. Gas within the chamber is drawn to the exhaust by negative pressure with the atmosphere outside the building.

The gas system is a complex system on its own and is currently grandfathered into current standards. A detailed analysis of the gas system is beyond the scope of this project; however, any changes to the current gas system will require updating this system to current codes.

### 2.1.6 Control Systems

The furnace has a control station which is used to turn the furnace on and off and monitor internal temperatures. The control station has also been fitted with a webcam so an operator can monitor the annealing process from off-site. The heating rates and control systems are programmed into the furnace systems and automatically monitored using inputs from the two thermocouples installed in the furnace. Based on the readings at these thermocouples the controller is able to individually engage or disengage each temperature zone to maintain an even temperature distribution. An unknown in this system is the precision of thermocouples themselves; determining this accuracy is a central objective of the experimental design in Section 2.5.

## 2.2 Maintenance and Refurbishment History

The annealing furnace was purchased in 1975 from Mulroney Electric company second hand [11]. In the time since then, multiple refurbishments, modifications, and repairs have been performed on the system. Table IV provides a summary of major work the Client has performed on the furnace.

TABLE III: CURRENT FURNACE MAINTENANCE AND REFURBISHMENT HISTORY [11], [14], [15], [18], [19], [20], [21]

| Component | Work Done | When | Cost (CAD$, tax not included) | Details |
|---|---|---|---|---|
| Base & Retort Assembly | Base 3 - Install upper base cone & redo brick work, updates to gas plumbing | 03-Aug-10 | $7,700 | Remove and replaced castable and brick work |
| | Acme Welding & Supply produced the redesigned steel cone for base 3 and made new domed tops for the retorts | 23-Jun-10 | $3,385 | Retort top is 12 Gage - RA 330 cone. Picked up June 23/10. Lower base lined with high heat brick, Upper Base with top 4 1/2" of Rowlock brick and remainder of the 9 " with refractory cement |
| | Nitrogen deflectors designed in 2004 | 2004 | Made in house - Estimating cost less than 100 | Deflectors designed, built and installed inhouse. Simple design, 45" brackets with hole on the bottom to go over gas inlet. |
| | Base 1 and 2 - redo brick lining & move the gas inlets and install larger gas exhaust | 2001 | Cost unknown - estimating 2000 / Base | The brickwork was redone on bases 1 and 2, and the positions of the inlet gas pipes was adjusted to the outer diameter or the upper base. |
| Plates & Charge Prep Equipment | Replaced load plates | 19-May-10 | 5502$ | 6 Replacement Plates made of 44W structural steel (917/plate) |
| | | 05-Dec-08 | 4158$ | 3 replacement plates from Brunswick Steel (1320$/plate) |
| | | 10-Nov-08 | 4158$ | 3 Replacement Plates from Brunswick Steel (1320$/plate) |
| | | Jan 23 2002 | 2240$ | 4 Replacement plates through Brunswick Steel ($560 Each) |
| | | Dec 12 2002 | 2240$ | 5 Replacement plates through Brunswick Steel ($560 Each) |
| | | 16-Nov-00 | 4480$ | 6 Replacement plates through Brunswick Steel ($560 Each) |
| | | 18-May-00 | 2240$ | 7 Replacement plates through Brunswick Steel ($560 Each) |
| | Plate Analysis | 03-Nov-04 | 650$ | Verified load capacity for plates to be 20 000lbs for current design |
| | Plates, pipes, straps | Ongoing | Est. Negligible | Straps, steel plates and pipes used in core packaging |
| | Proposed redesign of baseplates | 1983 | Quoted but not purchased 1138.00 Each | Low carbon steel plates with superior airflow design, incomplete design but 12 folded vanes form a circle of OD 58" with a 8" ID circle |
| Furnace | New cabling and heat shield | 2008 | 6873$ | Tri Star Electric Company - supplied and installed new cabling and the heat sheild of annealing furnace |
| | Hangars & Replacement Coils | Annual Maintenace | Cost unknown | Part of regular maintenance. |
| | Electrical Components Replaced | 1985 | less than $1500 total | Numerous components purchased to update / adjust electrical systems. No mention of outtages in files since repairs in 1985. |
| | 1984 - Report on regular electrical problems with controller | 1984 | N/A | Outages from Short Circuits - recommendations on changing electrical elements and that work could be done in house |
| Initial Purchase | Purchases Annealing Furnace, 2 Bases, 2 retorts | 1975 | $8500 - Used but in great condition | 2 Bases, 2 Retorts, 1 Oven Bell, Controls, Accessories and Spare Parts, Purchased Oct 15 1975, 31000 lbs - Loaded Oct 20 1975. |
| | WESTINGHOUSE CIRCULAR BELL TYPE ELECTRIC FURNACE USED IN CONNECTION WITH MONOGAS ATOMOSPHERE | Instruction Manual date 1948, date of build unknown | Unknown Original Cost | Purchaser - Moloney Electric Co. April 1948. Chamber Size 0 58" dia X 54" High, Zone # 1, 150 KW - 220 V - 3 Ph, Zone # 2 - 90 KW - 220 V - 3Ph, Max Temp 1650. |

Bases one and two were relined with refractory materials in 1991 and base three was relined and redesigned in 2001. The design of the upper base has been changed from the original design to move the gas system inlets positions from the original diameter of 32.00" to a new diameter of 55.50" and to add deflectors to the gas inlets. The deflectors were designed and built in-house. The deflectors were added after a previous set of experiments, performed in 2001, that indicated increasing turbulence in the incoming gases could improve convection within the furnace, and thereby alleviate temperature distribution concerns.

The inlets were moved to reroute the gas flow to the outer radius and the exhaust was increased in size to accommodate for gas expansion from the heating of the gas and to reduce flow restrictions on the outlet. The upper portion of base three was redesigned in 2001 to add a slight camber by setting the upper outer diameter at 60" and the lower at 58". This camber serves to prevent the steel ring from moving upwards during operation, a problem that was noted with the previous design [13]. While the third base was being worked on in 2001, the retort was redesigned to have a domed top to improve circulation in the chamber and increase chamber volume, while the thickness of the steel at the top of the retort was decreased [19].

All the electrical cabling for the furnace along with the insulating jacket were replaced in 2008 [14]. The hangars and coils on the interior are kept as stock items with maintenance and are replaced as required during the annual two week shut down period [13]. The blower on the furnace and the cooling tower are the only mechanical components which do not have any major repairs or modifications noted in recent years. The controller system saw updates to electrical components in 1985 that resolved issues of short circuiting which caused lengthy downtime for the furnace [15].

The largest and most frequent refurbishment cost is in replacing the base plates [18]. Since 2000, the Client has spent more than $25 000 replacing 32 plates. The average costs of plates has risen from $560 in 2002 to over $1000 in 2008.

## 2.3 Core Materials and the Annealing Process

The annealing process is very highly tailored not only to the specific equipment being used but also to the materials being annealed and the desired outcome of the heat treatment. A discussion of the grain oriented steels (GOES) used by the Client, the general annealing procedure for bell furnaces, and the specific methodologies used by the Client follows below.

### 2.3.1 Core Materials

The Client produces custom cores of varied weight, steel type, and dimension. The largest cores have dimensions of approximately 39 5/8” x 16” x 8 1/2” and weigh 600lbs [1]. The cores themselves are made of wound grain-oriented electrical steel (GOES). Numerous varieties of GOES are available and the four main types utilized by the Client in their products are M3, DR, KH, & T3 [22]. A separate steel variety, Unicore, is also occasionally used to produce transformer cores. Though it is much more expensive than common GOES stock, Unicore is beneficial in that, due to its particular properties, when used to produce larger cores annealing is not required [22]. Non-Unicore cores, and smaller cores made of Unicore, will require annealing after fabrication in order to restore magnetic properties that were lost due to deformations during the production process. The procedure for this annealing varies between furnace types and even between individual companies. To clarify the current situation, the general process for bell furnaces and the specific variations used by the Client follow below.

### 2.3.2 General Annealing Process

Transformer cores are annealed following the process shown in Figure 8. The base is initially empty while cores are packaged onto plates (step 1). The plates are then loaded onto the base to a maximum height of 69” [23], usually four but sometimes up to five levels of cores and plates (step 2). The retort is then placed on top of the charge (step 3) and water is added to the outer ring of the lower base to create a seal. Once the seal is adequate, a purge cycle (step 4) takes two hours to prepare the atmosphere before heat is applied. The furnace can be placed on top of the retort (step 5) before the purge cycle is complete, but only if it is cool. If the furnace is still at temperature the operator must wait until the purge cycle is complete. Once the furnace is in place and the purge cycle is complete the annealing cycle is commenced (step 6) by starting the heating cycle at the controller station. The controller system is set to deliver a 150F/hour heating rate to the cores. Once the furnace has reached the soaking temperature (1440F – 1550F) for two hours, the furnace automatically turns off. Once the furnace has reached 600F it can be removed and placed onto another base if the purge cycle is complete, otherwise it must be allowed to cool further. The furnace is removed (step 7) and the cooling tower is applied (step 8). The cooling tower blows ambient air to bring the retort and charge temperatures down from 600F. It should be expected that although the furnace reaches 600F at the time of removal the contents within the retort will still be at higher temperatures. The cooling tower cools the charge to at least 300F before removal (step 9). The retort can then be removed (step 10) and the charge should be allowed to cool to room temperature; in current practise plates are often removed early (step 11) allowed to cool at the end of the charge prep area.

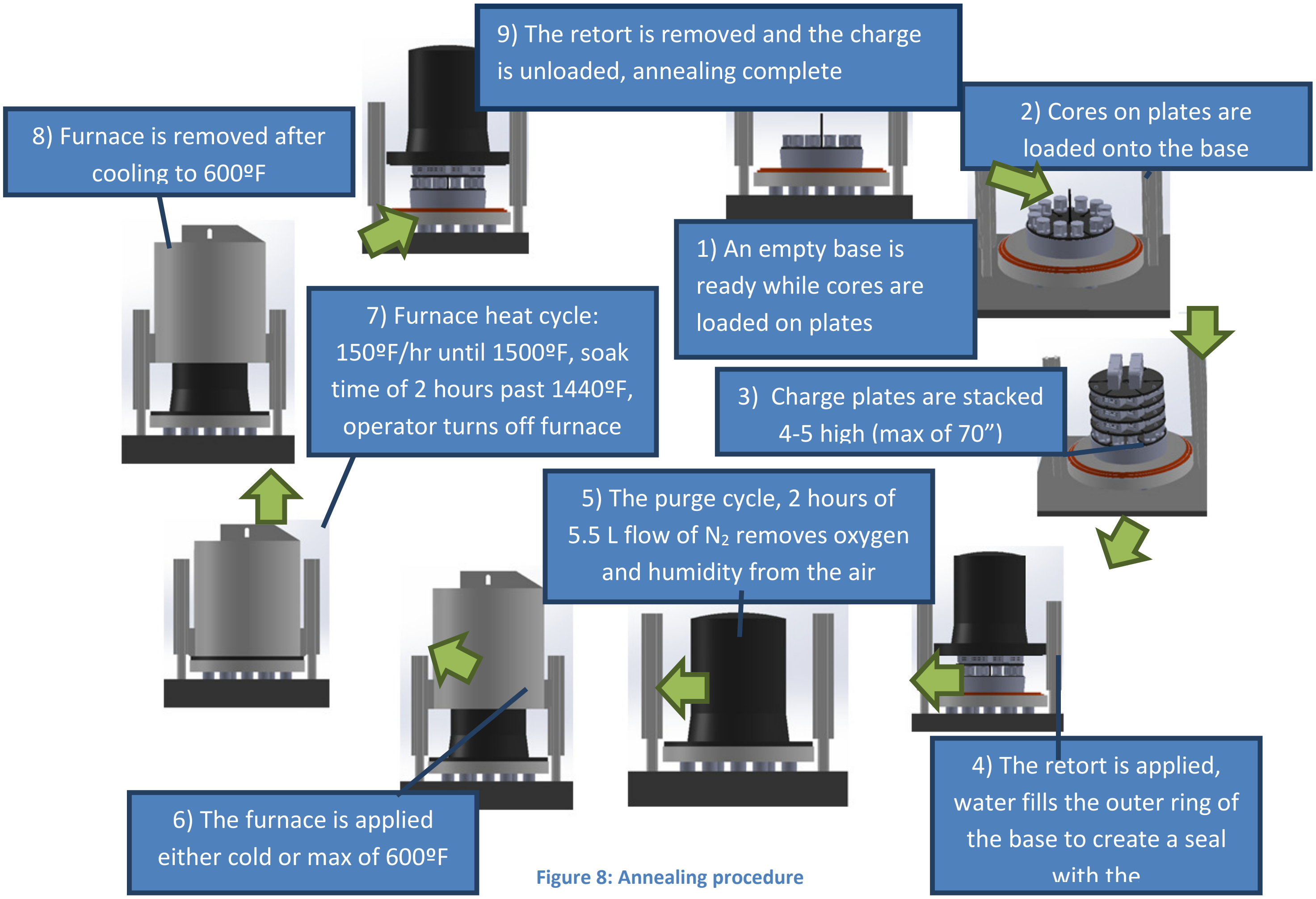


Figure 8: Annealing procedure

### 2.3.3 Client-Specific Annealing Procedure

The furnace currently used by the Client is a strictly batch-process system. This presents challenges which require compromises when dealing with high production flows and multiple GOES that will be annealed at the same time. The different GOES suppliers each have their own recommendations for annealing conditions; these are for the most part similar but have nevertheless required the Client to formalize the standard annealing conditions which were described in the previous section. The intent of this section is to illustrate the discrepancies and explain the details of the Client's annealing process for both the gas rates and the applied heating rates.

Table V contrasts the recommended annealing conditions of two GOES producers with the current values used by the Client. Nippon's prescribed heating cycle is shown in Figure 9. It is notable that this cycle diverges from the information they had previously provided to the Client. The recommended heating cycle shown in Figure 10 is actually less than the recommended 150F/hour [24] and this discrepancy should be followed up on with Nippon [25].

All manufacturers agree on an atmosphere with no oxygen and no humidity. Historically the Client has added 3.5 LPM (Litres per minute) of gas flow. In an effort to create a more uniform temperature distribution this was increased to 5.5LPM [17]. There are no sensors to measure the exhaust for oxygen content which could confirm the effectiveness of the purge.

The Client's prescribed annealing schedule allocates an extra hour of soak time (two hours). This is required because the controlling sensors should read temperatures higher than are actually experienced by the cores within the chambers and the extra hour is intended to accommodate the lag in actual temperatures within the shell. The soak temperature for ATI GOES is 1475F [24] and Nippon GOES is 1440F [26]. The two hour soak time starts when the thermocouples first read 1440F. It is possible that ATI steels do not get adequate soak time (minimum 1 hour).

TABLE IV: SUPPLIER RECOMMENDED AND ACTUAL CLIENT ANNEALING CONDITIONS [24], [25], [26], [27]

| | ATI Recommendations [24] | Nippon Steel & Sumitomo Metal Recommendations [26] | Client Annealing Conditions |
|---|---|---|---|
| **Atmosphere** | 100% Nitrogen of mix with 10-15% Hydrogen | Recommended neutral N2, oxygen free, | Bulk N2 @ 99.955%, Purges for 2 hours, Beyond 700F, $H_2$ is added to be 2% of the incoming gas mixture |
| **Oxygen** | Less than 0.1% (aim 0.05%), max of 0.5% | Oxygen free | Aim for 0 Oxygen |
| **Dew Point** | Aim less than 0 F, max +20F | Dew Point of Atmosphere at 0C | Dew Point of Atmosphere at 0C |
| **Temperature** | Heating profile not specified. 1 hour min (based on cold spot) at 1475F | Heat with uniform heat distribution, Heating Curve shown in Figure 9. Prescribed 150F/ hour. Soak at 800C for 2 hours, Must not exceed 850C. | As furnace finishes one heating cycle it must drop to 600F before moving onto next base which should already be purged. Furnace waits until down to 300F before starting heating cycles. 150F/hour until 1500F, soak for 2 hours beyond 1440F. The furnace then turns off until it cools to 600F. |
| **Flow Rate** | Adjust such that oxygen and dew point limits are met | Not Prescribed. | Nitrogen only up to 700F with flow of 5.5 Lpm, past 700F $H_2$ added to be 2% of gas composition. |
| **Cooling Rate** | Cooled at 100F / hour max to less than 700F before protective atmosphere removed. Furnace should be cooled to less than 700F before moving. Larger cores (200lbs and more require slower rates to minimize thermal distortion) | Cool at a slower rate due to influence of thermal strain. Do not take cores out of a furnace at 250C or higher. (600F) | Cooling rate dependent on ambient air temperature which varies from hot summer air to cool winter air. Cooling rate is a function of the power in the cooling tower blower and the intake air temperature. |

Figure 9: Recommended heating and cooling cycle [24]

The heating cycle shown in Figure 9 differs from that currently used by the Client, as indicated in Figure 10. The recommended heating cycle takes at least 14.68 hours [26] while the client has a total average annealing cycle of 16.45 hours. Accounting for cooling time, their total average processing time is in the range of 22-24 hours [16]. The figure below contrasts the applied heating rate used by the Client and the recommended heating and cooling rates from Nippon Steel & Sumitomo Metal Corporation. This figure illustrates that there is room for a more aggressive heating rate.

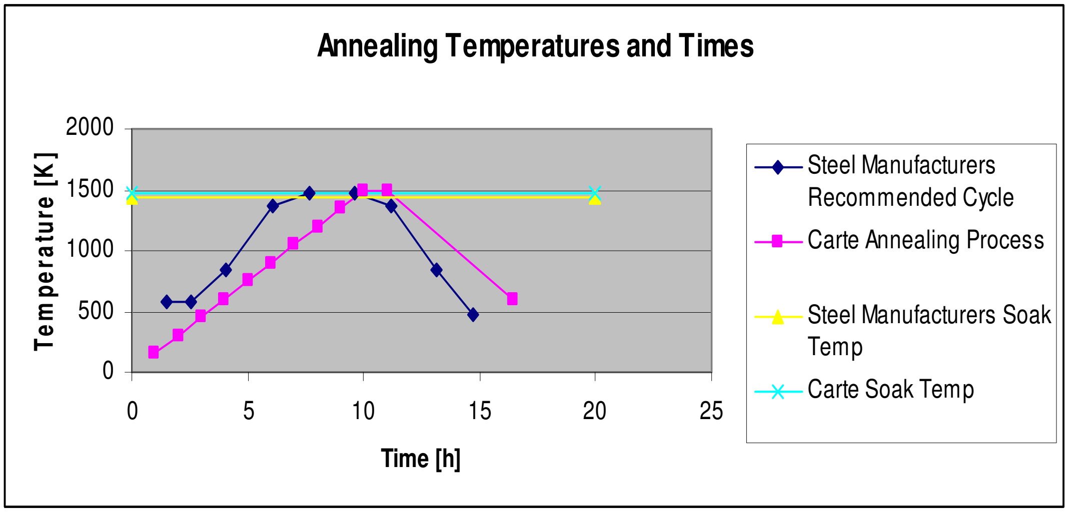


Figure 10: Annealing temperatures and times

### 2.3.4 Current Furnace Annealing Times

Using load sheets the average total annealing times, charge weights, and number of cores annealed were calculated and organized by baseplate as tabulated in Table VI. The average annealing time represents the entire time the heating oven is active during the heating cycle as well as the time it takes the furnace to cool down to the 600ºF before being moved to the next base.

TABLE V: ANNEALING TIMES, CHARGE WEIGHTS, AND NUMBER OF CORES [7]

| | Avg Annealing Time (Hours) | Avg # of Plates | Avg Charge [lbs] | Avg # of Cores |
|---|---|---|---|---|
| **Base plate 1** | 17.02 | 4.44 | 9346.60 | 47.00 |
| **Base plate 2** | 15.83 | 4.09 | 9561.70 | 54.00 |
| **Base plate 3** | 16.51 | 4.11 | 10226.00 | 46.67 |
| **Total** | **16.45** | **4.21** | **9711.43** | **49.22** |

Figure 11 shows each data point that was considered in determining the average annealing times. The shortest annealing time was 13.69 hours on base plate two with 30 cores at 8182 lbs. The longest annealing time was 19.78 hours on base plate one with 60 cores at 9760 lbs. From base plate to base plate the data suggests base plate two is faster than base plate one which may come from the condition of the base plate.

The average weights on base plate three are substantially greater than the other two and a linear weight-annealing time relationship is not expected.

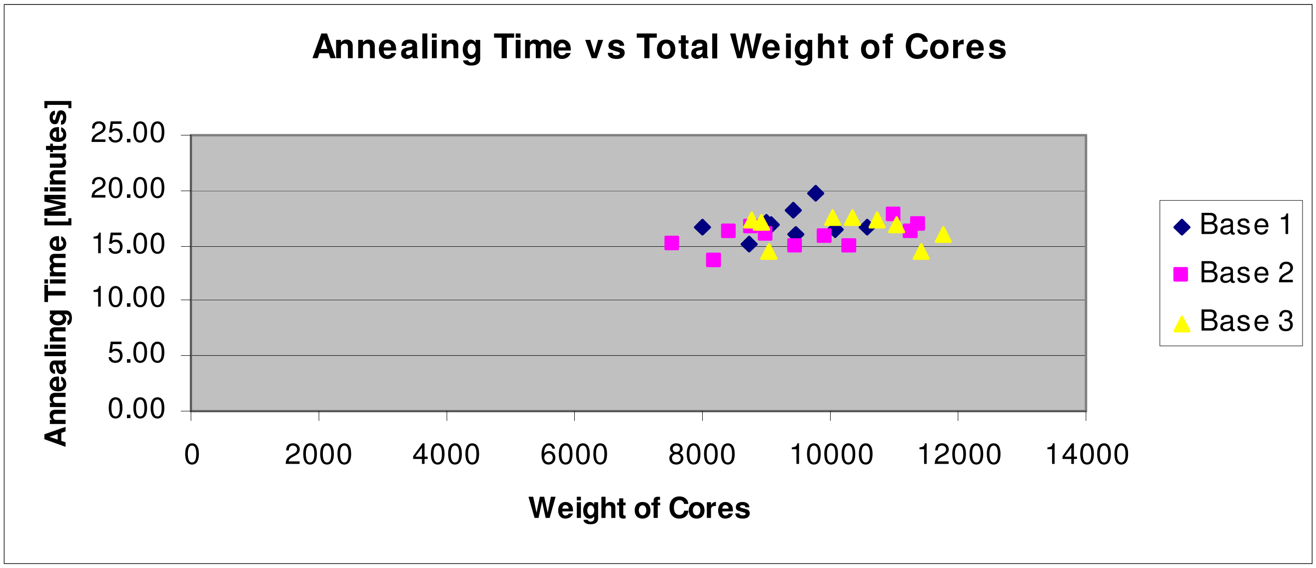


Figure 11: Annealing times by total weight of cores per baseplate

One of the Client's GOES suppliers has performed experiments showing that reducing the cooling rate to as low as 20C/h (36F/h) for larger pieces of steel could improve annealing results, particularly by improving the recovery of the steel's magnetic properties [25].

Based on the comparison of the recommended heating cycle and the Client's prescribed heating cycle and cooling cycle, there should be room for a more aggressive heating cycle without negative impact on the cores, however cooling rates could be slowed to improve core performance. There is also doubt in how well the controller sensors reflect the temperature within the retort, an experiment with thermocouples within the retort is proposed to determine this relationship.

The Client has a gas systems book published internally in 2009 with a different heating cycle. The heating cycle only has a one hour purge time but the entire prescribed heating cycle in that book takes more than 21 hours [27]. It is recommended that the Client update their publications to reflect the automation of the process and the currently prescribed annealing conditions.

## 2.4 Failure Modes and Effects Analysis

A Failure Modes and Effects Analysis (FMEA) was conducted on the Client's annealing furnace. The analysis reviewed the components and the processes to identify failure modes, possible sources of failure, the current controls and to recommend any actions where required. The FMEA remained qualitative while identifying methods of study which could help quantify the severity, or frequency, or to confirm if the problem exists at all.

Operators were interviewed, reviewing the annealing procedures step by step and looking for possible failures or safety concerns. Other inputs included discussions with the core department manager, maintenance personnel, and the head Industrial Manager at the Client's Winnipeg facility.

The FMEA is organized into failure modes which may negatively impact the end core quality. The major failure modes identified are: core oxidation, foreign material contamination, insufficient soak time or temperature, core overheating, uneven temperature distributions, and thermal shock. Each failure mode was considered, along with the possible sources, the current controls as well as any suggested additional action. Safety concerns were also identified in a similar manner.

### 2.4.1 Core Oxidation

Cores may be oxidized if oxygen is present within the chamber during the annealing process. The addition of an oxygen sensor to the exhaust line would enable the Client to monitor for oxygen within the chamber and minimize the risk of oxidation. Table VI summarizes possible sources of oxidation, the current controls in place, and any recommended action.

TABLE VI: OXIDATION SOURCES, CONTROLS, AND RECOMMENDED ACTIONS

| Possible Sources | Current Controls | Recommended Actions |
|---|---|---|
| Purge does not remove all the oxygen | Controller System does not allow, it reports gas flows and ensures the full two hour cycle is followed | Add sensors to exhaust to detect oxygen. |
| Furnace applied (turned on) before purge complete | Operator checks controller screen and load sheets to confirm 2 hours have passed of purge before initiating annealing cycle | No additional action recommended |
| Hot Furnace moved onto base before purge Complete | Operator must check furnace temperature from one cycle before moving it to the next, one operator interviewed was not away of the minimum movement temperature | Update procedures for operators and training. |
| Leaks in retort allowing atmospheric air in | Monthly application of zinc paint for leak checks, welds applied to fill any found leaks. | No additional action recommended |
| Improper water seal from incomplete draining, or overfilling | Under operator control, rust from water damage on both the lower base and retort suggest water might get into chamber | Investigate retort damage and consider testing for humidity within retort |
| Inadequate gas flows to reduce humidity during purge | Controller system monitors and reports gas flows at the controller station | Add sensors to exhaust to check for humidity |
| Contaminants which release oxygen when under heating | Contaminants are not allowed in retort but permanent markers used on cores contain volatile organic compounds | Develop new way of marking cores free of contaminants |

### 2.4.2 Foreign Contamination

Other than the electrical steel (GOES) cores, stainless steel supports, firebrick or refractory ceramics, nitrogen atmosphere, and max 3% hydrogen no external material is permitted within the furnace during operation. Table VII identifies possible sources for contaminants and recommended actions; no formalized contaminant controls are currently used by the Client. It is unknown how severe an impact contaminants can have but this merely makes determining the extent of the risk that much more of an imperative. The most likely source for contaminates at this time is the region where the plates and binding straps and clasps are in contact under pressure during the annealing process.

TABLE VII: CONTAMINANT SOURCES AND RECOMMENDED ACTIONS

| Possible Sources | Recommended Action |
|---|---|
| Carbon from plates, Plates are currently made of 44W, standard structural steel of medium carbon content | Consider replacing plates with steel with a lower carbon content |
| Unknown white residue is in retort | Identify the white residue and consider the impact on cores |
| Flakes of plates observed on cores | Change material for plates |
| Material from steel inserts | Oil should be cleaned from new inserts, consider using |
| Material from binding clasps | Verify if using low carbon content materials, investigate alternatives |

### 2.4.3 Insufficient Soak Time or Temperature

Cores must reach the annealing temperature and then maintain it for the required soak time. The soak temperature used by the Client is 1540F with a soak time of two hours. This two hour figure is double the required soak time for the materials used; the soak time was increased by the client as a form of safety factor to ensure the entire furnace has reached the required temperature. However unlikely, it is still possible that certain loads are not experiencing sufficient soak time. Possible sources of soak time failure are explored in Table VIII.

TABLE VIII: INSUFFICIENT SOAK TIME OR TEMPERATURE SOURCES, CONTROLS AND RECOMMENDED ACTIONS

| Possible Sources | Current Controls | Recommended Action |
|---|---|---|
| Sensors do not adequately represent the temperature within the chamber, the temperatures within the chamber may be lower. | Thermocouples placed at the top and bottom within the furnace and not actually within the chamber. | Run thermal analysis to compare temperatures within chamber with report sensor temps. Add sensors within the annealing chamber for the control system. |
| Inadequate convection increases the size and number thermal pockets, cool spots may exist. | Gas flow rates monitored by controller system, main sources of convection within the oven. | Conduct thermal analysis to check for thermal distribution within the chamber. If experiment confirms requirement then implement designs aimed at improving convection within the furnace. |
| If radiation is the main heat transfer mode, then some cores may be in the shadow of other cores and take longer to heat than other cores. | Operator arranges cores with min 1 inch spacing. | Return to recommended one fist spread between cores, conduct thermal analysis and look for evidence of radiation shielding. |
| Inadequate convection from core arrangements impeding air flow. | Operator arranges cores with min 1 inch spacing. | Increase spacing of cores. |
| Loading plates may impede air flow and affect temperature distributions. | Plates are designed with holes that line up with the old positioning of gas inlets, cuts are also included for improved air flow. | Change plate design to allow for more air flow. |
| Exhaust flow restricted may reduce convection within furnace. | Exhaust pipes were increased in opening size to account for 1.87 times the area of the inlets. | Measure exhaust flow rates, Consider adding a fan, reducing flow restrictions. |
| Air flow convection may be inadequate from inadequate turbulence generation in the flow. | Gas flows have were increased from an old value of 3.5 LPM to 5.5 LPM. | Conduct thermal analysis to check for thermal distribution within the chamber. |

The results from this section of the FMEA have emphasized the need for thermal analysis to examine the accuracy and reliability of temperature controls and distributions within the existing furnace.

### 2.4.4 Core Overheating

The next failure mode under investigation occurs when cores are heated beyond recommended maximum temperatures for annealing. Cores overheating may be a serious problem as cores are not currently tested for quality and the current temperature distributions within the annealing chamber are unknown. Hot spots may exist where temperatures rise in only certain locations. Key possible sources of overheating failures are shown in Table IX; the recommended action column has been omitted as it remains the same throughout.

A thermal analysis should be conducted to:

- Verify that the sensory equipment is reporting temperatures within acceptable tolerance to the temperatures within the chamber.
- Observe the temperature distribution and rate and different points throughout the chamber and make inferences on the level of convection within the chamber.

TABLE IX: CORE OVERHEATING SOURCES AND CONTROLS

| Possible Sources | Current Controls |
|---|---|
| inadequate convection allows for thermal pockets to grow | Thermocouples for controller system outside the furnace |
| Inadequate sensor equipment | Two thermocouples provide inputs for controller system, top and bottom of furnace, 1 thermocouple is used for safety purposes within the chamber |
| Inadequate controller system (reaction to temp) | The controller system reacts to the thermocouples to activate different heating coils |
| Inadequate sensor tolerances | The thermocouples are calibrated to all the operating temperatures annually |

### 2.4.5 Non-Uniform Temperature Distributions

There are no current controls to check for non-uniform heating and cooling within the chamber. The possible presence of thermal pockets cannot be discounted due to their potential to cause significant issues with efficiency and quality control. Table X presents several failure sources with the capability of producing temperature non-uniformity.

TABLE X: NON-UNIFORM TEMPERATURE DISTRIBUTION SOURCES AND SUGGESTED ACTIONS

| Possible Sources | Suggested Actions |
|---|---|
| Inadequate Convection | Conduct Thermal Analysis to compare temperatures within chamber to controller sensors |
| Improper control design for activation and deactivation of coils | If experimental analysis indicates uneven temperature distributions, the controller design may be investigated for improvements |
| Inadequate sensor inputs for controller to adjust the coils | If experimental analysis indicates uneven temperature distributions, the controller design may be investigated and more sensors may be required. |
| Arrangement of plates and cores could impede convection | Increase spacing to first width and line up slits on the plate with gas inlets |
| Arrangement of cores could impede radiation | Consider designing plate layouts to minimize radiation shadowing |
| Differences in thermal conductivity in the materials beyond the cores. | Use materials with thermal properties as similar as possible to the GOES |

### 2.4.6 Thermal Shock

Thermal shock occurs in materials when they are heated or cooled too fast. If the furnace is applied while it is too hot (above 600F) it may shock the load, leading to irreversible thermal strains and permanent reductions in performance. Operators control when the furnace is physically moved and are instructed to wait until the furnace reaches 600F before movement.  However, in discussions with site staff it was discovered that this requirement was not uniformly known or understood amongst operators. It is recommended that the importance of allowing the furnace to cool sufficiently before moving be reemphasized to site personnel.

### 2.4.7 Safety Failure Modes

The annealing process was reviewed with operators and the maintenance manager to look for safety concerns. Of particular note was the revelation from these interviews that Hydrogen explosions, caused by the gas reaching its flash point, have occurred in the furnace chamber.  Maintenance personnel also recounted an instance where the coils broke off from the hangars within the furnace and punctured the retort.  However, no record of either of these instances could be located in the furnace maintenance records.

More commonplace safety hazards are largely considered with lifting and moving of large equipment. The annealing process requires movement of many large components – such as load plates, retorts, cooling tower, and the furnace itself – and this is accomplished via the in-house crane. The most effective protective measures in these instances are communication and situational awareness on the part of floor personnel in conjunction with safety protocols and personal protective equipment (PPE). In these regards no apparent causes for concern exist and the Client's safety procedures seem robust. The only lingering issue to the Authors remains the evidence of eyelet deformation on the load plates likely caused by the plates being lifted before cooling (Section 2.1.2). These and other relevant sources of possible safety concerns are outlined in Table XI.

TABLE XI: SAFETY CONCERNS, SOURCES, AND RECOMMENDED ACTIONS

| Safety Concern | Possible Sources | Recommended Actions |
|---|---|---|
| **Explosions** | If gas flow controller gives too much H2 or not enough N2 and the exhaust is inadequate or plugged. H2 may build up in the chamber until it reaches its flashpoint causing an explosion. | Current controls seem adequate in measuring the gas flows of H2. |
| **Mechanical Failures** | Deformation or failure of plates from moving the plates while there are still hot | Do not move plates until they are at room temperature to reduce deformations. Inspect all lifting rings regularly. |
| **Burns** | Numerous causes (brick breakdown, protective shield pierced, inadequate communication when moving the furnace, not wearing protective clothing when moving the furnace, not pulling out heat shields and signage) | Current procedures and regular inspections of equipment should be adequate |
| **Igniting Hydrogen** | Leaks in retort | Current inspection protocol seems adequate |
| | Improper Seal in Retort | Conduct an inspection of the base seal area |
| | Hangars break and coil pierces retort while at high temperatures. | Inspect and replace hangars as required. |

As discussed throughout this report, truly appraising and understanding the conditions and operations of the current furnace is difficult, if not impossible, without valid experimental data. To address this issue an experimental analysis was proposed, and is described below.

## 2.5 Experimental Analysis

The proposed experiment measures temperatures within the annealing furnace at each core level and at inner and outer radial positions on each plate. The experiment is designed to address many of the concerns identified in Section 2.4. The thermocouples were ordered at the beginning of November, 2013. The lengths and thickness of the of the K type thermocouple cables required custom manufacturing and the lead time has exceeded the quoted two to three weeks. The experiment outlined in this section will be performed for the Client once the equipment is available.

### 2.5.1 Purpose

The experiment places 10 additional thermocouples within the annealing chamber and monitors the temperature at each with a data acquisition terminal. Two thermocouples will be placed on each layer, one near the inner radius and one near the outer radius of the load plate. The temperature distribution as a function of time will provide much valuable information. The experiment will do the following:

1. Illustrate the temperature distribution as a function of time within the annealing furnace
2. Compare the actual heating rates within the chamber to the intended rates
3. Allow for inferences on the dominance of the different heat transfer modes. A large temperature variance from top to bottom will indicate room for improvement on the convection within the furnace chamber. A large temperature variance from outer to inner positions can be from radiation shielding or inadequate convection.
4. Compare experimental readings to controller system thermocouples. The results of this comparison should indicate the lag time for temperatures within the chamber for the minimum temperature to meet the critical temperature.
5. Identify regions with strong temperature variance and make inferences on the convection flow and radiation.

### 2.5.2 Experimental Apparatus

The experiment requires the following apparatus, as outlined in Table XII.

TABLE XII: EXPERIMENTAL APPARATUS

| Component | Sourcing | Additional notes |
|---|---|---|
| **10 x Thermocouples, Type K Cable, +Details** | Carte Ordered from Eastman Engineering, | Type “K” Ungrounded, 2mm Diameter, C/w Standard Male Plug<br>10 cables lengths vary from 130” – 175”. |
| **Thermocouple Wire** | Supplied by Carte | |
| **Wire Cutters** | Supplied by Carte | |
| **DAQ – IO TECH 6200** | Supplied as temporary loan between Paul Labossiere and Adam Gamble. | Single unit can take inputs on up to 12 channels. |
| **Software CD** | Supplied as temporary loan between Paul Labossiere and Adam Gamble. | Use ENCORE CD the IO Tech 6222 DAQ |
| **Laptop** | Currently supplied by Adam Gamble | Any laptop could be used with Ethernet inputs and modern windows operating system (Vista or newer). |
| **Marking Supplies for Thermocouples** | Supplied by Adam Gamble | Masking tape markers, colored markers, and pen |
| **Protective tube for thermocouples while loading plates** | Creative solutions at Carte International | Ideally a 2-3” diameter Abs pipe ~ 5’ long |
| **Thermocouples fixing supplies** | Use steel plates from annealing department or extra straps | Be creative, reduce contaminants or extra material as much as possible. |
| **Step ladder** | Carte International | Used to get onto the higher plates while placing thermocouples |

### 2.5.3 Experimental Setup and Procedure

The following are the recommended steps to accomplish the setup and experimental procedure. The steps are illustrated with three figures following the written description. The figures illustrate experimental hardware setup, DAQ and software configuration, and thermocouple positions and corresponding thermocouple positions.

**Step 0** – *Prepare transformer cores and load plates. Add 1 loose strap to a core on the inner and outer radius of each plate at mid height to secure the thermocouples.*

**Step 1** – *Measure and label all the thermocouples. Put indicator tape at ~ 10"from the end of each thermocouple and identify the length of the cable, intended level and inner or outer radius position. Identify the cables also at the base of the cable.*

**Step 2** – *Feed all the thermocouples through the base with assistance from maintenance and department personnel. The thermocouples must be covered by a protective tube as they extend up to six feet from original thermocouple tube.*

**Step 3** – *Move the first load plate onto the base. Remove the thermocouple protective tube, identify the thermocouples marked for the appropriate level and plate them onto their plates. Replace the protective tubing on the remaining thermocouples, move over the next plate and repeat step 3 until all the layers and thermocouples are in place.*

**Step 4** – *Use thermocouple wire to connect the ends of the thermocouples to the DAQ. Use the markings on the base of the thermocouples to identify which port on the DAQ belongs to which thermocouple. Connect the DAQ to the laptop and turn on the IO Tech data acquisition software.*

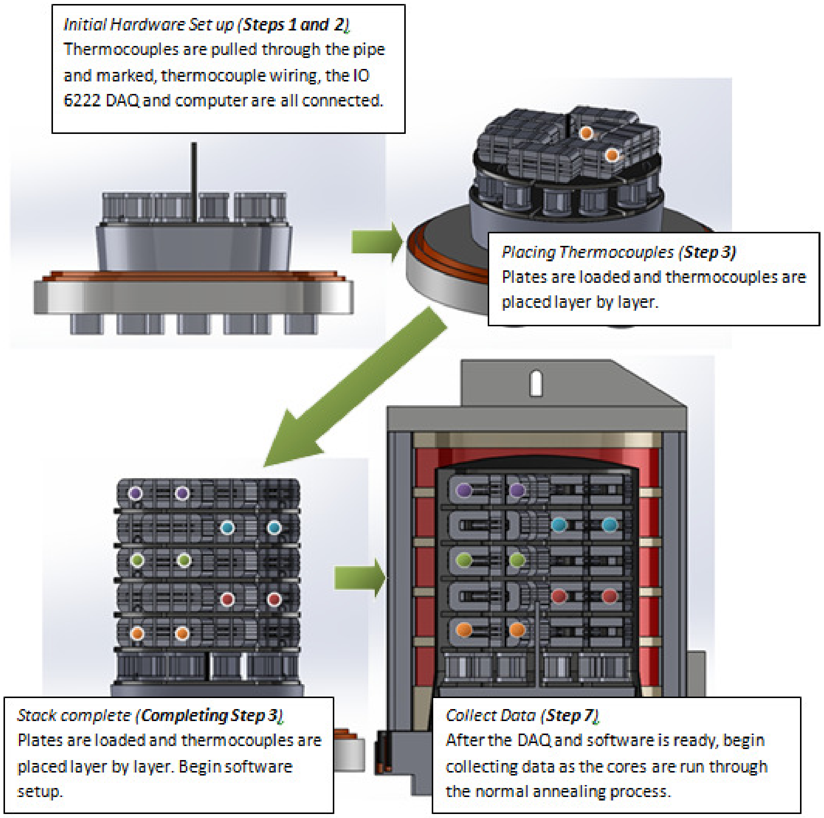
**Step 5** – *Configure and prepare the software for data recording.*

**Step 6** – *Configure and prepare the software for data recording. Data acquisition may be done by Carte International employee or by a member of 'The Annealers'. Data will be recorded on the laptop to record temperatures at 5 minutes time intervals. The temperatures from the controller station will be recorded at 15 minutes intervals or smaller.*

**Step 6** – *The normal annealing process is followed while data is collected automatically by the software and by manually recording the controller temperatures and times for both the top and bottom zones. Step 6 is complete once the annealing process is complete and the cores have cooled to room temperature.*

**Step 7** – *The thermocouples must be removed off the cores of each plate before the plates are unloaded. The protective tubing should be available but should not be necessary to protect the thermocouples for unloading. Once the base is unloaded the thermocouples can be removed from the annealing chamber and packaged for storage with Carte International.*

**Step 8** – *Data will be analyzed to accomplish the five goals outlined in the purpose section (2.5.1).*



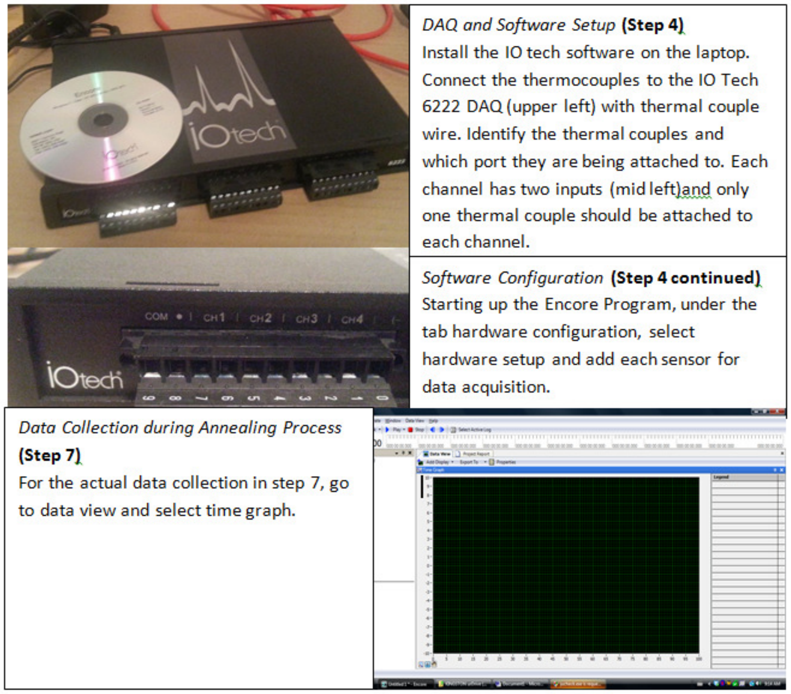
*Initial Hardware Set up* ***(Steps 1 and 2)***
Thermocouples are pulled through the pipe and marked, thermocouple wiring, the IO 6222 DAQ and computer are all connected.

*Placing Thermocouples* ***(Step 3)***
Plates are loaded and thermocouples are placed layer by layer.

*Stack complete* ***(Completing Step 3)***
Plates are loaded and thermocouples are placed layer by layer. Begin software setup.

*Collect Data* ***(Step 7)***
After the DAQ and software is ready, begin collecting data as the cores are run through the normal annealing process.

Figure 12: Experimental hardware setup



*DAQ and Software Setup* **(Step 4)**
Install the IO tech software on the laptop. Connect the thermocouples to the IO Tech 6222 DAQ (upper left) with thermal couple wire. Identify the thermal couples and which port they are being attached to. Each channel has two inputs (mid left)and only one thermal couple should be attached to each channel.

*Software Configuration* **(Step 4 continued)**
Starting up the Encore Program, under the tab hardware configuration, select hardware setup and add each sensor for data acquisition.

*Data Collection during Annealing Process* **(Step 7)**
For the actual data collection in step 7, go to data view and select time graph.

Figure 13: DAQ setup and software configuration settings

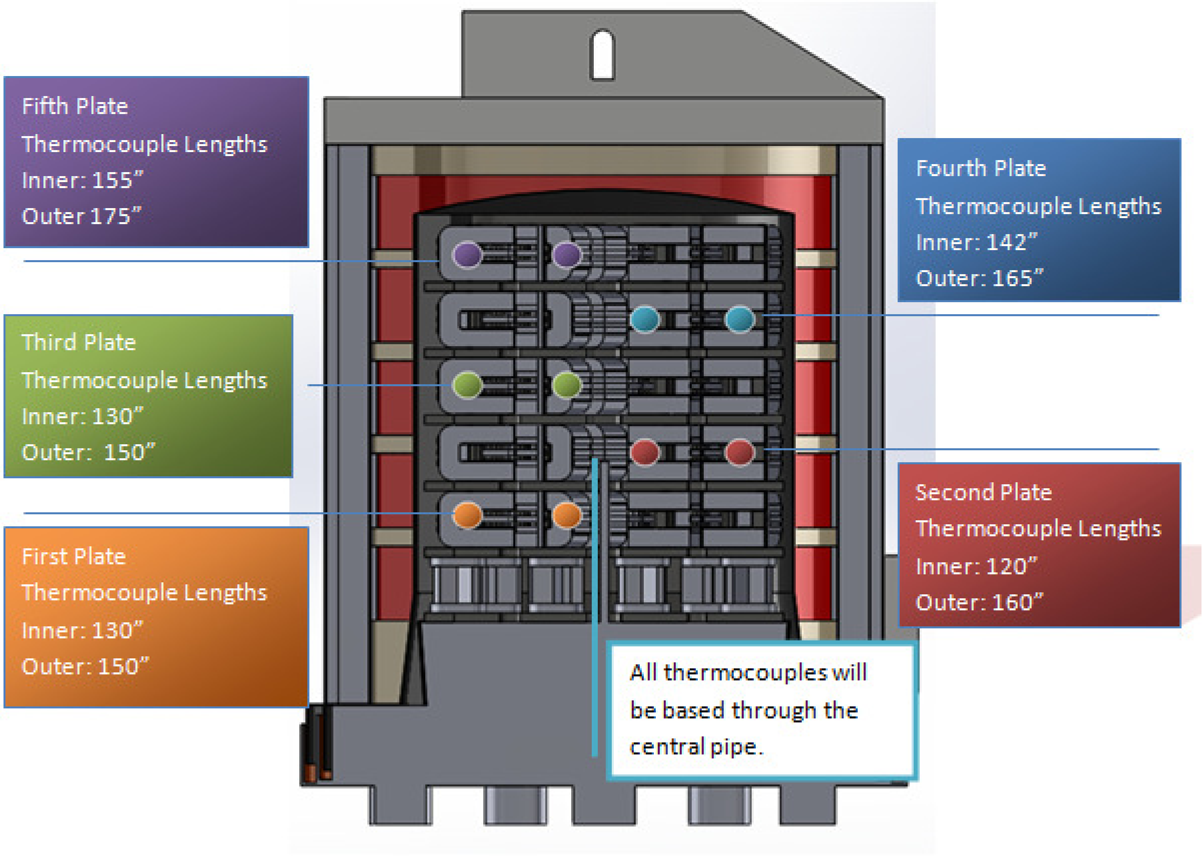


Figure 14: Thermocouple positions and corresponding thermocouple length

### 2.5.4 Data Collection, Analysis and Discussion

Data will be collected throughout step 7 of the experimental procedure. Temperatures will be recorded by the DAQ and software for the whole cycle. Each point's temperature profile will be used to compare against other temperature profiles within the chamber and with the temperatures used by the controller system. With the data collected and graphically represented temperature profiles we will be able to accomplish the tasks listed in the purpose section. The experimental results and discussion will include:

1. The temperature distributions within the chamber along with discussion on the dominance of radiation and convection within the chamber.
2. A comparison of the temperature distribution within the oven and the temperatures reported by the controller station. The soak time is supposed to be based on the cold spot [25] and this experiment can verify if the current controller settings are meeting the required annealing conditions.
3. Identify regions with strong temperature variance and make inferences on the convection flow and radiation.

The efforts described throughout Section 2.0 were performed in parallel with efforts to identify an optimal system to replace the current furnace. As the project proceeded, the results from the two streams were compared and traded to ensure that the project remained focused and on track. The proposed system work is presented in Section 3.0 below.

# 3.0 New Design Recommendations

*N.B. Shortly before the submission of this report the Authors discovered that the proposed bell furnace designs require a vertical clearance greater than that available. This left insufficient time to pursue additional quotes or otherwise substantially alter the analysis performed. As the Client currently utilizes a bell furnace of similar dimensions in their facility, it is suspected that this requirement is a characteristic of the specific supplier in question rather than bell furnaces in general. The supplier was the sole bell furnace manufacturer to respond to the issued Request for Quote and the Authors are confident that given more time and a better response rate a suitable bell furnace alternative could be located. As such, the Optimal Design recommendation is for a bell furnace in general and should be interpreted as such. The proposal described below is used solely to illustrate possible dimensions and equipment to be examined and the costs that can be expected.*

The Authors have identified an optimal annealing furnace system, described in Section 3.1, based on currently available information and reasonable assumptions outlined in Appendix A. Due to the high-level nature of the analysis undertaken, the remaining unknowns regarding several of the quotes, and the pending results of the proposed experimental work (Section 2.5), an alternate design is described in Section 3.2 that could supplant the currently recommended design should new information come to light, the experimental results conflict with expected outcomes, or one or more fundamental assumptions prove invalid. A summary of the cost analysis performed on both can found in Section 3.3 and specific discussion of how the two designs meet or could meet the client needs is carried out in Section 3.4.

The two designs outlined in this section are not the only proposals considered. Full details of other proposals, including discussion of the scoring and selection process, can be found in Appendix A.

## 3.1 Optimal Design

Using available data and the scoring methodology described in Appendix A, a large new bell furnace was selected as the optimal design. The proposal details are provided in Section 3.1.1, while the operation of the system is discussed in Section 3.1.2, and a specific explanation of how this design meets the Client needs is undertaken in Section 3.4.

### 3.1.1 Optimal Design Description

As per Appendix A, “Bell Furnace Proposal C” by Prolific Engineering was selected as the basis of the optimal design. Dimensioned drawings of the system itself are shown in Figure 15. The proposal is for an electrically heated bell-type annealing furnace system consisting of one heating hood, one cooling hood, three bases, three inner covers, and a control panel [28].

With useful interior dimensions of 6.1’ diameter and 12.5’ height and using HTHR strip/rod type heating elements drawing 300 KW, the furnace is capable of reaching 1472 F in 6 to 8 hours, offers a maximum operating temperature of 1652 F, and an approximate total processing time of 20 hours [28]. The heating hood is only required for the initial hours of the cooling process after which it is removed and replaced with the cooling hood. Due to the multi-base setup another charge can be waiting “on-deck” on these other bases with the heating hood transferred immediately to this second load when it is safe to remove it – allowing multiple loads to be processed in parallel. Based on this system the proposed furnace should be able to achieve an estimated average production rate of 1550 lbs./hour [29].

The furnace interior is divided into two zones that are monitored and temperature controlled separately to ensure an even temperature distribution [28]. This process is managed automatically through a self-tuned microprocessor-based Proportional-Integral-Derivative (PID) controller capable of dynamically correcting for variations in temperature.

The heating hood itself is largely cylindrical in shape and fabricated from 5 mm thick mild steel plates with a heavier 16 mm bottom flange [28]. The bottom of the hood is fashioned into a knife-edge shape which enables a tight sand seal with the protective cover, thereby mitigating bottom losses [28]. As a refractory the inner surface of the hood is lined with ceramic fibre blankets secured with strong anchors to the hood itself. The inner surface of the heating hood and the outer surface of the inner cover include guides to help align the furnace when being lowered into place [28].

The heating elements have a sinusoidal shape and trace the full circumference and height of the hood to provide even heating [28]. As mentioned, the furnace is divided into two functional zones that are separately controlled using basic on/off functionality that, combined with the provided PID controller, will automatically regulate the temperature based on the selected target soak temperature [28]. These elements are specifically designed to minimize surface loading and thereby maximize the operational life of the elements.

The three included bases are all constructed of mild steel and include a thick grooved flange fitting a neoprene seal. This seal acts to contain the water cooling jacket built into the base [28], which prevents unwanted over-heating of the base and reduces bottom losses. The required water inlet and outlet connections to fill and drain this jacket are included as well. Each base also includes a diffuser and a recirculating fan [28]. The purpose of these components are to ensure an even distribution of the protective nitrogen atmosphere within the furnace and to improve circulation, convection, and therefore generate a more even temperature distribution.  The base fans are centrifugal radial flow fans driven by individual 25 H.P. engines [28].  The protective atmosphere itself is nitrogen and must be provided by the client at 1 Kg/cm2 [28].

Other miscellaneous requirements include a 210 V, three-phase, 4 wire A.C. electrical supply and a minimum 10 ton crane with no less than 14-15 m of clearance from the furnace base to the middle of the crane hook [28].  This requirement was discovered late and it was only confirmed to be notably larger than the requirement for the current furnace shortly before completion of this report.  This technically disqualifies all quotes received from this supplier. However, the discussion above regarding the construction and features of this design is not highly specialized and should present a reasonable sense of the operation of modern bell furnaces.  There is no information to indicate that the quoted costs are any more non-standard and are retained as an estimation of expected capital outlay.

### 3.1.2 Optimal Design Operation

As a bell-type annealing furnace the operation of the proposed design is functionally identical to that of the current system.  For details, please refer to Section 2.3.

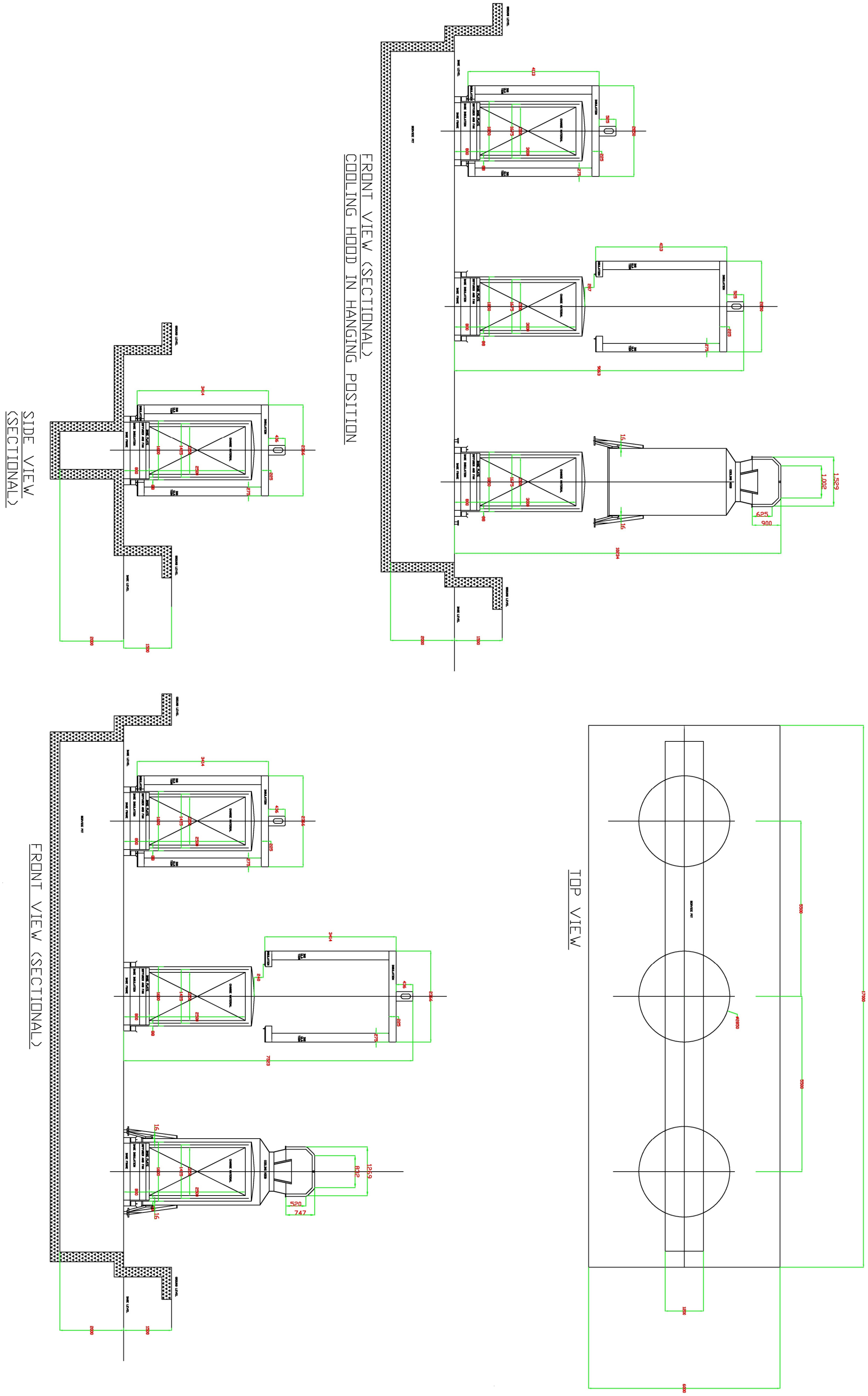


Figure 15: Optimal design dimensioned drawings [28]. Courtesy of Prolific Engineers.

## 3.2 Alternate Design

The design presented in Section 3.1 represents the Authors' best recommendation for an optimal system based on currently available information. However, several key unknowns remain regarding the system and its operating environment. These include the results of the proposed experimental work – which should indicate the areas most in need of improvement – and the Client's long-term plans. A general sense of future direction was communicated by the Client for the purposes of this report. However, the current operating conditions straddle the inflection point in the relative efficiencies of batch versus single-piece process workflows [30]. Should future growth and expansion estimates be revised conservatively the batch-style processes used by the bell furnace proposed in Section 3.1 will be the most cost-effective. Alternately, should forecasts and desired production rates be revised upward, more efficient – albeit more capital intensive – single-piece workflow designs will rapidly eclipse batch processes in desirability.

To account for this the Authors have endeavoured to present an alternate design proposed by Seco/Warwick Engineering that can be used should a situation such as that outlined above be encountered. The proposed alternate design is a rolling hearth annealing furnace (see Rolling Hearth Proposal 'B' in Appendix A) and is suitable for higher capacity production. The discussion of this system will follow the same format as that for the optimal system. Section 3.2.1 presents a description of the key components and features of the proposed rolling hearth while Section 3.2.2 lays out a detailed walkthrough of working procedure for the design. A discussion of cost considerations for both designs is found in Section 3.3, while Section 3.4 contains analysis of how both designs can specifically meet the various Client needs previously identified in Section 1.3.

### 3.2.1 Alternate Design Description

The alternate design is a controlled atmosphere roller hearth annealing furnace as per the dimensioned drawings in Figure 16. The proposal is for a full annealing furnace system including an electrically heated roller hearth annealing furnace, charge/discharge transfer tables and return conveyer, a control panel, and the installation/rigging of the previously mentioned components [31].

The furnace itself is designed for a net production capacity of 2080 lbs./hour and to accommodate loading trays 48" wide by 48" long [31]. The total design processing time for this system – including pre-heating, heating, soaking, slow cooling, fast cooling, purging, and air blast cooling – is approximately 17.5 hours [31]. This alone is an improvement over current conditions and is further enhanced by the design charge rate of 1 tray per hour [31]. Rather than large loads being completed simultaneously at 18-24 hour intervals as in the current system, individual packages of work can be completed at predictable one hour intervals.

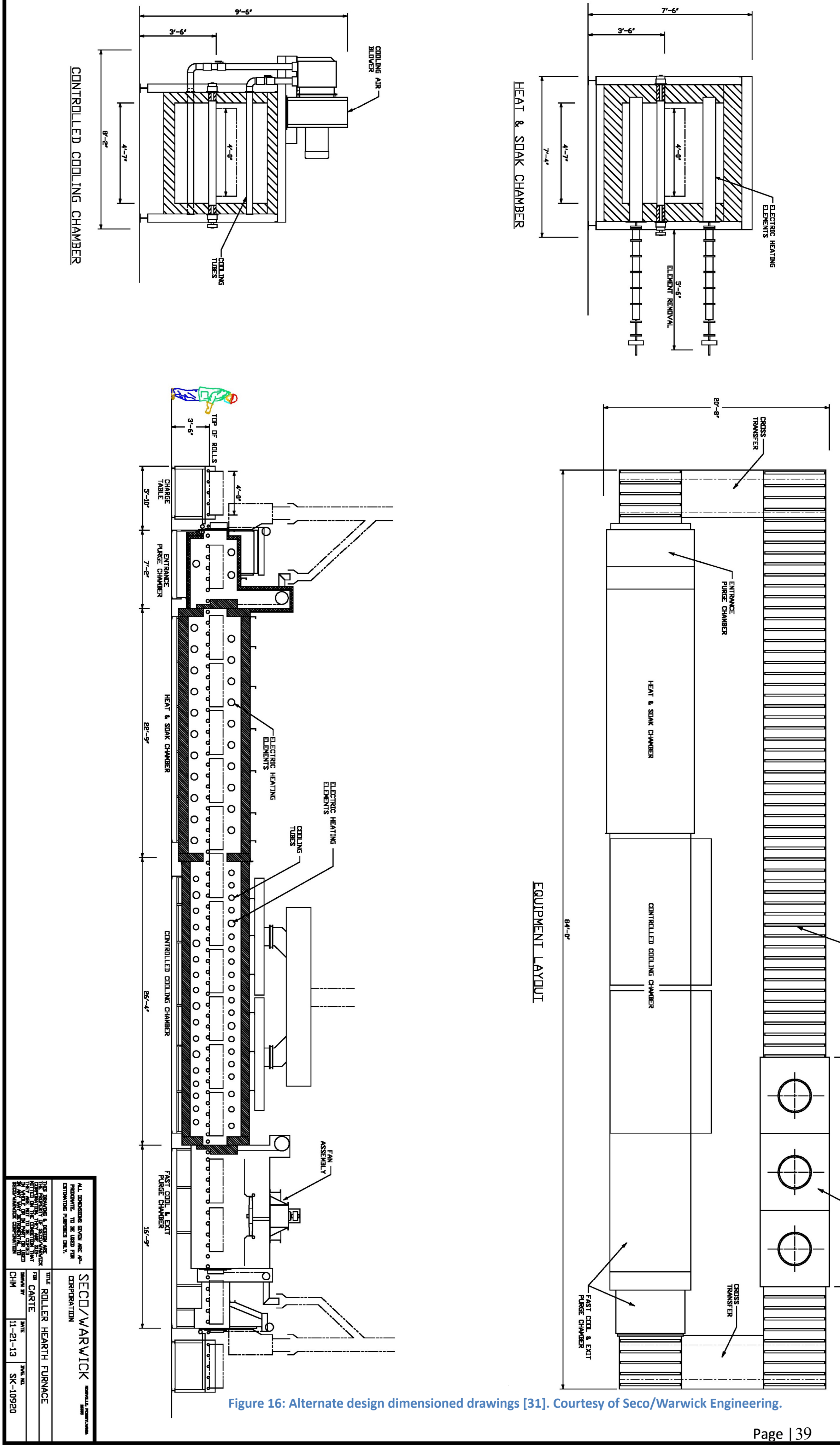


Figure 16: Alternate design dimensioned drawings [31]. Courtesy of Seco/Warwick Engineering.

#### 3.2.1.1 Furnace Chambers

As illustrated in Figure 16, the total external dimensions of this system are 84’ long and 20’-8” wide. This yields an approximate total footprint of 1736 $ft^2$, much higher than the optimal 750 $ft^2$ but still within the marginal 2000 $ft^2$. This total area is segmented into six discrete chambers, each corresponding to a stage of the annealing process [31]. Each chamber is sealed off from the others and contains an independently driven conveyer, allowing trays to be moved between and within chambers individually.

The first chamber is pre-heating, a 7’ long section fully insulated with 6” insulation on all sides [31]. The pre-heating chamber contains a single, 45 KW heating zone and maintains a nominal temperature of 500 F [31]. This serves to warm the load to a minimum temperature of 220 F [31] and thereby minimize thermal shock when transferred to the next chamber, heating and soaking.

The heating and soaking chamber is designed for a maximum operating temperature of 1600 F and a normal operating temperature of 1540 F + 10 F. The full chamber is 22’-9” long and divided into three temperature control zones, the first two of which have 9 heating elements and draw 120 KW of power and third has 3 elements and draws only 46 KW of power [31]. This chamber is also heavily insulated, with 12” thick ceramic fiber insulation on the roof and 9” thick insulating firebrick with an additional 2” thick insulating block layer on the sidewalls and floor [31]. In this region the load will be first heated to the full annealing temperature and then held there for the soak time before being transferred into the slow (or control) cooling chamber.

A major concern in annealing is preventing thermal shock and as such the load must be slowly and carefully cooled to a reduced temperature before it can be safely cooled at increased rates. This purpose is fulfilled by the control cool chamber, a two-zone chamber designed for cooling rates in the range of 125 F/hour. These two zones combined give the control cooling chamber a total length of 25’ – 2” and are each equipped with 84 KW of bayonet heating elements [31]. These elements are only required at start up to heat the chamber to the required operating temperature [31]. During normal operation the chamber is heated by the incoming trays of treated cores. Heat removal is furnished by 30 cooling tubes fed with ambient air at flow rates controlled by a variable speed fan which is in turn tied automatically to each zone temperature controller [31]. Each tube contains an individual manual damper that can be used to fine-tune the cooling rate. The chamber itself is insulated identically to the heating and soaking chamber [31].

Controlled cool is followed by the fast cool chamber. This chamber achieves high cooling rates through parallel systems. The first component is a 23” diameter, 7.5 HP, 10,000 CFM fan circulating cooling gasses directly over the work. The second level of cooling is accomplished via the double wall construction of this chamber, which allows cooling air to be circulated between the inner and outer walls and further increase heat transfer rates [31].

The final two components of the system are the exit purge chamber and the cross-transfer system. The exit purge chamber is simply a double door atmosphere lock designed to prevent air from entering the closed annealing system [31]. This leads directly into the cross-transfer system which serves the dual purposes of first transporting the trays to the air blast cooling stations and then returning the completed work to the loading/unloading point. The air blast cooling area consists of three tube axial fans, each rated at 11,000 CFM and powered by 5 HP motors, that pull room air up through the load and then discharge it into the room above the furnace [31]. This serves as the final cooling stage and returns the completed loads to room temperature.

#### 3.2.1.2 Roll/Drive System & Doors

Tray movement within and through the annealing furnace is accomplished via a motor-operated chain-driven drive system [31]. The rolls are mounted on 15" centres with bearings mounting on cast aluminum air-cooled supports [31]. Further, a backup compressed air system is included that can turn rolls at a low velocity in the heating and controlled cool sections in the event of a power failure. Roll materials and diameters vary between furnace sections with 5.0" outer diameter HK alloy rolls in the heating and soaking chamber, controlled cool, and fast cool chambers; 4.5" outer diameter HK alloy rolls in the pre-heat and exit purge chambers; and 4.0" outer diameter steel rolls for the return conveyor [31].

The doors separating each chamber are electric motor driven and automatically controlled by limit switches [31]. These include operation interlocks matched with the movement of the trays on the rolls to maintain isolation of each chamber.

#### 3.2.1.3 Protective Atmosphere

The roller hearth furnace is designed for use with a protective gas atmosphere and will accept high purity nitrogen or similar gas sources to be supplied by the Client [31]. Gas usage for this system is estimated at 3,225 ft3/hour [31].

#### 3.2.1.4 Tray Sensing

At all times during operation the location of each furnace tray is monitored by a system of sensors and programming logic [31]. In this way the system regulates when to open and close each door, preventing jams and downtime. Additionally, the position of each tray is dynamically indicated on the control panel [31]. A hard brick "rub rail" extending the entire length of the furnace acts as a protective bumper and prevents tray impacts from damaging the interior surfaces of the furnace [31].

#### 3.2.1.5 Monitoring, Controls, and Alarms

A full monitoring system is included with the proposed design, including an Allen-Bradley programmable logic controller and software, individual controllers for excess temperature control of each temperature zone, an uninterruptible power supply, and a personal computer for interfacing with the equipment [31]. A number of operator interface screens are standard with the proposal including a main furnace display, motor control display, heating element status, active alarms, heat control, roller drive control, historical trending data display, maintenance display, and others. Additional displays can also be added as per the needs of the Client [31].

An important feature included with the monitoring hardware is “recipe integration”. Recipe integration allows processing parameters – soak time and temperature, cooling rate, etcetera – to be programmed in for various products, materials, or dimensions [31]. When a tray of given product is being loaded, the operator need only select from the list of entered products and the appropriate parameters will be automatically loaded and associated with that tray [31]. An additional benefit of recipe integration lies in its ability to allow automatic transition of the furnace from idle to full production mode and back again [31].

#### 3.2.1.6 Safety and Security

The control system includes interlocks tied to operational parameters that can automatically shut down the entire system or a specific subsystem if critical values are exceeded [31]. Security logins and other safeguards can be activated to prevent unauthorized access to the furnace controls [31].

### 3.2.2 Alternate Design Operation

A rough outline of the system operation was communicated in Section 3.2.1, however, a systematic walkthrough of the annealing process using this rolling hearth furnace is undertaken here. It is worth reiterating that the lengths given for various stages assume standard usage at the design speed and production rate. The furnace is fully adjustable and capable of operating under other conditions if desirable, but this will necessarily effect the specifics of the treatment performed though not the general process. The step-by-step procedure listed below is adapted from [31].

1. A tray of cores (Tray 1) is loaded and the operator selects the menu entry (if applicable). Tray 1 advances into the Pre-Heat Chamber which is large enough to hold one tray at a time.
2. Tray 1 is preheated to a minimum temperature of 220 F (approximately 60 minutes) and is then automatically moved into the first of five available tray positions in the heating and soak chamber. The next tray (Tray 2) enters the pre-heating chamber.
3. While Tray 2 is preheating, Tray 1 advances through the heating and soaking chamber at a rate of 52” per hour.

4. After 60 minutes, Tray 1 has entered the second tray position in the heating and soaking chamber and Tray 2, having finished preheating, moves into the first position in the heating and soaking chamber.
5. The process of one new tray entering the heating and soaking chamber every hour will continue as long as there is waiting product.
6. After approximately 120 minutes (two hours) in the heating and soaking chamber Tray 1 will have reached the soaking temperature (1540 F) and will continue to advance at the nominal speed for the two hours of required soak time.
7. After two hours of soaking (four hours of total heating and soaking time) Tray 1 will enter the first of six available tray positions in the control cool chamber and will be moved further along as following trays exit the soaking chamber and enter the control cool chamber.
8. After six hours in the controlled cool chamber Tray 1 will have cooled sufficiently to avoid thermal shock – a bulk temperature of approximately 845 F – and will advance into the first of two available tray positions in the fast cool chamber.
9. The tray will spend two hours moving through the fast cool chamber until its temperature has dropped to approximately 500 F and will then move, briefly, into the exit purge chamber.
10. Tray 1 is transferred via high-speed drive to the cross transfer system which will transfer each tray in turn to one of the four available air blast tray positions.
11. The air blast system will finish cooling the cores to ambient temperature in approximately four hours, at which point the trays are transferred to the unloading point and removed from the system.

Allowing for 30 minutes of waiting in the exit purge system, should an air blast position not be immediately available, and summing the durations of each phase yields the previously mentioned 17.5 hours total processing time.

Having fully discussed the physical details of both the Optimal and Alternate systems it is necessary to turn one's attention to economic and cost considerations.

## 3.3 Cost Considerations

When comparing several annealing furnaces, various factors need to be considered which contribute to the final decision of selecting the best furnace. Cost evaluation is critical when making the decision of what type of furnace best suits the situation in order to maximize future profits. For this analysis factors such as initial costs for the equipment and installation, the energy cost of operation, and maintenance costs have been considered.

This section shows a selection of results for the optimal and alternate designs. Full discussion of the analysis details, and the results for the various other designs considered, can be found in Appendix A. Table XIII shows the power, maximum core size and production capacity per hour for these two final designs.

TABLE XIII: KEY COST PARAMETERS FOR OPTIMAL AND ALTERNATE DESIGNS

| Type of Furnace | Power | Maximum Transformer Core Size | Production capacity per hour | Expected Life |
|---|---|---|---|---|
| **Optimal Design** | (300kW) | 1500mm X 3000mm | 1550 lbs./hr. | 25-30 years |
| **Alternate Design** | (520kW) | 1066.8mm X 1066.8mm | 2080 lbs./hr. | 40-50 years |

The cost analysis can be divided into two main components. First are the initial or capital costs, addressed in Section 3.3.1, and second are the operational costs, consisting chiefly of maintenance and electrical costs, and discussed in Section 3.3.2. Section 3.3.3 briefly addresses possible environmental concerns and finally Section 3.3.4 attempts to quantify the long-term financial feasibility of the two designs.

### 3.3.1 Capital Costs

The first obvious cost is the initial capital cost for the equipment and the installation associated with the furnace. As per this project the client has allocated a capital budget of $800,000 and this will play a critical role in evaluating options and making the recommendation. The total capital cost of the two new furnaces are shown in Table XIV. The initial cost of the optimal design includes the cost of the furnace, freight and insurance costs required to bring the furnace to the Client while the alternate design capital cost consists of parts, assembly, and training. It should also be noted that the optimal design was quoted in USD and converted to CAD for this analysis.

TABLE XIV: CAPITAL COSTS OF OPTIMAL AND ALTERNATE DESIGNS

| Type of Furnace | Capital Cost |
|---|---|
| **Optimal Design** | $452,000 USD ($475,000 CAD) |
| **Alternate Design** | $1,397,000 CAD |

Installation of the new furnace will require the demolition and clearance of the current set up and the installation of a new gas piping system and exhaust system. Installation of the alternate design would require additional space as it is larger than the current floor space designated to the annealing process. For this study, it is assumed that the cost of clearing the space will be covered by the recovery value of the current furnace.

### 3.3.2 Operating Costs

Operating costs are the ongoing expenses associated with normal use of the equipment. This includes a variety of components including utilities, ongoing maintenance, labour, raw materials, and more. For the purposes of this analysis only two main components were considered: energy costs and maintenance. Each of these components are considered separately below.

#### 3.3.2.1 Energy Costs

Energy consumption costs over the operational life of the furnace need to be considered. Selecting an efficient furnace can decrease the cost of energy. In this study of cost analysis, the economic factors that that would lead to fluctuation in energy prices have not been considered as these cannot be easily predicted.

Manitoba Hydro's standard industrial rate scale was used to calculate the costs and details of the calculations performed can be found in Appendix A. Table XV lists the estimated annual energy costs for both designs.

TABLE XV: ESTIMATED ANNUAL ENERGY COSTS FOR OPTIMAL AND ALTERNATE DESIGNS

| Type of Furnace | Estimated Annual Energy Costs ($) |
|---|---|
| **Optimal Design** | 42,294.00 |
| **Alternate Design** | 115,296.00 |

#### 3.3.2.2 Maintenance Costs

Another key component of the ongoing expenses associated with a furnace are the operational and the maintenance costs. Regardless of the type of furnace recommendation made, there will inevitably be required maintenance. Components that likely need to be changed are the thermocouple, charge plates and painting of the furnace to minimize the heat loss from the furnace to the surroundings. Some parts may fail due to fatigue and procedures need to be laid to allow maintenance to detect such failures. The maintenance costs the Client currently pay are approximately $60 per hour and they perform four hours of maintenance every year. The maintenance cost is not likely to affect the decision of recommending the best furnace as it would apply to every design selected. The actual cost of maintenance will vary but the cost should not exceed $500 per year. The operational cost for the Client would be calculated on the basis of how many hours the furnace is in operation per year. Currently, the Client uses the furnace for 16.5 hours per day. The furnace is in operation for six days per week and they operate for 50 weeks a year as they usually shut down for two weeks to carry out the necessary maintenance.

Table XVI shows the major maintenance cost associated with the optimal design, as communicated by the supplier. When calculating the total maintenance cost of the bell furnaces, the lower value of expected life was used – see Appendix A for details.

TABLE XVI: OPTIMAL DESIGN MAINTENANCE REQUIREMENTS

| Type of Maintenance | Cost | Expected life |
|---|---|---|
| **Impeller** | $3800 | 1-2 years |
| **Fan assembly** | $8500 | 3-4 years |
| **Inner cover** | $25000 | 5-6 years |
| **Heating elements, insulation, holding system** | $35000 | 4-5 years |
| **Thermocouples (every base has one and the furnace has three)** | $500 | 1-2 years |
| **Temperature controllers** | $140 | 2-3 years |
| **Programmable controllers** | $500 | 2-3 years |
| **Neoprene seal** | $1000 | 1 year |
| **Labor** | $500/year | - |

For the alternate design, the maintenance and operational costs are estimated to be 1-2% of the initial cost per year [32]. For the purposes of this analysis the maintenance costs for all rolling hearth furnaces were assumed to be equal to 2% of the capital cost of the most expensive proposal. This was based on the assumption that all roller hearth designs would have similar maintenance requirements and the desire for a conservative, high-end estimate. Table XVII summarizes the expected maintenance costs for the alternate design.

TABLE XVII: ALTERNATE DESIGN MAINTENANCE REQUIREMENTS

| Type of Maintenance | Cost ($/year) |
|---|---|
| **General Maintenance (1-2% of capital cost)** | 40,000.00 |
| **Regular minor Maintenance (Greasing of bearing, etc.)** | 500.00 |
| **Labor** | 500.00 |

### 3.3.3 Environmental Costs

The final major cost considered in this furnace redesign is the environmental cost. Again, this cost will affect the decision as codes and standards require minimum energy efficient system that can actual be used. The environmental cost as this point time is unknown and it is assumed that the electricity is fairly environmental friendly. Changes in codes and standards are likely to affect this cost and therefore it will be a better idea to aim for the maximum efficiency of a furnace.

### 3.3.4 Payback Period

Sufficient data was not available to quantify positive cash flows associated with the various designs. Lacking these it was not possible to directly calculate the payback period. To solve this issue an alternate hybrid metric was developed.

The chosen metric is based on normalizing the Present Worth of Costs (PWC) of each design by their respective approximate annual production rates, with the resulting ratio having units $/lbs./year and denoted as PWC*. This was rationalized on the basis that the ratio of PWC to production rate represents the average dollars per pound of revenue that must be generated for a particular design to break even over its lifespan. Hence, a design with a lower PWC* value would have a shorter payback period for a given revenue/lbs. This metric has its own limitations in that it assumes that each design would be operated at its design production rate, which varies dramatically between various designs. Additionally, the level of detail available regarding expected costs varied between designs and as such the relative expense of individual designs may be over- or under-estimated. Regardless, for the purposes of this analysis it was considered an acceptable metric.

The calculations used to obtain the PWC* value are detailed in Appendix A; however Table XVIII summarizes this and other calculated values for the optimal and alternate designs.

TABLE XVIII: FINAL COST CALCULATION SUMMARY

| Cost | Optimal Design | Alternate Design |
|---|---|---|
| **Capital Cost ($)** | 475,000 | 1,397,000 |
| **Maintenance Cost ($/year)** | 20,208 | 41,000 |
| **Energy Cost ($/year)** | 42,294 | 115,296 |
| **Annual Production Capacity (lbs./year)** | 6,249,600 | 12,480,000 |
| **Annual Energy Cost ($/lbs./year)** | 0.0067 | 0.0092 |
| **Present Worth of Costs ($)** | 1,059,205.24 | 2,815,700 |
| **PWC* ($/lbs./year)** | 0.17 | 0.23 |

The data in Table XVIII indicates that based on currently available information the optimal design represents the most cost-effective alternative, both immediately and over the lifetime of the system. This is indicated both by the lower initial (capital) costs required for the optimal system as well as the lower PWC*value, implying a shorter payback period for the optimal design versus the alternate design. However, the difference between the PWC* values is much smaller than that between the capital cost values – the capital cost difference is 194% of the optimal design capital cost while there is a mere 35% difference between the PWC* values. This suggests that should the higher production rates be desirable much of the larger capital expenditures require for the alternate design could be justified in the long term. Additionally, the error inherent to these calculations suggest that the actual values could be much closer to each other, or alternately much further apart. In either case the difference is small enough to warrant further analysis to more fully ascertain the long term economic feasibility of both designs.

With the details and capabilities of the alternate and optimal designs more firmly established, it is possible to directly compare these results to the required needs. This comparison is performed below.

## 3.4 Satisfaction of Needs

A detailed discussion of the identification process for Client needs, as well as the content of those needs is undertaken in Appendix A. For clarity, the needs and metrics can be reviewed in Section 1.3. Additionally, Appendix A contains further details not only on the analysis and scoring of the optimal and alternate designs, but also for additional proposals that were considered in parallel.

The metrics listed in Table II, page 5, can be grouped into 7 categories that define the overall requirements of the proposed design. These demand that the design anneals cores (1), is compatible (2), controllable (3), reliable (4), safe (5), efficient (6), and economical (7). The numbers correspond to the first digit of the metric identification numbers in Table II. In the following sections how the optimal and alternate designs do, or could, meet each need and metric is discussed within each category in the order they are listed above.

### 3.4.1 Design Anneals Cores

The ability of the design to anneal cores is adjudicated by two key needs. First, the design must be able to accommodate the largest reasonably expected core – with dimensions of 35 5/8” x 16” x 8 ½” [1] – and second, it must reliably and accurately reach the annealing temperature, between 1475 F and 1550 F [2].

The optimal design, bell furnace proposal ‘C’ in Appendix A, meets both of these criteria handily. The internal usable space is roughly cylindrical with a diameter of 59.06” and a height of 118.11” [28]. Thus it is more than capable of accepting even the largest cores. Fitting a large number of these cores simultaneously could still prove challenging, but as cores of this size are not overly common it is not expected to be a serious issue. Additionally, reaching the target temperature is not a problem for this design as it has a design maximum operating temperature of 1652 F [28], over 100 degrees above the upper end of the annealing temperature range. It is not currently known what the accuracy of this furnace is regarding target versus actual temperature, but this can be easily verified with the supplier before an order is placed.

The alternate design, rolling hearth proposal ‘B’ in Appendix A, is not expected to present any greater difficulties in meeting either of these requirements. The sizing of the furnace was performed with these maximum dimensions in mind and, as such, it is designed to accommodate trays 48” x 48” [31], large enough to comfortably fit the largest expected cores. The specific vertical clearance available is not known. However, the lack of this information is purely due to the late receipt of this quote in the project and is once again something that can be easily verified with the supplier. It should also be noted that as the vertical clearance required even for the largest of cores is only 8 ½” it is not unreasonable to assume for the sake of this analysis that the required vertical clearance is feasible and present. With a design operating temperature of 1540 F (+10 F) [31] the thermal operating abilities of the alternate system are also well within the desired range.

### 3.4.2 Design is Compatible

Compatibility is a measure of how well the design would work within and with the existing shop floor layout. The first of the two needs in this category is the requirement that any proposed design fit within available floor space. This ranges from the optimal value of 750 $ft^2$, representing the approximate footprint currently utilized by the core annealing shop, to a marginal value of 2000 $ft^2$ accounting for an enlarged area added by planned plant expansions. The second need is that the design must fit with existing workflow. This is somewhat subjective in that it refers to anything ranging from compatibility with plant infrastructure to whether drastic and negative changes would be required to the layout and workflow of the plant in general to accommodate it.

Regarding footprint the optimal design is almost ideal in that, as a very similar system to that currently used by the Client, the required footprint is not expected to vary greatly from the current 750 $ft^2$ value. The bell furnace's compatibility with current workflow is more complicated. Of the considered designs, bell furnaces are undoubtedly the most compatible with the workflow and processes currently used within the core annealing shop, as the current system utilizes a bell furnace and the processes used would likely require few substantive modifications. Conversely, one of the key reasons for the Client's interest in a new furnace is that while the plant at large has been "leaned-out" and is progressively moving towards single-piece workflow, the core annealing shop is locked into batch-processing due to their use of a bell furnace. While replacing the old bell furnace with a new, updated bell system would require much less disruption in the short term, it would commit the Client to extending the incompatibility issues between the core annealing shop and the rest of the facility into the foreseeable future. It is the conclusion of the Authors that this is outweighed by the much larger barrier to entry present with single-piece workflow furnaces compared to traditional batch systems. However it speaks to the precarious edge that this conclusion stands on – and the ease with which changes to growth forecasts or the results of current system analysis could tip the balance in the opposite direction – that it was felt imperative to include a detailed analysis of an alternate system.

The dichotomy between the operations of the optimal and the alternate designs is clearly demonstrated in this category. The alternate design requires an estimated footprint of 1736 $ft^2$, which much larger than the optimal but within the 2000 $ft^2$ marginal value. This value still indicates that installation of this system would necessitate utilizing a large percentage of the space added by planned expansions and also extensive modifications and rearrangement of the core annealing shop and surrounding workstations would be required. However, should this be undertaken and completed the ability of the rolling hearth design to provide regular single, or near single, piece output and to tailor each annealing cycle to the specific materials and dimensions of the cores being annealed would likely prove a much better long-term fit for the workflow desired by the client.

### 3.4.3 Design is Controllable

The only specific need under the controllability category is that the design must provide some type of operator input/output. However, implicitly built into this category is also some measure of the degree to which control is afforded, what kind of data can be displayed, how it can be presented or processed, and in general how finely the operator can adjust the operation of the machine for various conditions.

In this regard the optimal design offers nearly identical options to the furnace currently used. Operators can enter a target temperature and the system automatically monitors the temperature in each of the two temperature zones and adjusts using basic on/off commands accordingly. A basic control system is included which displays the temperatures measured in each of the zones and the status of key mechanical and thermal components of the system throughout the annealing process.

The control options offered by the alternate design are numerous and of very fine detail. Overall production times and the duration of specific stages of the annealing process can be modified at will, additionally cooling and heating rates can be adjusted for specific circumstances. A key feature is the ability to store a library of “recipes” for various products. When a tray of cores of a given material or dimensions are loaded the operator can simply select the appropriate item from a list – assuming it had been entered previously – and the pre-set operating parameters for that product will be automatically set and associated with that particular tray. A variety of monitors and data outputs are also offered and are discussed in depth in Section 3.2.1.5.

### 3.4.4 Design is Reliable

Reliability is a key issue as broken or otherwise unusable equipment is akin to setting money on fire. Hence, a high priority was given to this category and it was judged based on the expected operational lifespan of the design – with a marginal value of 30 years and an optimal value of 60 or above – and the required annual downtime for maintenance, repairs, and overhauls. The metric for this second need was given an optimal value of 10 days per year and a marginal value of 14 days per year. This was based on the currently required maintenance schedule for the existing furnace and a desired 25% improvement in overall performance.

The operational lifespan for the optimal design was estimated by the supplier as 25-30 years, with the addendum that regular maintenance could increase this value [33]. Thus it can be reasonably expected that this design will meet at least the marginal lifespan of 30 years, assuming recommended maintenance is followed. While the short lead time from the alternate quote did not allow a specific lifespan estimate to be obtained from the supplier, discussions with suppliers of similar systems indicated that most roller hearth furnaces can reasonably expect to continue operating for 40-50 years with regular maintenance [34], allowing a reasonable estimation of the alternate design's lifespan to be put somewhere in the mid to high range of the optimal value.

Information regarding the specific required annual maintenance downtime for the various designs could not be located. This is very dependent on the specific operating conditions of the furnace in question and, while something that would ideally be clarified as part of a continue quotation process, was evaluated heuristically based on available knowledge for the purposes of scoring and ranking the examined designs. Details of this process are available in Appendix A.

### 3.4.5 Design is Safe

Safety is tantamount above all other concerns and this category was given the highest priority. Evaluation was based on three specific needs, the design must protect the operator from heat – based on the observed temperature at the operating station during the annealing process – it must use gasses safely, and it must allow some form of emergency shutdown.

Data on the externally experienced temperature for the various designs could not be located as this was not information that suppliers had readily available and time constraints eliminated any options for deeper engagement. This metric was evaluated heuristically using available data, with full details available in Appendix A. Should additional time have been available, retrieving specific data on this metric would be of high priority.

While the optimal design does not include a manual emergency override in the system controls, Miniature Circuit Breakers (MCBs) are included at key points within the electronic system. If a fault is trigged for any reason, these will automatically shut off the furnace to prevent injury or damage to the system [35]. Furthermore the supplier has stated that relevant gas standards are adhered to and that pressure switches are installed throughout the gas system to shut off gas flow in case of fault or excess pressure readings [35]. However this has not been confirmed by the Authors.

Some details of the safety systems present in the alternate design are missing due to the short turnaround time previously mentioned. However, available data is promising. Provided information on the insulation materials and methods used – described in Section 3.2.1.1 – suggests that heat loss is not likely of a critical or dangerous magnitude, alleviating concerns of unsafe operating temperatures outside of the furnace. The proposal also indicates that relevant ventilation standards related to the use of dangerous gasses are followed [31]. Finally, detailed information is provided on the various interlock and automatic failsafe systems included in the alternate proposal. Key parameters are automatically monitored by the system and should critical values be exceeded the system has the ability to immediately shut off the entire system, or the specifically affected subsystem, to prevent damage, loss of production, or injury to site personnel [31].

### 3.4.6 Design is Efficient

Efficiency is less targeted at the ability of the design to perform a task than at the ability of the design to perform it well. The evaluation of this ability is based on three specific needs, specifically requiring that the design must be able to accommodate the expected work volume, that it process cores quickly, and that it deliver a uniform temperature distribution.

The production rate of the optimal design was calculated as approximately 1550 lbs./hour (See Appendix A) which is less than the marginal value of 2000 lbs./hour. This was not felt a major concern for two reasons. The first is that when the desired production rate was calculated a substantial safety factor was added to account for future growth and to generate a conservative estimate – the actual value may be lower than this. The second reason is that if additional production is required the final design can be easily scaled up by the supplier before the project is accepted. The total processing time for the optimal design was estimated at approximately 20 hours. This is within the 14-24 hour range of acceptable processing times and represents an improvement over current practise. Finally, the experimental data necessary to determine the temperature distributions within the furnace could not be obtained by the supplier in time for the submission of this report. Based on the multiple temperature zone PID control system used, as well as the addition of a protective atmosphere recirculation fan, the Authors are confident that the temperature distribution achieved by the optimal design will represent a substantive improvement over current practise.

The ability of the alternate design to meet these requirements is similarly well supported. The proposal was specifically designed with an operating capacity of 2080 lbs./hour to meet the requested production capacity. Further, this can be modified up or down, within reason, by adjusting annealing times and load sizes. Should production rates be substantially underestimated rolling hearth furnaces with production rates of 3000 lbs./hour or more are feasible and well documented [36]. Nominal processing time, based on design production rates, is given by the supplier as 17.5 hours [31]. This includes preheating, heating, soaking, slow and fast cooling and represents a notable improvement over the currently used system. Finally, much like the optimal design it was not possible to get firm data on the temperature distributions experienced within the furnace. However, the relatively small volume of each chamber, the horizontal orientation of the furnace, and the high level of automatic temperature control included are indicative of a system designed to minimize non-uniformity in temperature distributions.

### 3.4.7 Design is Economical

In a side by side comparison the alternate design may seem a superior choice over the selected optimal design. The reason the alternate was not selected as the optimal can be found in two areas. First are the already discussed compatibility and space concerns. The second is cost and financial matters. The economic feasibility of the project is paramount as even the most ideal system is useless if it is out of financial reach. Three metrics were used to assess this category. The first is a direct measure of the required capital outlay, the second examines the annual or average hourly maintenance costs, and the third demands a reasonable buyback period for the design.

Details of the economic analysis of the Optimal and Alternate designs have already been presented in Section 3.3. Further details on these calculations and similar analysis for other considered proposals can be found in Appendix A. The conclusion of this analysis is that based on currently available information the optimal design provides the greatest cost-effectiveness. However, when examining costs over the lifetime of the system the analysis suggests that should the expanded capacity of the alternate design be required, and the capital cost and logistical modifications be overcome, the benefits of the single-piece workflow system may outweigh the costs. However, this must be confirmed through a deeper follow up analysis.

In all three economic metrics the optimal design outscores the alternate and is within the desired ranges. The capital cost for the optimal design is quoted by the supplier as approximately $475,000.00 CAD [28], 41% under budget. Total annual operating and maintenance costs of this design were calculated as $62,502/year. Assuming 140 hours of usage a week and 50 weeks of work per year it was estimated that the furnace is in operation for approximately 7000 hours per year. From this an average hourly operating and maintenance cost of $8.93/hour was calculated, well below the $45/hour optimal value. The difficulties in calculating payback period, and the rationale for the selection of PWC* as an interim metric are detailed in Section 3.3 and Appendix A. Based on that discussion it is sufficient to note that the calculated PWC* for the optimal design ($0.17/lbs./year) is lower than that for the alternate design ($0.23/lbs./year) implying that the optimal design would have a shorter payback period than the alternate for a given revenue per pound.

The alternate design is hampered by the large capital cost required, $1,397,000.00 CAD [31] – 75% over budget. In this regard the alternate design is not able to meet the Client needs. Should the positive aspects of this design - namely higher production rates, singe-piece flow, and highly detailed process control – be desirable to the Client this cost barrier will have to be overcome. In operational costs the alternate is again more expensive than the optimal, with total operating and maintenance costs calculated at $156,296/year. Making the same assumptions regarding 7000 hours of operation per year, an approximate hourly operating cost of $22.33/hour is obtained. This is notably higher than for the optimal design but still less than half of the optimal metric value of $45/hour. As previously discussed the PWC* for the alternate design is $0.23/lb/year – higher and therefore less desirable than that for the optimal.

Compared to the difference between the maintenance and capital costs for the optimal and alternate designs the PWC* values are closely grouped. The indication found from this fact is that much of the additional costs involved with the alternate design are justified by its improved performance, operation, and lifespan over the optimal. Acknowledged gaps and assumptions in this analysis, coupled with the varying level of information detail available for the various designs, could potentially add a significant plus or minus to these values and the actual PWC* values could be much more similar than currently thought – or alternately much more varied.

Regardless, these results indicate that in the short term the alternate design does not meet the Client requirements for economic feasibility, particularly when compared to the optimal design. However, in the long term analysis if the increased capacity is required and the logistical and capital cost requirements overcome, the benefits of the Alternate design may outweigh the costs. Should this option be considered by the Client further economic analysis is warranted to refine these conclusions and more reliably ascertain the long term costs and benefits of each design.

# 4.0 Summary & Conclusions

The Client requested the assistance of the Authors for the purposes of assessing the status and condition of their current electric bell annealing furnace and recommending corrective action, specifically in the form of a replacement furnace. This task was of significant complexity and import, involving the assessment of legacy equipment with incomplete records, understanding and synthesis of Client requirements and processes, and the adjudication and recommendation of a replacement design to satisfy these needs and remain the optimal decision over a 25 to 50 year lifespan.

To address these various needs a wide range of tasks were undertaken by the Authors. All available data on the existing furnace has been collated and organized to the best of the Authors' abilities, providing a centralized resource on the key components of the existing system. Further, operational procedures – both recommended and currently utilized – the condition of critical components, and a brief history of significant retrofits and modifications that have been undertaken on the furnace during its known operational history have been summarized. Additionally a Failure Modes and Effects Analysis (FMEA) was performed to identify vulnerabilities in the current system and recommend relevant corrective action. A full experimental design has also been completed to provide the Client with a test framework allowing them to test the validity of concerns regarding the uniformity of temperature distributions within the current furnace.

Based on the data and results extracted from these efforts, a set of Client needs were identified and quantified, quotes were obtained for various replacement options and then scored against these needs. In the final analysis a recommendation was made to replace the current furnace with a newer electric bell furnace and that the existing batch-type process should be retained. The bell furnace was found to be optimal by providing acceptable capacity, reliability, and efficiency for costs well within the capital budget and maintenance requirements of equal or lesser expense and difficulty than the current system.

The critical qualification was made that this recommendation is only based upon currently available information and that current Client operations and projections are in the transition zone between batch-optimal and single-piece-optimal production. An alternate design, consisting of a rolling hearth annealing furnace quoted by Seco/Warwick Corporation, was also presented for this reason.

Should projected production rates have been underestimated, or Client operations or projections otherwise become more optimistic or aggressive, bell furnaces and the batch-processing they utilize will become progressively more unwieldy and the increased cost and complexity of rolling hearth furnaces more justified. By allowing single-piece workflows rolling hearth furnaces can minimize inventories and streamline production lines at high production rates when used in conjunction with other lean manufacturing methods.

Before either recommendation can be acted upon key areas of work remain that must be completed. The experimental design created by the Authors for the Client could not be performed within the time available. All equipment and procedures have been procured and identified but it remains for the Authors to perform the experiment in the coming weeks. Further engagement with suppliers by the Client would also be highly advisable. Annealing furnaces are highly customized to the needs of each client; in the interests of expediting the process of quote creation high-level general designs were pursued. This often required assumptions to be made about the performance or operation of various components and designs where data was not available. Every effort was made to ensure assumptions were reasonable and logical, and wherever such assumptions are present they are clearly indicated. However, a more detailed quote process with suppliers based upon these general proposals would yield much more detailed and optimized designs and enable more reliable analysis and assessment.

Finally, as mentioned the estimated operational needs of the Client are on the lower edge of the range in which batch processing rapidly becomes untenable and more expensive single-piece workflow systems become increasingly cost effective. A rough picture of the Client's future objectives and projections were provided to the Authors to facilitate this analysis. Given the inconclusive nature of the results and the long term ramifications of the final decision, a more detailed internal assessment of future projections, operational needs, and long term direction is encouraged. A more concrete picture of expected needs and requirements over the lifespan of this equipment would enable the Client to more readily ascertain the truly optimal design. In conjunction with this, a more detailed cost analysis – ideally compared to the ongoing costs of maintaining the current furnace – would provide a clearer picture of the economic environment the decision is being made in.

Regardless of the design chosen, the expected lifespan is measured in decades. This reinforces the import and ramifications of the decision to be made. Unknowns are unavoidable in engineering, and the variables only increase the further ahead one looks. In the end, all that can be done is to gather the most reliable data available at the time and to make the best decision that is possible under the circumstances. In this regard the Authors are confident that, though not every question could be answered, they have assembled the best and most complete data available. The final decision must, as always, rest with the Client.

## 5.0 References

[1] J. Bremser. (2013, October 15). “RE: Maximum Core Size / Weight?” Personal e-mail.

[2] Carlite. “AK Steel Product Data Bulletin”. Product Data Sheet.

[3] D.Kuzmenko (private communication), October 9, 2013.

[4] D. Mikita (private communication), September 30, 2013.

[5] D. Mikita (private communication), October 7, 2013.

[6] OSHA (1999, January 20). OSHA Technical Manual (OTM) Section III: Chapter 4 [Online]. Available: https://www.osha.gov/dts/osta/otm/otm_iii/otm_iii_4.html,accessed October 8, 2013.

[7] Carte International Inc., “Annealing Department Charge Load Sheet”, October, 2013 unpublished.

[8] R. Purushothaman, “*Evaluation and Improvement of Heat Treat Furnace Model*” [Online], Ph.D. Dissertation, Mft. Eng., Worcester Polytechnic Institute, 2008. Available: http://www.wpi.edu/Pubs/ETD/Available/etd-082208-114851/unrestricted/Purushothaman.pdf [accessed October 10, 2013].

[9] D. Mikita. (2013, October 17). “Financial Analysis Follow-Up.” Personal e-mail.

[10] Carte International Inc., “Core Department Floor plan,” unpublished.

[11] Carte International Inc., “Purchase order – Used annealing bell”, August 8, 1975, unpublished.

[12] Carte International Inc., “Stacking Plate Core Oven”, November 5, 2004, unpublished.

[13] R. Yanecki (private communication), October 9, 2013.

[14] Tri-Star Electric Company Ltd., “Invoice No. 11513”, March 29, 2008, unpublished.

[15] J. Cross, “Core Annealing Oven Controller”, April 11, 1984, unpublished.

[16] J. Bremser (private communication), October 9, 2013.

[17] Carte International Inc., “Core Annealing Process”, March 15, 1991, unpublished.

[18] Brunswick Steel, “Plate Invoice”, unpublished.

[19] Acme Welding & Supply, “Invoice No. 3482: Retort and Base Inner Ring”, June 23, 2010, unpublished.

[20] MZ Contracting Ltd, “Invoice No. 79376: Base Work”, April 19, 2010, unpublished.

[21] Zandrsta Farag Consultants, “Load Capacity Analysis of Stacking Plates”, 3 Nov 2004, unpublished

[22] D. Mikita (private communication), September 23, 2013.

[23] M. Adel. (private communication), November 23, 2013.

[24] L. McLean. (2013, October 10). “Steel Data Inquiry from ‘The Annealers’.” Personal e-mail.

[25] Carte International Inc., “Meeting notes with Nippon Steel”, December 9, 1991, unpublished.

[26] L. McLean. (2013, October 15). “Steel Data Inquiry from ‘The Annealers’.” Personal e-mail.

[27] Carte International Inc., “Core Department Gas System,” unpublished.

[28] M.K. Soota (private communication), November 9, 2013.

[29] M. K. Soota (2013, November 15). “Bell Furnace.” Personal e-mail.

[30] G. Poschmann (private communication), November 15, 2013.

[31] G. Poschmann (private communication), November 21, 2013.

[32] G. Stanley (private communication), November 20, 2013.

[33] M. K. Soota. (2013, November 18). “Bell Furnace.” Personal e-mail.

[34] G. Stanley (private communication), November 1, 2013.

[35] M.K. Soota (2013, November 25). “Bell Furnace.” Personal e-mail.

[36] G. Stanley. (2013, October 8). “Rolling Hearth Information.” Personal e-mail.

# Appendix A: Design Evaluations and Selection

## Table of Contents

## List of Figures

## List of Tables

## A.1 Introduction

In this project, numerous alternative were examined leading to a multi-stage scoring process that eliminated all but two optimal solutions: a rolling hearth furnace or a new bell furnace. Multiple quotes from various suppliers were pursued for each of these designs and the results were adjudicated based on their known operational parameters. This process is presented in the following sections along with the ancillary processes surrounding it. The methodology for determining customer needs, metrics, and optimal and marginal values is discussed in Section A.2, details of each of the designs are provided in Section A.3, while the specific designs are evaluated, and the optimal identified, in Section A.5.

## A.2 Selection Criteria

Before any manner of design work could be completed, it was necessary to first identify and quantify the needs of the client. This was an evolving process that has been ongoing since project initiation. The final results of these efforts are described in Section A.2.1, which describes how the needs evolved. A.2.2 lays out the development of technical specifications to complement these needs.

### A.2.1 Determination of Client Needs

Preliminary client needs were presented in the Project Definition Report. However, as the project continued further refinement and consultation with the Client led to the development of the final client needs, shown in Table I. The needs are divided into 7 categories that focus on different desirable characteristics that the proposed design must possess. These desirable qualities consist of: the ability to anneal cores or to obviate the need for annealing; compatibility with existing infrastructure and methodologies; controllability, encompassing both the ability of the operator to modify the operation of the design and the information that the design displays to the operator; reliability; efficiency; and economic feasibility. Within each of the categories one to three sub-needs are identified that specify precise areas in which the main category can be improved or optimal ways to assess the fulfillment of that main category.

### TABLE I: CLIENT NEEDS

| Number | Need | Description |
|---|---|---|
| **1.0** | **Design Anneals Cores** | **This category assesses the ability of the design to anneal cores in general, or to obviate the need for annealing** |
| **1.1** | Design accommodates maximum core dimensions | The final design must be able to handle the largest core dimensions produced by the client |
| **1.2** | Design achieves annealing temperature | The final design must be capable of reaching the required annealing temperature for the materials used |
| **2.0** | **Design is Compatible** | **This category assesses the compatibility of the design with existing infrastructure and methodology** |
| **2.1** | Design fits in available footprint | The final design must fit within the allowable floor space in the factory |
| **2.2** | Design fits existing workflow | The final design must mesh with existing or desired productions methods |
| **3.0** | **Design is Controllable** | **This category assesses the ability of the design to accept input from operators and to display outputs to them** |
| **3.1** | Design allows operator input/output | The final design must communicate status and other data to operator, and should ideally modifications to operator parameters |
| **4.0** | **Design is Reliable** | **This category assesses how reliable the design is in general** |
| **4.1** | Design has long operational life | The final design should have an acceptable predicted operational life before replacement |
| **4.2** | Design requires minimal downtime | The percentage of time the final design is in use/available for use should be as high as possible |
| **5.0** | **Design is Safe** | **This category assesses the ability of the design to operate safely and to be controllable in case of an emergency** |
| **5.1** | Design protects operator from heat | The final design must not expose operator to unsafe temperatures at any time |
| **5.2** | Design uses gasses safely | If the final design utilizes gasses, it must prevent dangerous gas discharges or ignitions |
| **5.3** | Design allows emergency shutdown | The final design must allow for the system to be immediately shut off in an emergency |
| **6.0** | **Design is Efficient** | **This category assesses how efficiently the design operates** |
| **6.1** | Design can accommodate expected work volume | The final design must be capable of processing the work flow maintained by the client |
| **6.2** | Design processes cores quickly | The final design must anneal cores to an acceptable standard in the shortest time possible, or obviate the need for annealing |
| **6.3** | Design delivers uniform temperature distribution | The final design must operate with minimal internal temperature gradients, or obviate the need for heat treatment |
| **7.0** | **Design is Economical** | **This category assesses the economic feasibility of the design** |
| **7.1** | Design has capital cost within budget | The final design should require a capital investment less than or equal to the available capital budget |
| **7.2** | Design has minimal operating costs | The final design should be as inexpensive to operate as possible |
| **7.3** | Design has acceptable buyback period | The design should "pay for itself" within a reasonable period of time, and much less than the expected operational life |

### A.2.2 Determination of Technical Specifications

Once the needs were finalized metrics were selected for each one, representing the optimal method of measuring that need. For each of these metrics technical specifications were identified in the form of marginal and optimal values. The result of these efforts are shown in Table II which displays the need number, the selected metric, and the optimal and marginal values for each. The optimal value represents the ideal target specification while the marginal represents the minimal (or maximum) acceptable value.

The specifications were developed from numerous sources. 1.1 was based upon the dimensions of the largest core that the client regularly produces, and these were used as optimal values. A marginal value was not felt appropriate as the goal would be to develop a design that would get as close to that as value as possible, but if the very largest designs could not be made to fit they could be fabricated using Unicore steel. Unicore steel is a high-quality steel that, due to its particular properties and structure, does not require annealing when used for larger core dimensions [1]. The values for 1.2 came from the annealing temperature range of the steel varieties commonly used by the Client while 2.1 is based on estimated available square footage from a plant layout blueprint. The optimal value for 4.1 is derived from the approximate age of the current furnace while its marginal value is based on the maximum payback period desired by the Client.

The marginal values for 4.2, 6.1, and 7.2 are based on the estimated current performance of the existing furnace, while their optimal values are calculated using the Client's desire for an overall 25% improvement over the existing system. The marginal value for 6.1 in particular was calculated by averaging daily production figures supplied by the Client then calculating an approximate hourly production capacity assuming 12 hours of work per day for a conservative estimate.

The marginal value for need 5.1 is based on U.S. government recommended values for continuous work in elevated temperature environments while 6.3's marginal value derives from research indicating that temperature variations of 10 C (+/- 5C) or more during annealing can result in defects within the steel structure [2]. Other values are based on discussion with the Client or fundamental assumptions by the team.

TABLE II: CLIENT METRICS AND TECHNICAL SPECIFICATIONS

| Number | Metric Description | Units | Optimal Value | Marginal Value |
|---|---|---|---|---|
| **1.1** | Maximum dimensions that design can accept | [Inches] | 35 5/8" x 16" x 8 1/2" [3] | N/A |
| **1.2** | Maximum temperature that design can reach | [F] | 1550[4] | 1475[4] |
| **2.1** | Approximate floor area required for design | [$ft^2$] | 750 [5] | 2000 [5] |
| **2.2** | Does design mesh with existing/desired workflow? | [Binary] | Yes | No |
| **3.1** | Does design allow controller input/offer data output? | [Binary] | Yes | Yes |
| **4.1** | Expected operational life of design | [Years] | 60 | 30 |
| **4.2** | Estimated planned downtime per year | [Days/Year] | 10 [6] | 14 [7] |
| **5.1** | Average temperature at operator station | [F] | Ambient | 80 [8] |
| **5.2** | Does design follow relevant gas safety standards? | [Binary] | Yes | Yes |
| **5.3** | Does the design incorporate an emergency shutdown feature? | [Binary] | Yes | Yes |
| **6.1** | Maximum production capacity of design | [Lbs/Hour processed] | 2500 [6] | 2000 [9] |
| **6.2** | Average total processing time for each core | [Hours] | 14 [6] | 24 [6] |
| **6.3** | Maximum temperature difference after 1 hour | [F] | 0 | +/- 9 [2] |
| **7.1** | Estimated capital cost of design | [$Cdn] | <$800,000 | $800,000 [10] |
| **7.2** | Estimated hourly operating costs | [$Cdn/hour] | $45/hour [6] | $60/Hour [7] |
| **7.3** | Estimated buyback period of design | [Years] | 15 [6] | 20 |

## A.3 Design Overviews

Two categories of designs are examined, rolling hearth and new bell furnaces. Each broad category is discussed separately and generally in Section A.3.1 and Section A.3.2. Wherever multiple quotes were obtained and important structural or functional differences exist they are discussed and identified separately within each category.

Due to the particular time constraints of this project all quotes listed below – particularly in areas of cost and operating capacity – should be taken as initial estimates. Should the Client wish to pursue one or more of the presented options further engagement with suppliers will be necessary to refine the requirements, likely resulting in various modifications to the final proposal.

## A.3.1 Rolling Hearth Summary

Rolling hearth furnaces are single-piece workflow systems that are, generally speaking, laid out in a single production line. This line is made up of an enclosed volume consisting of multiple discrete chambers each having their own set of independent rollers or conveyers. Untreated product is loaded onto one end of the system and travels along a set of conveyers through the various chambers. A common format for rolling hearth furnaces will consist of several consecutive chambers of increasing heat, soaking chambers set at the required treatment temperature, and a long cooling area where the product is gradually returned to room temperature.

Though generally cost- and space-intensive, rolling hearth furnaces are advantageous in that they offer increased efficiency over batch processes at higher production rates and provide a steady stream of finished product that can be more easily predicted and planned around.

In total, two (2) quotes were obtained for rolling hearth furnaces from two (2) suppliers.

### A.3.1.1 Rolling Hearth Proposal A (Can-Eng)

On request, Can-Eng Engineering was able to provide an initial quote and specification on a roller/rolling hearth furnace system, shown in Figure 1. Due to time constraints the proposed system is based upon a bright annealing furnace the company had earlier designed for another client. Bright annealing is a similar process to that used in this application [11], and should provide a reasonable picture of required equipment and costs.

Dimensionally the Can-Eng quoted design is approximately 122’ long and roughly 5’ wide [12] however an additional 18’ of side clearance is required to facilitate removal and replacement of U-Tubes and rolls. This yields a footprint of 2806 ft2, a prohibitively large system that likely would not fit in the current or expanded available footprint. The smallest region of the furnace identified is 60” long by 36” tall by 60” wide [12]. Though these do not necessarily represent the precise internal dimensions, even allowing for internal surfaces and wall thickness the interior clearance should be sufficient to accommodate the largest normal dimensions encountered by the Client. The internal volume can also be scaled up or down by the supplier during further consultation.

The design itself includes a digital operator interface, as well as loading, heating, soaking, and cooling components [12]. The particular system quoted is specified for 2000 lbs/hour of production [11] and the supplier has indicated that such systems can be scaled for production rates up to 25,000 lbs/hour [13].

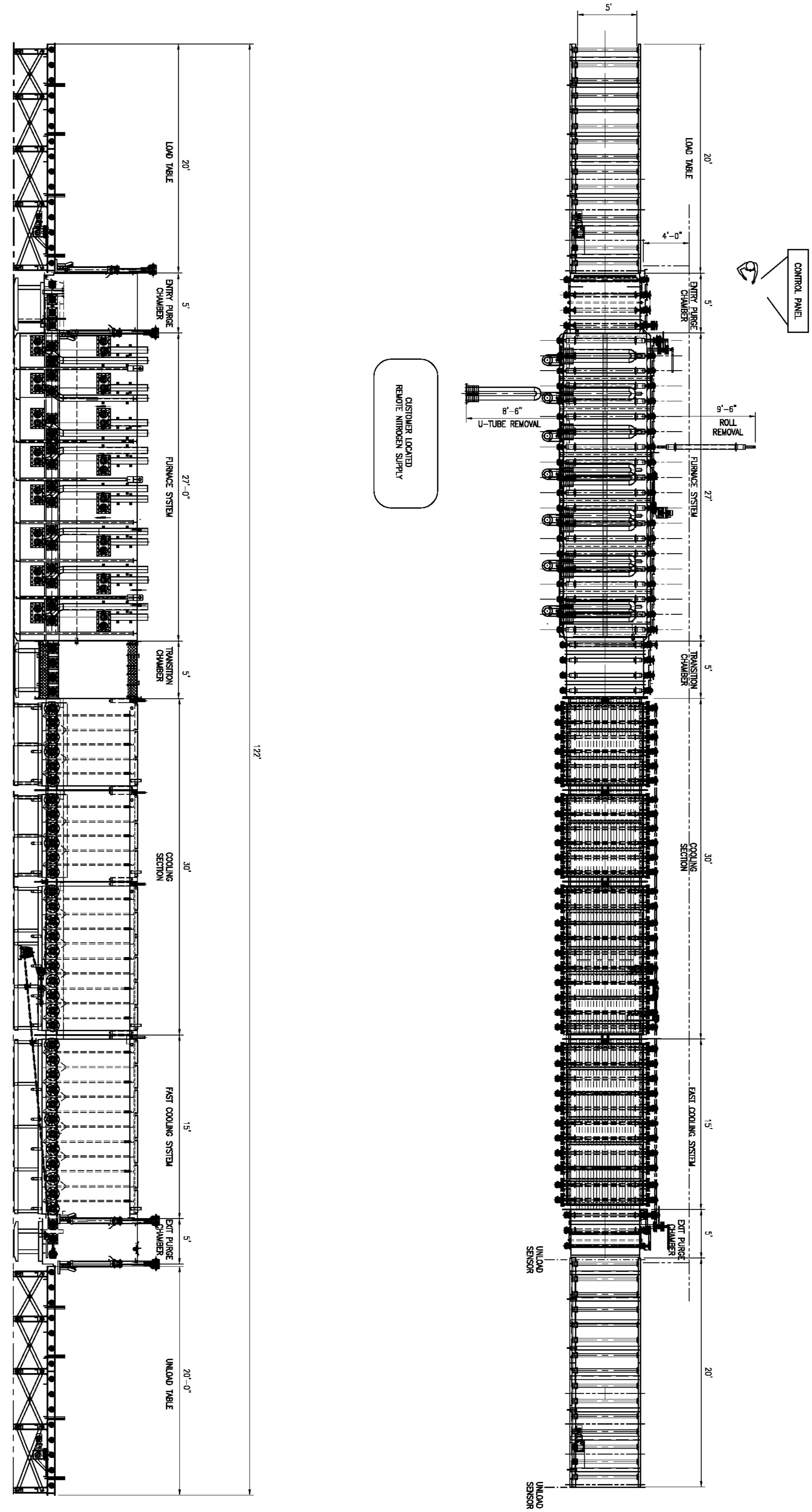


Figure 1: Rolling hearth proposal 'A' dimensions [12]. Courtesy of Can-Eng Furnaces International Ltd.

A point of serious concern must be raised regarding the economic status of this design. With a capital cost of [redacted]. Barring significant savings in maintenance or operating costs this renders the design unfeasible. However, should it yield greater benefits in the final analysis that outweigh these costs, if the Client is committed to single-piece workflow, or if the allowable capital budget increases in the future these concerns could be ameliorated. Benefits are observed with this design regarding lifespan and maintenance costs. With regular maintenance, including greasing the bearings as needed and replacing worn components as required, these systems can reasonably be expected to work reliably for 40-50 years from the time of purchase [14]. The nature of the required maintenance is not expected to be overly onerous and, averaged over the life of the machine, is estimated at 1-2% of the capital costs [14] [redacted]

Regarding compatibility and efficiency the Can-Eng design is promising. A key feature of this design, uniform across all rolling hearth furnaces, is that it is designed for single-piece workflow rather than batch processing. While the annealing process currently used by the Client is batch-based, the rest of their operations have been leaned out and are pursuing single-piece workflow. As such, while installation of a rolling hearth would require substantial adjustment to the Client's annealing processes and shop layout it would ultimately mesh much more cleanly with their operations as a whole.

In terms of safety all annealing furnaces must adhere to strict minimum standards (see Appendix B) and this is indeed the case with the Can-Eng design [14]. A full system of automated fail safes – including automatic valves and a full emergency purge – are built into the furnace [14].

Inquiries for more data have been made to the supplier, but if they are unable to furnish the required information in time for the publication of this report the design will be judged in the missing categories using the most accurate and reliable information available, as determined by the Authors' judgement and best efforts. This information could range from external sources to heuristics and logical reasoning. In all instances the Authors have endeavoured to clearly state the source of information, the reasonable level of confidence in it, and possible effects that changes in that particular value could have on the results and conclusions made herein.

Currently known and unknown specifications for the Can-Eng quoted rolling hearth annealing furnace are summarized in Table III. Unless stated otherwise, all data in Table III is from [12]

TABLE III: ROLLING HEARTH PROPOSAL ‘A’ PARAMETERS

| Parameter | Value |
|---|---|
| **Internal Clearance** | Length: 60”<br>Width: 60”<br>Height: 36” |
| **Maximum Operating Temperature** | 1650 F |
| **Required Footprint** | 2806 ft$^2$ |
| **Controls System** | Full System Included |
| **Operational Life** | 40-50 years [12] |
| **Required Downtime** | **Unknown** |
| **Heat Shielding Abilities** | **Unknown** |
| **Gas Safety** | Adheres to all relevant standards |
| **Allows Emergency Shutdown** | Yes |
| **Design Production Capacity** | 2000 lbs/hour |
| **Charge Rate** | **Unknown** |
| **Total Processing Time** | Variable – comparable to current system [15] |
| **Temperature Distribution** | **Unknown** |
| **Annual Maintenance Costs** | estimated 2% of capital cost [15] |
| **Estimated Capital Cost** | [redacted] |

### A.3.1.2 Rolling Hearth Proposal ‘B’ (Seco/Warwick)

Shortly before the project deadline Seco/Warwick submitted a quote and project proposal for a controlled rolling hearth annealing furnace [16]. The Authors’ best efforts were made to incorporate this late quote into this report and perform a thorough analysis and discussion of the proposed system. However, rigorous follow up contact was not possible in the short period between receipt of the proposal and submission of this report and, as such, certain knowledge gaps and unclear details remain. Should the fundamentals of this proposal be attractive to the Client, further engagement with Seco/Warwick would quickly fill in any missing information required.

The Seco/Warwick proposal, shown in Figure 2, has a quoted total capital cost of $1,397,000.00 CAD [16], approximately 75% over budget, but offers a production capacity of 2,080 lbs/hour, a reduced total processing time of 17.5 hours, and a charge rate of approximately one tray every 60 minutes [16]. Dimensionally, the proposed system is space intensive but still within the 2000 ft$^2$ upper limit, having a length of 84’, a width of 20’ 8” and an approximate total required footprint of 1736 ft$^2$. This space accounts for all required components of the system, including loading and unloading areas; heating, soaking, slow cool, and rapid cool sections; and a full set of control and observation panels [16].

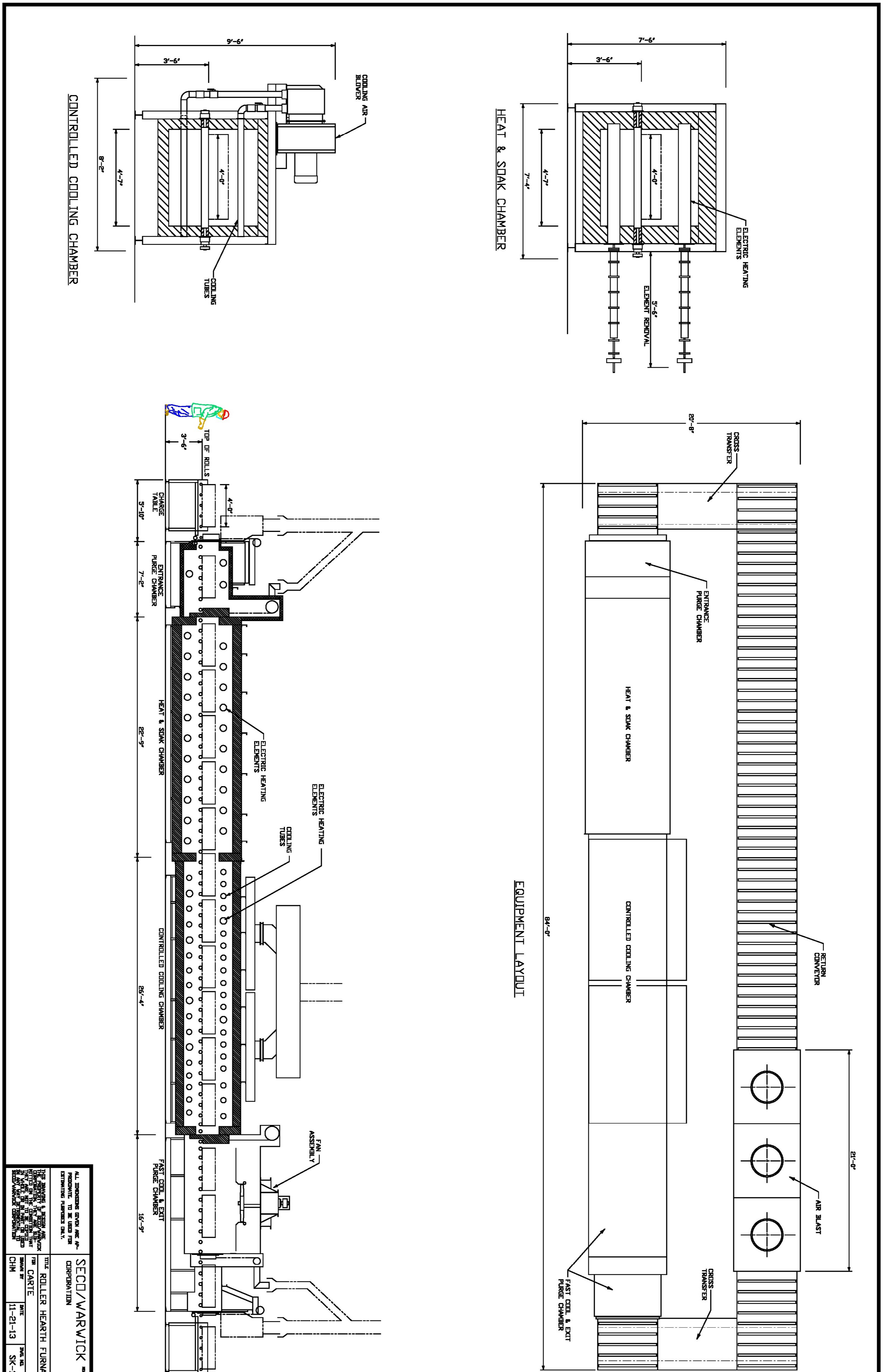


Figure 2: Rolling hearth proposal 'B' dimensions [16]. Courtesy of Seco/Warwick Corporation.

Internally the system is designed to accept loading trays 48" wide by 48" long [16], large enough to accommodate the width and length of the largest dimensioned cores expected by the Client. It is not known definitively what vertical clearance is present or whether it is sufficient to allow the expected cores sizes. As the maximum expected core thickness is only 8 ½" [3] it does not seem unreasonable to believe that this would be the case, however, should this quote be pursued the question of vertical clearance should be addressed before proceeding.

The system also includes a full control system interlock to monitor critical parameters and trigger alarms should thresholds be exceeded. In the event of a critical fault the machine or the effected subsystem will automatically shut down to prevent injury, equipment damage, or production loss [16].

Due to the lack of certain pieces of information several assumptions from the Can-Eng quote were also applied to this design for the purposes of comparison. Key examples are the assumption of a 40-50 year operational life with regular maintenance and the estimation of average annual maintenance costs as 2% of the original capital costs. Other unknown data includes required annual downtime, heat shielding abilities, and the uniformity of temperature distribution. As mentioned previously, areas of missing data were evaluated using best-efforts as determined by the Authors for each particular circumstance. Details of this process are given in Section A.5, while known and unknown parameters in the provided quote are summarized in Table IV. Unless otherwise noted, all data in Table IV is from [16].

TABLE IV: ROLLING HEARTH PROPOSAL 'B' PARAMETERS

| Parameter | Value |
|---|---|
| **Internal Clearance** | Length: ≥ 48"<br>Width: ≥ 48"<br>Height: **Unknown** |
| **Maximum Operating Temperature** | 1540 F |
| **Required Footprint** | 1736 $ft^2$ |
| **Controls System** | Full System Included |
| **Operational Life** | **Unknown (estimated 40-50 years)** [12] |
| **Required Downtime** | **Unknown** |
| **Heat Shielding Abilities** | **Unknown** |
| **Gas Safety** | Adheres to all relevant standards |
| **Allows Emergency Shutdown** | Yes |
| **Design Production Capacity** | 2080 lbs/hour |
| **Charge Rate** | 1 Tray/60 minutes at design production rate |
| **Total Processing Time** | 17.5 hours at design production rate |
| **Temperature Distribution** | **Unknown** |
| **Annual Maintenance Costs** | **Unknown (estimated 2% of capital cost)** [15] |
| **Estimated Capital Cost** | $1,397,000.00 CAD |

## A.3.2 New Bell Furnace Summary

Bell annealing furnaces are batch-process systems and the furnace type currently utilized by the Client. They generally consist of a large base on which several plates of unannealed cores are stacked. An inner cover is lowered over this stack and the heating hood is then placed over the entire stack using a crane and sealed. At this point the interior is purged of oxygen and a protective nitrogen atmosphere pumped in. The outer hood is then heated along a predefined temperature profile using various means, with gas and electric elements being common. Once the coolest part of the furnace has reached the required annealing temperature it is held steady for a characteristic length of time referred to as the "soak time". When this time has elapsed the slow cool phase begins. In slow cooling the furnace is shut off and allowed to gradually cool to a low enough temperature that exposing the annealed load to the ambient air would not thermally shock the material. Once this safe temperature has been achieved the hood is lifted off the load and lowered onto a second, unannealed load stacked on a second base – the same procedure that was followed for the first load is then repeated. Simultaneously a cooling hood is lowered onto the first load which rapidly cools the steel to ambient temperature, often through forced air convection. Once cool, the cooling hood is lifted, the cores removed, and the next load can be stacked on the base.

The general advantages of bell furnaces are that they are typically smaller and require a less significant capital outlay than comparable rolling hearth systems. Additionally, as a bell furnace is already being used by the Client they are known quantities to site personnel - thereby requiring minimal retraining. A newer design would undeniably offer notable improvements in efficiency and performance over the current equipment while retaining a sense of familiarity.

The drawbacks to bell furnace systems are that they generally offer less precise control over the annealing process and are purpose-designed for batch processing. This may be desirable under certain conditions but renders bell furnaces progressively less efficient than single-piece flow designs at higher production rates – typically at rates of 2000 lbs/hour and above [17].

In total three (3) quotations were obtained for new bell furnaces from one (1) supplier. Each of these is discussed in more detail in the following pages.

### A.3.2.1 Bell Furnace Proposal A (Prolific Engineers)

The first of three similar quotes received from Prolific Engineers is a relatively small design, with an inner cover of diameter 1250 mm (4.1') and 2300 mm (7.5') height, useful inner dimensions measuring 920 mm (3.0') in diameter and 1550 mm (5.1') in height, and other key dimensions as shown in Figure 3. The full system consists of one heating hood, 2 bases, 2 inner covers, 1 panel, and 1 cooling hood [18]. This produces a minimum required footprint of approximately 26 ft$^2$. However, the actual utilized space will likely be much higher as this does not account for loading/unloading areas, clearances between equipment, the operator station, and other necessary components. In function the size of the bases themselves are a small component of the actual required area, and as such most bell furnace designs will likely require a footprint comparable to that of the current system (~750 $ft^2$).

Other important components included in the design are temperature indicators and control units, as well as a recirculating fan [18] - to ensure uniform temperature distribution. A detailed breakdown of the technical data of this quotation is provided in Table V.

Regarding production capacity, the supplier has indicated that this design can reliably and uniformly heat a 9000 lb load to the soak temperature – 1550 F – in 6 hours [19]. Using a soak time of 2 hours and assuming the cooling rate – which is critical to maintaining material integrity within the cores – remains the same at approximately 12 hours, a total processing time of 20 hours can be estimated. However, for the purposes of calculating production rate this number must be reduced as the heating hood only remains on the load for part of the cooling process – until the temperature drops below 600 F – and is then available to be used for the next load. Currently the time required for the temperature to drop to 600 F from the soak temperature is approximately 4.45 hours – 16.45 hours average processing time less 10 hours average heating time and 2 hours soak time [20]. This yields an approximate processing time for the proposed system of 12.45 hours and an average production rate of 722 lbs/hour. Though this is significantly lower than the marginal 2000 lbs/hour production rate, other factors must be considered that could have a significant effect on this value.

The heating rate is an important parameter to ensure that the cores are not thermally shocked and thereby damaged. The current heating rate reaches the soak temperature in approximately 10 hours [6], however, it is believed that this is artificially high due to temperature non-uniformity within the existing furnace. Thus it is feasible that a furnace capable of reliably uniform temperature distributions may be able to safely heat the load at an accelerated rate. This must be balanced with the knowledge that while a faster heating rate will reduce total processing times, a slower rate allows more material to be annealed simultaneously. Hence a balance must be struck between a safe heating rate to avoid thermal shock, minimal processing time, and maximum load size. Further engagement between the Client and the supplier, should the Client wish, would be able to accurately determine an optimal balance between these variables and may increase the viable production rate for this design.

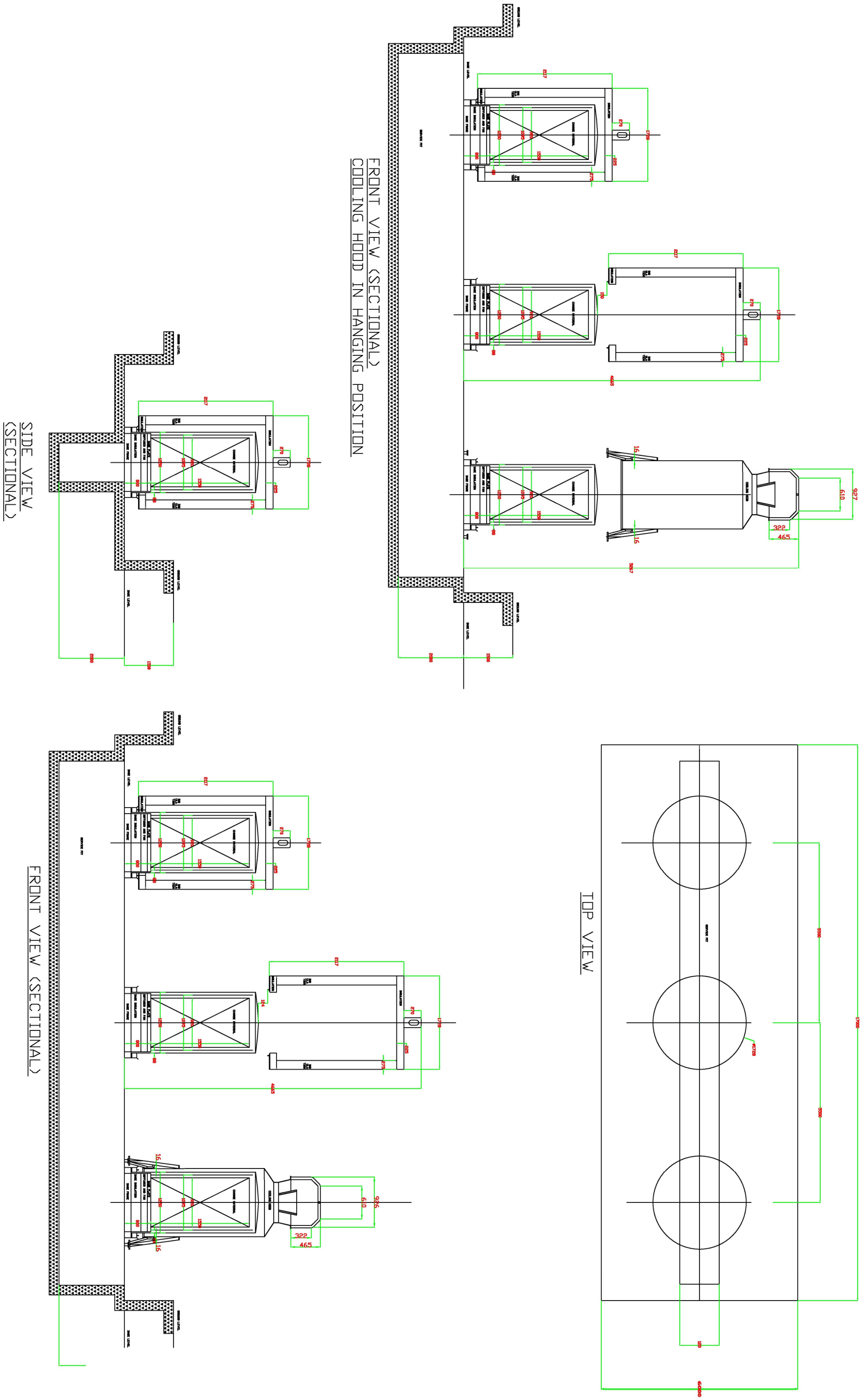


Figure 3: Bell furnace proposal 'A' dimensions [18]. Courtesy of Prolific Engineers.

Low cost is an area of particular strength for bell furnaces in general and this design in particular. The estimated capital cost for this system - including shipping to the nearest port (Vancouver) – is $109,200 USD (~ $114,300 CAD) [18]. As with all quotes provided in this report it is necessary to understand the preliminary nature of these values, however, even a drastic increase would not likely push the estimated costs beyond the $800,000.00 CAD capital budget. This opens the possibility, space and logistics permitting, to ameliorate the issues regarding low production rates by purchasing several of these small furnaces. Though this does present an exponential increase in complexity as each separate furnace will require additional electrical and gas connections; equipment including crane time; personnel to load, unload, and monitor each furnace; and will increase the difficulty of coordinating the schedule of each furnace. The supplier has estimated the life span for all three of their proposed designs at 25 – 30 years with good maintenance [21].

Finally it should be noted that in order to facilitate lifting the hoods on and off of the loads, or charges, bell furnaces require a minimum vertical clearance from the furnace base to the middle of the hook used to lift the covers. This value is dependent on the external dimensions of the furnace in question and is estimated above the base of the furnace related to the outer dimensions. For this small design the minimum is given by the supplier as approximately 10 metres [18]. The Authors did not fully appreciate this requirement until late in the project; it was assumed that as the obtained bell furnace quotes were of a similar size to the currently utilized furnace the required vertical clearances would not be dissimilar. It was only when the matter was directly investigated that it was realized that even the smallest of the required clearances is much greater than what is available. This necessarily disqualifies all three bell proposals from acceptance, and the tight time constraints impeded any opportunity to furnish new quotes for the final report. Due to the Client's successful utilization of a bell furnace with the available vertical clearance it is believed that these large clearances are a characteristic of the supplier in question rather than bell furnaces in general. The three quotes were retained as examples of expected dimensions, equipment, and costs; but further quote requisition must be performed by the Client should they wish to pursue a bell furnace design.

Key outstanding or otherwise unknown operational parameters for this proposal are the required annual downtime, heat shielding abilities, and the uniformity of temperature distribution. Also missing are any specific references to safety features of the design. The supplier has indicated in communications that safety features including interlocks and emergency pressure relief valves are included in the design [22], though this is not referenced in the proposal and should be verified and pressed in more detail.

Data on the expected schedule and cost for component repairs and replacements was received from the supplier. This was used to calculate an estimated annual maintenance cost in Section A.4.

The parameters discussed above, both known and unknown, are outlined in Table V. Unless otherwise noted, all data in Table V is from [18].

TABLE V: BELL FURNACE PROPOSAL 'A' PARAMETERS

| Parameter | Value |
|---|---|
| **Internal Clearance** | Diameter: 36.2”<br>Height: 61.02” |
| **Maximum Operating Temperature** | 1652 F |
| **Required Footprint** | ~750 $ft^2$ |
| **Controls System** | Full System Included |
| **Operational Life** | 25 – 30 Years [21] |
| **Required Downtime** | **Unknown** |
| **Heat Shielding Abilities** | **Unknown** |
| **Gas Safety** | **Unknown (Likely Yes)** |
| **Allows Emergency Shutdown** | **Unknown (Likely Yes)** |
| **Design Production Capacity** | 722 lbs/hour [19] |
| **Required Base-to-Hook Clearance** | 10 m |
| **Total Processing Time** | 20 hours [19] |
| **Temperature Distribution** | **Unknown** |
| **Annual Maintenance Costs** | **To be Calculated** |
| **Estimated Capital Cost** | $114,300.00 CAD |

### A.3.2.2 Bell Furnace Proposal B (Prolific Engineers)

The system presented in this quote is functionally very similar to that discussed in Section A.3.2.1, consisting of two bases, 2 inner covers, 1 heating hood, and 1 cooling hood [18]. An identical control system to the smaller furnace is included and the components of the system are largely identical. Unless explicitly stated otherwise all components present in the smaller design are present in this design as well. The key difference between the proposals lies in the dimensions of the furnace, which can be seen in Figure 4.

The inner cover is listed as having a diameter of 1600 mm (5.2’) and a height of 3300 mm (10.8’) and useful inner volume of diameter 1250 mm (4.1’) and height 2500 mm (8.2’) [18]. Using the same reasoning as in Section A.3.2.1 this yields a minimum footprint of approximately 42 $ft^2$. Accounting for storage space for the various covers and hoods, loading/unloading areas, an observation/control station, and other associated requirements will likely yield a space requirement of similar magnitude to that currently occupied by the existing system (~750 $ft^2$). As with all bell furnaces a minimum vertical clearance is also required for this design to facilitate the lifting and movement of the various covers and hoods by crane. The minimum clearance dictated by the supplier for a furnace of these dimensions is 12-14 m [18]. As with the 10 m requirement for bell furnace proposal A it was determined that this requirement could not be met; further quotes with more acceptable vertical clearance requirements will need to be identified subsequent to this report.

In correspondence with the supplier it has been indicated that this design can heat a 12000 lb. load to the soak temperature in 6 hours [19]. As with bell quote A, assuming 2 hours of soak time and 4.45 hours of hood cooling yields a total processing time of 12.45 hours and an average production rate of 964 lbs./hour. Once again this is far below the desired 2000 lbs./hour minimum, however, the discussion carried out in Section A.3.2.1 regarding the balance between load size and annealing times is applicable in this case as well and its conclusion – that this production capacity may increase or decrease as an optimal compromise is identified – should be considered.

The estimated capital costs for this system are $191,000 USD ($200,000 CAD) [18]. While certainly more costly than bell quote A this is still well below the $800,000.00 capital budget and presents the same possibility to compensate for the low production rates by buying multiple furnaces – however the same unknowns regarding space, infrastructure, and logistics apply equally.

Bell furnace quotes A, B, and C were received as a package and as such the remaining points of research and data gathering are consistent across all three quotes. Summarizing the discussion of bell quote A, the outstanding or otherwise unknown data for this design are the feasibility of the 12-14 metre vertical clearance, required annual downtime, heat shielding abilities, the uniformity of temperature distribution, and specifics on safety features included. As with bell quote A it is assumed for this purposes of this comparison that all three designs meet relevant safety standards, however, explicitly confirming this should be of high priority going forward.

A full summary of key parameters, both known and outstanding, is given in Table VI. Unless otherwise stated, all data in Table VI is from [18].

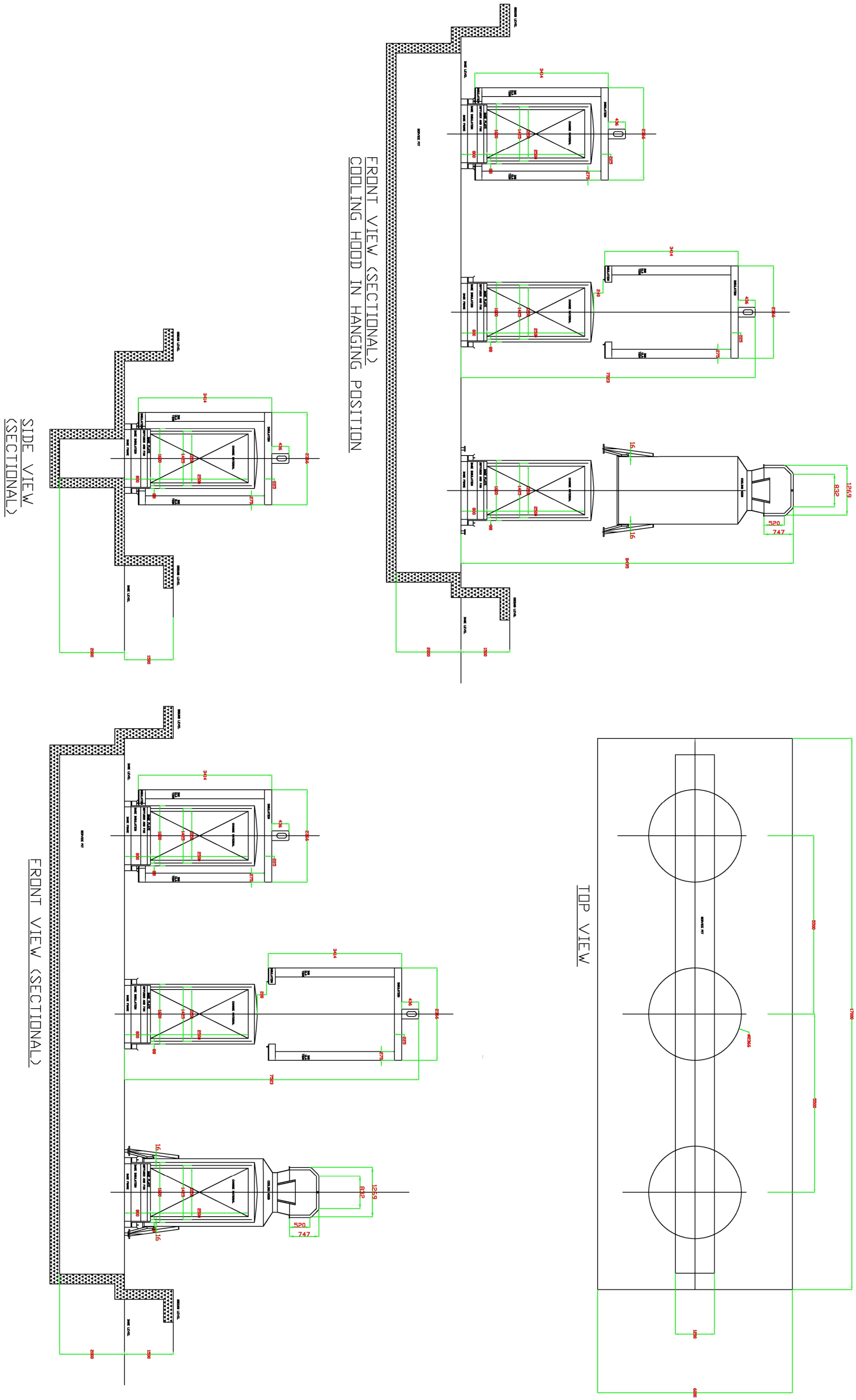


Figure 4: Bell furnace proposal 'B' dimensions [18]. Courtesy of Prolific Engineers.

TABLE VI: BELL FURNACE PROPOSAL 'B' PARAMETERS

| Parameter | Value |
|---|---|
| **Internal Clearance** | Diameter: 49.21"<br>Height: 98.43" |
| **Maximum Operating Temperature** | 1652 F |
| **Required Footprint** | ~750 ft2 |
| **Controls System** | Full System Included |
| **Operational Life** | 25 – 30 Years [21] |
| **Required Downtime** | **Unknown** |
| **Heat Shielding Abilities** | **Unknown** |
| **Gas Safety** | **Unknown (Likely Yes)** |
| **Allows Emergency Shutdown** | **Unknown (Likely Yes)** |
| **Design Production Capacity** | 964 lbs/hour [19] |
| **Required Base-to-Hook Clearance** | 12-14 m |
| **Total Processing Time** | 20 hours [19] |
| **Temperature Distribution** | **Unknown** |
| **Annual Maintenance Costs** | **Unknown** |
| **Estimated Capital Cost** | $200,000.00 CAD |

### A.3.2.3 Bell Furnace Proposal C (Prolific Engineers)

Once again this proposal is largely identical to bell quote A and B and unless otherwise noted all components listed in Section A.3.2.1 and Section A.3.2.2 are present in this quote as well. Similarly the only tangible difference is in the size, which is increased over the previous two designs to an inner cover diameter of 1850 mm (6.1') and height of 3800 mm (12.5') [14]. The useful inner space is similarly enlarged to an inner diameter of 1500 mm (4.9') and inner height of 3000 mm (9.8'). Reflecting this expanded geometry the required vertical clearance from the base to the crane hook has grown to approximately 14-15 m [14]. These and other key dimensions are shown in Figure 5.

The supplier has indicated that this design can reliably heat 19300 lbs. of core to the soak temperature in 6 hours [19]. Assuming the same profile as in the other sections (6 hours heating, 2 hours soak, 4.45 hours cool) the same 12.45 hour processing time can be assumed and an average production rate of 1550 lbs./hour calculated. This is still below the marginal 2000 lbs./hour threshold. However, this is again offset by the relatively low estimated capital costs required - $452,000 USD ($475,000 CAD) [14]. From this perspective, if 2000 lbs./hour is a hard requirement it may be feasible to purchase two units of this type, slightly exceeding the capital budget but providing over 3000 lbs./hour of production, assuming that space and logistical difficulties can be overcome. Additionally the 2000 lbs./hour production rate was calculated using production schedules for previous months with an added factor for future growth. The rough nature of these calculations provides some error on the result and actual requirements may be lower. Should a higher production rate be required it should not be overly onerous for the supplier to provide a slightly scaled-up version of this design, with increased production rate and a proportionally larger capital cost.

Outstanding data is identical to that of bell proposals A and B. To summarize, information is still pending on the required annual downtime, heat shielding abilities, the uniformity of temperature distribution, and specifics on safety features included. Once again this comparison assumes that the proposed designs conform to all legal and standardized requirements, however, this must be explicitly confirmed prior to committing to any proposals.

A summary of the specifications discussed above, key data that requires identification, and any other important data points is given in Table VII. Unless otherwise noted, all data in Table VII is from [14].

TABLE VII: BELL FURNACE PROPOSAL 'C' PARAMETERS

| Parameter | Value |
|---|---|
| **Internal Clearance** | Diameter: 59.06"<br>Height: 118.11" |
| **Maximum Operating Temperature** | 1652 F |
| **Required Footprint** | ~750 ft2 |
| **Controls System** | Full System Included |
| **Operational Life** | 25 – 30 Years [21] |
| **Required Downtime** | **Unknown** |
| **Heat Shielding Abilities** | **Unknown** |
| **Gas Safety** | **Unknown (Likely Yes)** |
| **Allows Emergency Shutdown** | **Unknown (Likely Yes)** |
| **Design Production Capacity** | 1550 lbs/hour [19] |
| **Required Base-to-Hook Clearance** | 14-15 m |
| **Total Processing Time** | 20 hours [19] |
| **Temperature Distribution** | **Unknown** |
| **Annual Maintenance Costs** | **Unknown** |
| **Estimated Capital Cost** | $475,000.00 CAD |

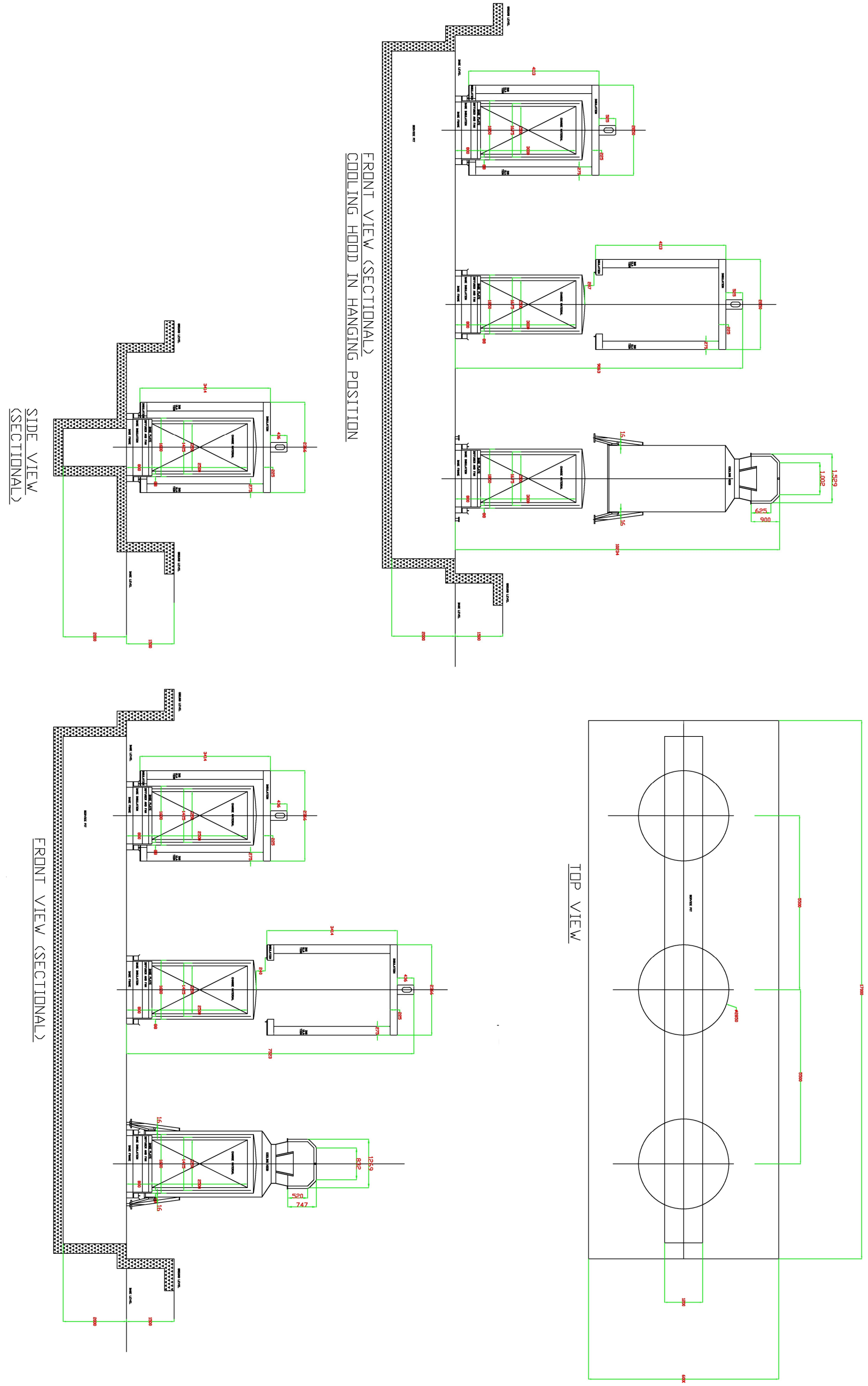


Figure 5: Bell furnace proposal 'C' dimensions [14]. Courtesy of Prolific Engineers.

## A.4 Cost Analysis of Designs

The final piece that must be considered regarding these designs are their economic feasibility, both immediately and in the long-term. Suitably, the cost analysis can be divided into two main categories: capital (immediate) costs, and operational (ongoing) costs. Each of these are treated separately below. Additionally, Table VIII identifies the key parameters for each design that are essential to completing their respective cost analyses.

TABLE VIII: CONSIDERED DESIGNS KEY COST PARAMETERS

| Type of Furnace | Power | Maximum Transformer Core Size | Production capacity per hour | Expected Life |
|---|---|---|---|---|
| **Roller Hearth A** | (790kW) | 1524mm X 1524mm | 2000lbs/hr. | 40-50 years |
| **Roller Hearth B** | (520kW) | 1066.8mm X 1066.8mm | 2080 lbs./hr. | 40-50 years |
| **New Bell Furnace A** | (140kW) | 920mm X 1550mm | 722 lbs./hr. | 25-30 years |
| **New Bell Furnace B** | (180kW) | 1250mm X 2500mm | 964 lbs./hr. | 25-30 years |
| **New Bell Furnace C** | (300kW) | 1500mm X 3000mm | 1550 lbs./hr. | 25-30 years |

### A.4.1 Initial Costs

The first obvious cost is the initial capital cost for the equipment and the installation associated with the furnace. The Client has allocated a capital budget of $800,000.00 [23] and this will play a critical role in evaluating options and making the recommendation. The total initial cost of the roller hearth and new bell furnace is shown in Table IX below. The initial cost of the three new bell furnaces includes the cost of the furnace, freight and insurance cost required to bring the furnace to the Client. The roller hearth costs generally include parts and assembly. All these cost were considered as initial cost at it paid once when the furnace is purchased.

TABLE IX: CAPITAL COSTS OF CONSIDERED DESIGNS

| Type of Furnace | Initial Cost |
|---|---|
| **Roller Hearth 1** | [redacted] |
| **Roller Hearth 2** | $1,397,000 [16] |
| **New Bell Furnace (140kW)** | $114,300 [18] |
| **New Bell Furnace (180kW)** | $200,000 [18] |
| **New Bell Furnace (300kW)** | $475,000 [14] |

Installation of the new furnace will require the demolition and clearance of the current set up and the installation of new gas piping system and exhaust system. Additionally, installation of the new roller hearth would require additional space as it is larger than the current floor space designated to the annealing process. For this study, it is assumed that the cost of clearing space and installing a new furnace will be covered by the recovery value of the current furnace.

## A.4.2 Operating Costs

Operating costs are generally expressed as average annual quantities and represent the ongoing costs associated with operating a piece of equipment. These costs are extremely broad and incorporate various categories such as utilities, worker salaries, maintenance, raw materials, and any other periodic cost that can be associated with operations. For this analysis, operating costs were considered to be composed of two parts: energy and maintenance costs. Energy costs are discussed in Section A.4.2.1, while maintenance costs are analyzed in Section A.4.2.2.

### A.4.2.1 Energy Costs

Energy consumption costs over the operational life of the furnace need to be considered. In this study of cost analysis, the economic factors that that would lead to fluctuation in energy prices have not been considered as it is not easily predictable at present.

The current electricity rates were taken from Manitoba Hydro under an assumption that they fall under the general service medium category (SGM) [24]. Table X shows the energy rates used in the cost analysis.

TABLE X: ENERGY RATES [24]

**General Service Medium (Non – Residential; Utility–owned Transformation exceeding 200kVA)**

| | |
|---|---|
| **Monthly Basic Charge** | $28.57 |
| **Plus Energy Charge:** | |
| **First 11,000 kWh @** | 7.545cents |
| **Next 8,500 kWh @** | 5.237cents |
| **Balance of kWh @** | 3.457 cents |
| **Plus Demand Charge:** | |
| **First 50kVA of monthly Recorded Demand @** | No Charge |
| **Balance of Recorded Demand @** | $8.85 |

For the energy calculations, the maximum power usage of the furnace has been used. The energy costs of all 5 designs have been calculated below.

#### A.4.2.1.1 New Bell Furnace A

Basis of Calculation

Batch Weight = 722lbs. /hrs. X 12hrs = 8664lbs.

Temperature = 820Deg C

Process Details

Heating Time = 8Hrs

Soaking Time = 6hrs

Heating Cost Details

During heating Time = 140 KW X 8 Hrs. = 1120 kWh

During Soaking Time = 140 KW X 6 Hrs. X 0.5 = 420 kWh

(Assuming furnace will be on only 50% of time during soaking)

Motor for Fan Assembly = 20 KW X 20 Hrs. = 400 kWh

Motor for Cooling Hood = 20 KW X 17 Hrs. = 340 kWh

Cost Calculation per lbs.

The average time for a full batch to be processed is 20 hours. Assuming that the annealing is carried out continuously for 7 days a week, the energy cost per month will be given by:

Electric cost during Heating Time = 1,120 kWh

Electric cost during Soaking Time = 420 kWh

Motor Electric Cost = 740 kWh

Total Energy per Batch = 1120 kWh + 420 kWh + 740 kWh = 2,280 kWh

Assuming the oven runs for 140 hours per week and operates for all the four weeks in a month. This would mean that the oven would be firing approximately 28 batches per month, operating 12 months per year. The total energy used per month will be given by:

Total Energy per Month = 28 batches x 2280kWh = 63,840kWh/month

The energy rates given in table above are based on monthly charges so the energy cost per month is:

Total Energy Cost per Month = Monthly Basic Charge + Energy Charge

= $28.57/month + (11,000 kWh/month x 7.545 cents + 8,000 kWh/month x 5.237cents + 44,840 kWh/month x 3.457 cents)

= $2827.60/month

The total energy cost per year would be $2827.60/month X 12months/year = $33,932, assuming the oven operates for the 12 months and the maintenance is carried out in short length time intervals.

In a month the oven will be firing for 28 batches meaning that the total weight of the core annealed will be 28 x 8664 lbs. = 242,592 lbs. /month

The annual production capacity = 242,592 lbs. /month x 12month/year = 2,911,104 lbs. /year

Energy Cost per Pound = Total Energy Cost per Batch per month / Batch weight per month

= $2827.60/month / 242,592 lbs. /month

= $0.012/lbs.

### A.4.2.1.2 New Bell Furnace B

Basis of Calculation

Batch Weight = 964lbs. /hrs. X 12hrs = 11568lbs.

Temperature = 820Deg C

Process Details

Heating Time = 8Hrs

Soaking Time = 6hrs

Heating Cost Details

During heating Time = 180 KW X 8 Hrs. = 1440 kWh

During Soaking Time = 180 KW X 6 Hrs. X 0.5 = 540 kWh

(Assuming furnace will be on only 50% of time during soaking)

Motor for Fan Assembly = 20 KW X 20 Hrs. = 400 kWh

Motor for Cooling Hood = 20 KW X 19 Hrs. = 380 kWh

Cost Calculation per lbs.

The average time for a full batch to be processed is 20 hours. Assuming that the annealing is carried out continuously for 7 days a week, the energy cost per month will be given by:

Electric cost during Heating Time = 1,440 kWh

Electric cost during Soaking Time = 540 kWh

Motor Electric Cost = 780 kWh

Total Energy per Batch = 1440 kWh + 540 kWh + 780 kWh = 2,760 kWh

Assuming the oven runs for 140 hours per week and operates for all the four weeks in a month. This would mean that the oven would be firing approximately 28 batches per month, operating 12 months per year. The total energy used per month will be given by:

Total Energy per Month = 28 batches x 2760kWh = 77,280kWh/month

Total Energy Cost per Month = Monthly Basic Charge + Energy Charge

= $28.57/month + (11,000 kWh/month x 7.545 cents + 8,000 kWh/month x 5.237cents + 58280 x 3.457 cents)

= $3,292/month

The total energy cost per year would be $3,292/month X 12months/year = $39,506, assuming the oven operates for the 12 months and the maintenance is carried out in short length time intervals.

In a month the oven will be firing for 28 batches meaning that the total weight of the core annealed will be 28 x 11568 lbs. = 323,904 lbs. /month

The annual production capacity = 323,904 lbs. /month x 12month/year = 3,886,848 lbs. /year

Energy Cost per Pound = Total Energy Cost per Batch per month / Batch weight per month

= $3,292/month / 323,904 lbs. /month

= $0.01/lbs.

### A.4.2.1.3 New Bell Furnace C

Basis of Calculation

Batch Weight = 1550lbs. /hrs. X 12hrs = 18600lbs.

Temperature = 820Deg C

Process Details

Heating Time = 6Hrs

Soaking Time = 4hrs

Heating Cost Details

During heating Time = 300 KW X 6 Hrs. = 1800 kWh

During Soaking Time = 300 KW X 4 Hrs. X 0.5 = 600 kWh

(Assuming furnace will be on only 50% of time during soaking)

Motor for Fan Assembly = 20 KW X 20 Hrs. = 400 kWh

Motor for Cooling Hood = 20 KW X 10 Hrs. = 200 kWh

Cost Calculation per lbs.

The average time for a full batch to be processed is 20 hours. Assuming that the annealing is carried out continuously for 7 days a week, the energy cost per month will be given by:

Electric cost during Heating Time = 1800 kWh

Electric cost during Soaking Time = 600 kWh

Motor Electric Cost = 600 kWh

Total Energy per Batch = 1800 kWh + 600 kWh + 600 kWh = 3000 kWh

Assuming the oven runs for 140 hours per week and operates for all the four weeks in a month. This would mean that the oven would be firing approximately 28 batches per month, operating 12 months per year. The total energy used per month will be given by:

Total Energy per Month = 28 batches x 3,000kWh = 84,000kWh/month

Total Energy Cost per Month = Monthly Basic Charge + Energy Charge

= $28.57/month + (11,000 kWh/month x 7.545 cents + 8,000 kWh/month x 5.237cents + 65,000 kWh/month x 3.457 cents)

= $3,524.53/month

The total energy cost per year would be $3,524.53/month X 12months/year = $42,294, assuming the oven operates for the 12 months and the maintenance is carried out in short length time intervals.

In a month the oven will be firing for 7 batches meaning that the total weight of the core annealed will be 28 x 18600 lbs. = 520,800 lbs. /month

The annual production capacity = 520,800 lbs. /month x 12month/year = 6,249,600 lbs. /year

Energy Cost per Pound = Total Energy Cost per Batch per month / Batch weight per month

= $3,524.53/month / 520,800 lbs. /month

= $0.0067/lbs.

### A.4.2.1.4 Roller Hearth A

Basis of Calculation

Batch Weight = 2000lbs. /hrs. X 20hrs = 40,000lbs.

Temperature = 820Deg C

Process Details

Heating Time = 12Hrs

Soaking Time = 8Hrs

Heating Cost Details

During heating Time = 790 KW X 20 Hrs. = 15,800 kWh

(Assuming furnace will be operating for 25 days per month)

Total heating Time = 15,800 kWh X 25days/month = 395,000kWh/month

Cost Calculation per lbs.

Total Energy Cost per Month = Monthly Basic Charge + Energy Charge

= $28.57/month + (11,000 kWh/month x 7.545 cents + 8,000 kWh/month x 5.237cents + 376,000 kWh/month x 3.457 cents)

= $14,275.80/month

The total energy cost per year would be $14,275/month X 12months/year = $171,300, assuming the oven operates for the 12 months and the maintenance is carried out in short length time intervals.

Total batch weight/month = 40,000lbs. X 25 days/month

= 1,000,000lbs. /month

Energy Cost per Pound = Total Energy Cost per Batch per month / Batch weight per month

= $14,275/month / 1,000,000lbs. /month

Energy Cost per Pound = $0.014/lbs.

### A.4.2.1.5 Roller Hearth B

Basis of Calculation

Batch Weight = 2,080lbs. /hrs. X 20hrs = 41,600lbs.

Temperature = 820Deg C

Process Details

Heating Time = 12Hrs

Soaking Time = 8Hrs

Heating Cost Details

During heating Time = 520 KW X 20 Hrs. = 10,400 kWh

(Assuming furnace will be operating for 25 days per month)

Total heating Time = 10,400 kWh X 25days/month = 260,000kWh/month

### Cost Calculation per lbs.

Total Energy Cost per Month = Monthly Basic Charge + Energy Charge

= \$28.57/month + (11,000 kWh/month x 7.545 cents + 8,000 kWh/month x 5.237cents + 241,000 kWh/month x 3.457 cents)

= \$9,608.85/month

The total energy cost per year would be \$9,608.85/month X 12months/year = \$115,306, assuming the oven operates for the 12 months and the maintenance is carried out in short length time intervals.

Total batch weight/month = 41,600lbs. X 25 days/month

= 1,040,000lbs. /month

Energy Cost per Pound = Total Energy Cost per Batch per month / Batch weight per month

= \$9,608.85/month / 1,040,000lbs. /month

= \$0.0092/lbs.

Table XI shows the cost per pound of core for the two roller hearths and the three bell furnaces.

TABLE XI: ENERGY COST PER POUND SUMMARY

| Type of Furnace | Energy Cost ($/lbs./year |
|---|---|
| **Roller Hearth A** | 0.014 |
| **Roller Hearth B** | 0.0092 |
| **New Bell Furnace A (140kW)** | 0.012 |
| **New Bell Furnace B (180kW)** | 0.010 |
| **New Bell Furnace C (300kW)** | 0.0067 |

### A.4.2.2 Maintenance and Operational Costs

Another cost associated with a furnace is the operational and the maintenance cost. Regardless of the type of furnace recommendation made, there will be component failures in the furnace. Components that likely need to be changed are the thermocouple, charge plates and painting of the furnace to minimize the heat loss from the furnace to the surroundings. Some parts may fail due to fatigue and procedures need to be laid to allow maintenance to detect such failures. The maintenance cost the Client currently pays is \$60 per hour and they perform four hours of maintenance every year. The maintenance cost is not likely to affect the decision of recommending the best furnace as it would apply to every design selected. The actual cost of maintenance will vary but the cost should not exceed $500 per year. The operational cost for the Client would be calculated on the basis of how many hours the furnace is in operation per year. Currently, the Client uses the furnace for 16.5 hours per day. The furnace is in operation for six days per week and they operate for 50 weeks a year as they usually shut down for two weeks to carry out necessary maintenance.

The maintenance cost for the three new bell furnaces is approximately the same. The new furnace requires certain maintenance to be carried out in a certain period of time. Table XII indicates the major maintenance cost associated with the new bell furnaces. When calculating the total maintenance cost of the bell furnaces, the lower value of expected life was used.

TABLE XII: MAINTENANCE REQUIREMENTS FOR BELL FURNACES [25]

| Type of Maintenance | Cost | Expected life |
|---|---|---|
| **Impeller** | $3800 | 1-2 years |
| **Fan assembly** | $8500 | 3-4 years |
| **Inner cover** | $25000 | 5-6 years |
| **Heating elements, insulation, holding system** | $35000 | 4-5 years |
| **Thermocouples (every base has one and the furnace has three)** | $500 | 1-2 years |
| **Temperature controllers** | $140 | 2-3 years |
| **Programmable controllers** | $500 | 2-3 years |
| **Neoprene seal** | $1000 | 1 year |
| **Labor** | $500/year | - |

For the roller hearth furnaces, the annual maintenance costs are estimated to be 1-2% of the highest capital cost (roller hearth A). This was based partly on the assumption that most rolling hearth furnaces would have similar maintenance requirements, and also ensure a conservative (high) maintenance estimate. Table XIII below summarises the maintenance cost of the roller hearths. The cost of the installation of the roller hearth will be greater than the cost of installation of a bell furnace at it requires demolition of the nearby space to create the additional floor space. The other option available is to move the annealing process to a different location within the Client facility that can accommodate easy installation of the furnace. If the annealing process is taken to a different location, it would mean that the exhaust fan and piping of the gas system will have to be redone hence adding a large expense.

TABLE XIII: MAINTENANCE REQUIREMENTS FOR ROLLER HEARTH FURNACES [12]

| Type of Maintenance | Cost ($/year) |
|---|---|
| **General Maintenance (1-2% of capital cost)** | [redacted] |
| **Regular minor Maintenance (Greasing of bearing, etc.)** | 500 |
| **Labor** | 500 |

Using this data, the previously calculated electrical costs, and basic economic analysis techniques it was possible to estimate approximate annual maintenance and operational costs using Present Worth (PW) calculations. This is carried out below.

## A.4.3 Present Worth Calculations

The present worth, also known as the Present Value (PV) is defined as:

$$\text{Present value (PV)} = \frac{C}{i_{eff}}[1 - \frac{1}{(1+i_{eff})^{n}}]$$

Where: C is the cost, $i_{eff}$ is the effective rate, and n is the number of payments. The effective rate per n years is calculated as:

$$i_{eff} = (1+i)^{\frac{n}{g}} - 1$$

Where i is the annual rate, n is the number of years the annuity occurs over a given period of time, and g is the give rate which is one year for this study.

### A.4.3.1 Present Value Calculations for New Bell Furnaces

For one year cash flows, the present value of the cash flows is calculated using an effective rate $i_{eff}$ of $(1+0.1)^{1}-1 = 0.10$, the total value of all the maintenance costs that occur every one year is the total cost of the impeller - $3800, thermocouples - $500, neoprene seal- $1000, labour $500, which is equal to $5,800. The number of payments n, in the 25 year life span is 25 payments

$$\text{Present value (PV)} = \frac{5800}{0.10}\left[1 - \frac{1}{(1 + 0.1)^{25}}\right]$$

$$= \$52.646.80$$

For two year cash flows, the present value of the cash flows is calculated using an effective rate $i_{eff}$ of $(1+0.1)^2$-1 = 0.21, the total value of all the maintenance costs that occur every two years is the total cost of the temperature controllers - \$140 and programmable controllers - \$500, which is equal to \$640. The number of payments n, in the 25 year life span is 12 payments.

$$\text{Present value (PV)} = \frac{640}{0.21}\left[1 - \frac{1}{(1 + 0.21)^{12}}\right]$$

$$= \$2{,}738.21$$

For three year cash flows, the present value of the cash flow is calculated using an effective rate $i_{eff}$ of $(1+0.1)^3$-1 = 0.33, the total value of all the maintenance costs that occur every three year is the cost of the fan assembly - \$8500. The number of payments n, in the 25 year life span is 8 payments.

$$\text{Present value (PV)} = \frac{8500}{0.33}\left[1 - \frac{1}{(1 + 0.33)^{8}}\right]$$

$$= \$23{,}126.75$$

For four year cash flows, the present value of the cash flow is calculated using an effective rate $i_{eff}$ of $(1+0.1)^4$-1 = 0.46, the total value of all the maintenance costs that occur every four year is the cost of the heating elements, insulation, holding system - \$35,000. The number of payments n, in the 25 year life span is 6 payments.

$$\text{Present value (PV)} = \frac{35{,}000}{0.46}\left[1 - \frac{1}{(1 + 0.46)^{6}}\right]$$

$$= \$68{,}231.10$$

For five year cash flows, the present value of the cash flows is calculated using an effective rate $i_{eff}$ of $(1+0.1)^5$-1 = 0.61, the total value of all the maintenance costs that occur every three year is the cost of the inner cover replacement - \$25,000. The number of payments n, in the 25 year life span is 5 payments.

$$\text{Present value (PV)} = \frac{25{,}000}{0.61}\left[1 - \frac{1}{(1 + 0.61)^{5}}\right]$$

$$= \$38{,}630.45$$

The total present value of the maintenance cost is the sum of all the cash flows:

Total Present Value = \$52.646.80 + \$2,738.21 + \$23,126.75 + \$68,231.10 + \$38,630.45

= \$183,377.50

This is only for 25 years, the estimated lifespan of one furnace. In order to have a valid analysis to compare with the rolling hearth furnaces the study length must be set to the lowest common multiple of both lifespans. This is 50 years, the estimated operational lifespan of the rolling hearth furnaces. Hence, this value must be calculated for two furnace lifetimes. This is accomplished using the equation:

$$\text{Present Value} = \$183{,}377.5 + \$183{,}377.5(P/F,\ i,\ N)$$

$$\text{Where } \frac{P}{F} = \frac{1}{(1+i)^N}$$

$$\text{Present Value} = \$183{,}377.5 + \$183{,}377.5(P/F,\ 10,\ 25)$$

$$\text{Present Value} = \$183{,}377.5 + \$183{,}377.5(0.0923)$$

$$\text{Present Value} = \$200{,}303.24$$

As the replacement schedule and costs are the same for all three bell furnaces, this value remains constant throughout all three analyses. Variation comes into the calculations when the energy costs are considered, as is done for all three bell furnace quotes below.

Present Worth of Energy Costs

New Bell furnace A:

$$\text{Present Value} = \$33{,}932(P/A,\ i,\ N)$$

Where $\frac{P}{A} = \frac{(1+i)^N - 1}{i(1+i)^N}$

$$\text{Present Value} = \$33{,}932(P/A,\ 10,\ 50)$$

$$\text{Present Value} = \$33{,}932(9.077)$$

$$\text{Present Value} = \$308{,}000$$

New Bell Furnace B:

Present Value = $39,506(P/A, i, N)

Present Value = $39,506(P/A, 10, 50)

Present Value = $39,506(9.077)

Present Value = $358,596

New Bell Furnace C:

Present Value = $42,294(P/A, i, N)

Present Value = $42,294(P/A, 10, 50)

Present Value = $42,294(9.077)

Present Value = $383,902

Present Worth of Costs for the three bell furnaces is given by:

Present Worth of Costs = Initial Costs + Maintenance Costs + Energy Costs

New Bell Furnace A = $114,300 + $200,303.24 + $308,000 = $622,603.24

New Bell Furnace B = $200,000 + $200,303.24 + $358,596 = $758,899.24

New Bell Furnace C = $475,000 + $200,303.24 + $383,902 = $1,059,205.24

### A.4.3.2 Present Value Calculations for Roller Hearth Furnaces

Present worth (value) calculations for the roller hearth are similar to those for the bell furnaces. For simplicity, it was assumed that the annual maintenance costs for both roller hearth quotes were approximately [redacted], based on 2% of the largest capital cost.

Maintenance Costs

Present Value = [redacted](P/A, i, N)

Present Value = [redacted](P/A, 10, 50)

Present Value = [redacted](9.077)

Present Value = [redacted]

Energy Costs

Once again, the energy costs provide the difference in ongoing costs between the two roller hearth designs.

Roller Hearth A:

Present Value = $171,309.60(P/A, i, N)

Present Value = $171,309.60 (P/A, 10, 50)

Present Value = $171,309.60 (9.077)

Present Value = $1,554,977.25

Roller Hearth B:

Present Value = $115,296(P/A, i, N)

Present Value = $115,296(P/A, 10, 50)

Present Value = $115,296 (9.077)

Present Value = $1,046,541.80

Present Worth of Costs for the two roller hearths are given by:

Present Worth of Costs = Initial Costs + Maintenance Costs + Energy Costs

Roller Hearth A = [redacted] + $1,554,977.25 = [redacted]

Roller Hearth B = $1,397,000 + [redacted] + $1,046,541.80 = $2,815,698.80

### A.4.4 Environmental Costs

The final major cost considered in this furnace redesign is the environmental cost. Again, this cost will affect the decision as codes and standards require minimum energy efficient system that can actual be used. The environmental cost as this point time is unknown and it is assumed that the electricity is fairly environmental friendly. Changes in codes and standards are likely to affect this cost and therefore it will be a better idea to aim for the maximum efficiency of a furnace.

### A.4.5 Payback Period Calculations

Sufficient data was not available to quantify positive cash flows associated with the various designs which eliminated any opportunity to directly calculate the payback period. Lacking this information, an alternate hybrid metric was developed.

The chosen metric was based on normalizing the Present Worth of Costs (PWC) of each design by their respective approximate annual production rates. This was rationalized on the basis that the ratio of PWC to production rate represents the average revenue per pound produced that must be generated for a particular design to break even over its lifespan. Hence, a design with a lower PWC/Production ratio would have a shorter payback period for a given revenue/lbs. value. The main limitation of this metric is that it assumes that each design would be operated at its design production rate, which is not a trivial assumption. Additionally, the level of detail available regarding the various expected costs varied between designs and as such the relative expense of individual designs may be over or under estimated. Regardless, for the purposes of this analysis it was considered an acceptable metric.

With all five quotes, the PWC/lb/year (denoted as PWC*) ratio was calculated using the formula

$$PWC^* = \frac{\frac{PWC}{lbs\ of\ Production}}{year}$$

This simple formula is applied to each of the quotes below, using the previously calculated PWC values

$\text{PWC}^*_{\text{Roller Hearth A}}$ = [redacted]

$\text{PWC}^*_{\text{Roller Hearth B}}$ = \$2,815,698.80 / 12,480,000 = \$0.23/lbs.

$\text{PWC}^*_{\text{New Bell A}}$ = \$622,603.24/ 2,911,104 = \$0.21/lbs.

$\text{PWC}^*_{\text{New Bell B}}$ = \$758,899.24 / 3,886,848 = \$0.19/lbs.

$\text{PWC}^*_{\text{New Bell C}}$ = \$1,059,205.24 / 6,249,600= \$0.17/lbs.

### A.4.6 Hourly Operating and Maintenance Costs

One of the key metrics selected for the adjudication of the each design is the approximate hourly operating and maintenance cost. This is an approximate value that includes averaged maintenance costs, electricity, and other general operational costs. By assuming 140 hours of operation per week, and 50 weeks of use per year the hourly maintenance cost can be determined using the simple formula

$$H = \frac{E + M}{7000}$$

Where H is the average cost to operate the furnace for one hour, E is annual energy costs, and M is the annual maintenance costs. 7000 has units hours per year and represents the estimated hours of operation per year for 140 hours per week, 50 weeks per year.

Performing this calculation for each of the five quotations yields the data indicated in Table XIV.

TABLE XIV: OPERATING COSTS SUMMARY

| Cost | Roller Hearth A | Roller Hearth B | New Bell Furnace A | New Bell Furnace B | New Bell Furnace C |
|---|---|---|---|---|---|
| **Maintenance Cost ($/year)** | [redacted] | [redacted] | 20,208.00 | 20,208.00 | 20,208.00 |
| **Energy Cost ($/year)** | [redacted] | 115,296.00 | 33,932.00 | 39,506.00 | 42,294.00 |
| **Annual Operating Costs ($/year)** | [redacted] | [redacted] | 54,140.00 | 59,714.00 | 62,502.00 |
| **Hourly Operating Costs ($/hour)** | [redacted] | 22.33 | 7.73 | 8.53 | 8.93 |

### A.4.7 Cost Considerations Summary

Table XV summarizes the results of the economic analysis performed for all five quotes.

The most important value in Table XV is the PWC* results. These indicate that based on the performed analysis the new bell ‘C’ quote is the most economically feasible – assuming that it is used at or near capacity. The new bell ‘B’ and ‘A’ quotes have the 2nd and 3rd lowest PWC* values, respectively, indicating that for a given revenue per pound produced value they should offer the 2nd and 3rd shortest payback periods.

The two roller hearth quotes have the largest PWC* values ([redacted] and 0.23) and therefore are expected to have the longest payback periods. However it is worth noting that the difference between the PWC* values for the new bell furnaces and the roller hearth furnaces, particularly the roller hearth 'B' quote, are very small compared to the initial differences in capital and operating costs. Despite capital costs 3-5 times those of the most expensive new bell furnaces and total operating costs of similar relative magnitudes, the largest roller hearth PWC* value ([redacted]) is [redacted] the size of the smallest bell furnace PWC* value (0.17). The PWC* value for the roller hearth 'B' quote is just 35% larger than that of the new bell 'C' quote. This implies that, assuming the additional production capacity is utilized, much of the additional costs involved with the roller hearth designs are compensated for by improved production. There are enough unknowns in these calculations that there is a significant likelihood that a fuller analysis with more complete information could yield PWC* values much more close together. This suggests that despite the significant barriers-to-entry present with the roller hearth designs they may be justified in the long term, a prospect that is worthy of further study at a later date.

TABLE XV: COST CALCULATIONS SUMMARY

| Cost | Roller Hearth A | Roller Hearth B | New Bell Furnace A | New Bell Furnace B | New Bell Furnace C |
|---|---|---|---|---|---|
| **Initial Cost ($)** | [redacted] | 1,397,000 | 114,300 | 200,000 | 475,000 |
| **Maintenance Cost ($/year)** | [redacted] | [redacted] | 20,208 | 20,208 | 20,208 |
| **Energy Cost ($/year)** | [redacted] | 115,296 | 33,932 | 39,506 | 42,294 |
| **Annual Operating Costs ($/year)** | [redacted] | [redacted] | 54,140.00 | 59,714.00 | 62,502.00 |
| **Hourly Operating Costs ($/hour)** | [redacted] | 22.33 | 7.73 | 8.53 | 8.93 |
| **Production Capacity per Year (lbs./year)** | [redacted] | 12,480,000 | 2,911,104 | 3,886,848 | 6,249,600 |
| **Energy Cost/pound ($/lbs.)** | [redacted] | 0.0092 | 0.012 | 0.010 | 0.0067 |
| **Present Worth of Costs, PWC($)** | [redacted] | 2,815,700.00 | 622,603.24 | 758,899.24 | 1,059,205.24 |
| **PWC* ($/lbs./year)** | [redacted] | 0.23 | 0.21 | 0.19 | 0.17 |

## A.5 Design Evaluations & Selection

The task of scoring the concepts was a fiendishly tricky one. This was in large part due to the complexity of the designs presented. If the concerns in this project were of a structural or physical nature, basic stress analysis could be performed to yield a simplified understanding of the performance of various designs. However, in this case the focus is on the thermal and fluid properties of the systems in question. This is inherently more complicated than basic stress analysis but the variety of systems to be analyzed – mixed heat transfer methods, time variant analysis, complicated geometries and materials – put a full analytical discussion beyond the abilities of the authors. Even a very simplified analysis would necessitate so many assumptions as to make the results meaningless. The alternative is a numerical analysis using CFX or similar software. Though the authors abilities in this field are rudimentary, initial efforts were made. These were unfortunately halted when preliminary research revealed that numerical simulation of these systems are on a graduate or Ph.D. level, and even then generally require months to perform.

The net result of this has been to render the Authors' understanding of the proposed designs completely reliant on results published in externally completed analyses of similar geometries and data provided to the Authors by suppliers. The latter option was the preferred approach, and was successful insofar as five quotes were obtained by the Authors in time for inclusion in this report. However, this undertaken was itself complicated by the fact that each of these systems are custom built. In order for suppliers to provide data on performance or cost they must first have a full understanding of the Client's needs and then design a system to fit those requirements. It was communicated to the Authors by several suppliers that to do this fully is a task measured in more weeks than were available for the completion of this report. In an effort to expedite the process it was impressed upon suppliers that big-picture, general data was more important than detailed specifics, wherever possible gaps or inaccuracies could be filled in via further engagement between the Authors and suppliers. This task was undertaken and ongoing dialogue was maintained between the Authors and each of the contacted suppliers, to various degrees, over the course of the project.

In scoring the proposed designs a hybrid set of known and approximated data had to be used. The approximated data was obtained using the most reasonable practises that were felt would produce results analogous to those expected from actual data. These methods ranges from selecting suitable stand-in metrics that could be calculated to heuristically arguing for the relative performance of a specific design, to logical reasoning. A summary of particular data points where these methods were used, and the reasoning behind them, can be found in Section A.5.1.

With all required data obtained or otherwise approximated each design was compared against the needs and metrics laid out in Section A.2. In each case the value for each metric associated with each design was compared against the optimal and marginal values for that need and assigned a score out of 5 based on the comparison. The general guidelines used for assigning these scores are shown in Table XVI. However, exceptions to this rule do exist and are discussed as needed.

TABLE XVI: SCORING GUIDELINES

| Score | Guideline |
|---|---|
| **5** | Meets or exceeds optimal value. |
| **4** | Between marginal and optimal value. |
| **3** | At, around, or just better than marginal value. |
| **2** | Worse than marginal value. Difference large enough not to be within margin of error. |
| **1** | Nowhere near acceptable range. Unlikely to be capable of achieving even marginal value. |

In each case this score is then multiplied by the weighting for that particular need to generate a numerical sub-ranking. The weightings were determined through Client consultation and internal team discussion. The sub-rankings are then summed to yield an overall ranking out of 5 for each design which was used to assess its overall suitability.

The results of this process are shown in Table XVII.

## TABLE XVII: FINAL SCORING RESULTS

**Scoring Matrix**

| Need | Metric | Optimal Value | Marginal Value | Weighting | Rolling Hearth A (Can-Eng) | Value | Rolling Hearth B (Seco/Warwick) | Value | New Bell Furnace A (Prolific) | Value | New Bell Furnace B (Prolific) | Value | New Bell Furnace C (Prolific) | Value |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Design Anneals Cores | | | | | | | | | | | | | | |
| Design accomodates maximum core dimensions | Inches | L:35 5/8" x H:16" x W:8 1/2" | N/A | 0.09 | 5 | L:60" x H:36" x W:60" | 4 | W: 48" X L: 48" X H: Unknown | 2 | D: 36.2" X H: 61.02" | 4 | D: 49.21" x H: 98.43" | 5 | D: 59.06" x H: 118.11" |
| Design achieves annealing temperature | F | 1550 | 1475 | 0.1 | 5 | 1650 | 5 | 1540 | 5 | 1652 | 5 | 1652 | 5 | 1652 |
| Core Annealing Ranking: | | | | | 0.95 | | 0.86 | | 0.68 | | 0.86 | | 0.95 | |
| Design is Compatible with Existing Infrastructure | | | | | | | | | | | | | | |
| Design fits in available footprint | ft^2 | 750 | 2000 | 0.05 | 1 | 2806 | 3 | 1736 | 5 | ~750 | 5 | ~750 | 5 | ~750 |
| Design fits existing workflow | Binary | Yes | No | 0.02 | 5 | Yes | 5 | Yes | 3 | Possible crane height issues | 3 | Possible crane height issues | 3 | Possible crane height issues |
| Compatibility Ranking: | | | | | 0.15 | | 0.25 | | 0.31 | | 0.31 | | 0.31 | |
| Design is Controllable | | | | | | | | | | | | | | |
| Design allows operator input/output | Binary | Yes | Yes | 0.03 | 5 | Yes | 5 | Yes | 5 | Yes | 5 | Yes | 5 | Yes |
| Controllability Ranking: | | | | | 0.15 | | 0.15 | | 0.15 | | 0.15 | | 0.15 | |
| Design is Reliable | | | | | | | | | | | | | | |
| Design has long operational life | Years | 60 | 30 | 0.05 | 4 | 40 - 50 | 4 | 40-50 | 3 | 25-30 | 3 | 25-30 | 3 | 25-30 |
| Design requires minimal downtime | Days/year | 10 | 14 | 0.05 | 3 | Heuristic | 3 | Heuristic | 4 | Heuristic | 4 | Heuristic | 4 | Heuristic |
| Reliability Ranking: | | | | | 0.35 | | 0.35 | | 0.35 | | 0.35 | | 0.35 | |
| Design is Safe | | | | | | | | | | | | | | |
| Design protects operator from heat | Temperature at operator station [F] | Ambient | 80 F | 0.11 | 5 | Heuristic | 5 | Heuristic | 4 | Heuristic | 4 | Heuristic | 4 | Heuristic |
| Design uses gasses safely | Binary | Yes | Yes | 0.12 | 5 | Yes | 5 | Yes | 5 | Yes | 5 | Yes | 5 | Yes |
| Design allows emergency shutdown | Binary | Yes | Yes | 0.12 | 5 | Yes | 5 | Yes | 5 | Yes | 5 | Yes | 5 | Yes |
| Safety Ranking: | | | | | 1.75 | | 1.75 | | 1.64 | | 1.64 | | 1.64 | |
| Design is Efficient | | | | | | | | | | | | | | |
| Design can process expected work volume | Lbs/hour annealed | 2500 | 2000 | 0.08 | 5 | 2000+ | 5 | 2080 | 1 | 722 | 1 | 964 | 2 | 1550 |
| Design processes cores quickly | Total core processing time [hours] | 14 | 24 | 0.01 | 4 | Variable - on par with current | 5 | 17.5 | 4 | 20 | 4 | 20 | 4 | 20 |
| Design delivers uniform temperature distribution | Max temperature difference at one hour [F] | 0 | +/- 9 | 0.03 | 5 | Heuristic | 5 | Heuristic | 4 | Heuristic | 4 | Heuristic | 4 | Heuristic |
| Efficiency Ranking: | | | | | 0.59 | | 0.6 | | 0.24 | | 0.24 | | 0.32 | |
| Design is Economical | | | | | | | | | | | | | | |
| Design has capital cost within budget | $Cdn | 0 | 800000 | 0.03 | 1 | [redacted] | 2 | 1397000 | 5 | 114300 | 5 | 200000 | 5 | 475000 |
| Design has minimal operating costs | $Cdn/hour | $45/hour | $60/hour | 0.03 | 5 | [redacted] | 5 | 22.33 | 5 | 7.73 | 5 | 8.53 | 5 | 8.93 |
| Design has acceptable buyback period | Years | 15 | 20 | 0.08 | 1 | Relative | 2 | Relative | 3 | Relative | 4 | Relative | 5 | Relative |
| Cost Ranking: | | | | | 0.26 | | 0.37 | | 0.54 | | 0.62 | | 0.7 | |
| | | | | | | | | | | | | | | |
| **Overall Ranking:** | | | | | 4.2 | | 4.33 | | 3.91 | | 4.17 | | 4.42 | |

## A.5.1 Special Case Discussion

It has previously been mentioned that special cases exist in the final scoring, both regarding the values used for the various designs and in the scores themselves. A brief discussion of a few critical examples of each of these, including the rationale behind their presence, is included below.

### A.5.1.1 Data Special Cases

Due to time constraints, data unavailability, or other issues several key pieces of data could not be obtained prior to the submission of this report. In these instances various methods were used to approximate or otherwise simulate the missing data while retaining the best degree of accuracy possible under the circumstances. Table XVIII summarizes the instances where this occurred, any assumptions that were made, and the rationale behind them.

TABLE XVIII: DATA SPECIAL CASE SUMMARY

| Missing Data | Assumption | Rationale |
|---|---|---|
| **Internal vertical clearance for Roller Hearth B** | Vertical clearance is sufficient | Proposal was assembled with the maximum core size in mind. Required vertical is only 8 ½”. |
| **Operational life for Roller Hearth B** | Operational life is the same as that for Roller Hearth A | Both designs are of the same type and structurally very similar. |
| **Required annual downtime for all quotes** | Roller hearth designs will require an average amount of maintenance per year, bell furnaces will require less | Bell furnaces are much less complicated than roller hearths. Fewer parts to maintain, fewer components to fail and require replacement. |
| **Ability to protect operator from heat for all quotes** | Roller hearth designs will meet optimal requirements. Bell furnace designs will be slightly lower functioning | Roller hearths are enclosed systems and the insulation is known to be substantial. Bell furnaces require more exposure to elevated temperatures during lifting and unloading. |
| **Uniformity of temperature distribution for all quotes** | Roller hearth designs will achieve functionally uniform distribution. Bell furnaces slightly less so | Small volume of individual chambers, numerous temperature control zones, and horizontal orientation benefit heat distribution. Temperature control on bell furnaces is less precise and they are vertically oriented. |
| **Buyback period for all quotes** | Relative buyback period between quotes is proportional to PWC* ratio | See Section A.4 for full discussion. |

### A.5.1.2 Scoring Special Cases

In general the guidelines laid out in Table XVI were followed. However, certain cases arose when other factors took precedence in determining the score or that require explanation as to why the given score was chosen. The most notable examples of this are tabulated in Table XIX.

TABLE XIX: SCORING SPECIAL CASE SUMMARY

| Score Modified | Score Given | Rationale |
|---|---|---|
| **Max dimension score for Bell Furnace A** | 2 | There is little clearance between the max dimensions core and the maximum inner dimensions. Larger cores would only fit in the bottom layers. |
| **Footprint score for Roller Hearth B** | 3 | Utilizing space beyond 750 ft2 is exponentially more costly and challenging than the existing 750 ft2. Greater weighting given to scores closer to optimal. |
| **Production rate scores for Roller Hearths** | 5 | Designs only just reach marginal value. 2000 lbs/hr is already a relatively high end estimate. Rolling hearth designs can also be relatively easily scaled up if greater production is required. |
| **Payback period scores for all quotes** | Variable | Scores were assigned on a 1-5 ranking with the design with the best PWC* getting a 5 and the worst a 1 |

## A.5.2 Scoring Summary and Design Selection

Generally speaking Table XVII indicates that roller hearth designs offer benefits over bell furnaces in safety and efficiency while bell furnaces are superior with regards to space requirements and cost. In the ability to anneal cores the scores vary with each particular design and scores are uniform for reliability.

Overall the highest scoring design is the new bell furnace ‘C’ quote by Prolific Engineers. This design scores relatively poor in efficiency and slightly lower than the rolling hearth designs in safety but is otherwise at the top of every need category. As such this design is the considered by the Authors to represent the optimal solution given currently available information and is presented as such in the report body. As mentioned earlier this particular design is not feasible for the Client due to its unprecedented vertical clearance requirement. In this case, bell furnace quote ‘C’ is used merely as a template for the nature of the bell furnace which is recommended.

The second highest scoring design is the roller hearth ‘B’ quote by Seco/Warwick which, with the exception of cost, scored at or near the top of every category. Despite this, it still presents a substantial capital outlay and demands substantial dedicated floor space to operate. The myriad positive aspects of this design, the promising results of its PWC* analysis, and the position of the Client’s current operation on the boundary between batch-optimal and single-piece-optimal operations have convinced the Authors to include a discussion of this design in the report body as an alternate design should the Client’s situation change in such a way as to render it more desirable.

## A.6 Conclusion

A substantial amount of effort has been expended to develop client needs and metrics, collate available designs and cultivate proposals, and to then assess these proposals against the finalized Client needs.

As a result of these efforts the Authors have settled on an optimal design, consisting of a large electric bell furnace similar to that quoted by Prolific Engineers, and an alternate design, consisting of a complete roller hearth furnace system proposed by Seco/Warwick. These two designs are discussed further within the body of the text.

## A.7 References

[1] AEM Cores. Overview and Benefits of Unicore [Online]. Available:http://www.aemcores.com.au/technology/annealing/overview-and-the-benefit-of-unicore/ [October 19, 2013].

[2] R. Purushothaman, "Evaluation and Improvement of Heat Treat Furnace Model" [Online], Ph.D. Dissertation, Mft. Eng., Worcester Polytechnic Institute, 2008. Available: http://www.wpi.edu/Pubs/ETD/Available/etd-082208-114851/unrestricted/Purushothaman.pdf [accessed October 10, 2013].

[3] J. Bremser. (2013, October 15). "RE: Maximum Core Size / Weight?" Personal e-mail.

[4] Carlite. "AK Steel Product Data Bulletin". Product Data Sheet.

[5] D.Kuzmenko (private communication), October 9, 2013.

[6] D. Mikita (private communication), September 30, 2013.

[7] D. Mikita (private communication), October 7, 2013.

[8] OSHA (1999, January 20). OSHA Technical Manual (OTM) Section III: Chapter 4 [Online]. Available: https://www.osha.gov/dts/osta/otm/otm_iii/otm_iii_4.html,accessed October 8, 2013.

[9] Carte International, "Annealing Department Charge Load Sheet," October 2013, unpublished.

[10] D. Mikita. (2013, October 17). "Financial Analysis Follow-Up." Personal e-mail.

[11] G. Stanley. (2013, November 11). "RE: Rolling Hearth Information." Personal e-mail.

[12] G. Stanley (private communication), November 1, 2013.

[13] G. Stanley. (2013, October 8). "RE: Rolling Hearth Information." Personal e-mail.

[14] M.K. Soota (private communication), November 9, 2013.

[15] G. Stanley (private communication), November 20, 2013.

[16] G. Poschmann (private communication), November 21, 2013.

[17] G. Poschmann (private communication), November 15, 2013.

[18] M.K. Soota (private communication), October 30, 2013.

[19] M.K. Soota. (2013, November 15). “BELL FURNACE.” Personal e-mail.

[20] D. Mikita (private communication), September 23, 2013.

[21] M.K. Soota. (2013, November 18). “Bell Furnace.” Personal e-mail.

[22] M.K. Soota. (2013, November 24). “Bell Furnace.” Personal e-mail.

[23] D. Mikita (private communication), October 21, 2013.

[24] Manitoba Hydro. *Current Electricity Rates* [Online]. Available: http://www.hydro.mb.ca/regulatory_affairs/energy_rates/electricity/current_rates.shtml [November 18, 2013].

[25] M.K. Soota. (2013, November 17). “Bell Furnace.” Personal e-mail.

# Appendix B: Codes & Standards

# Table of Contents

## B.1 Introduction

The design, manufacture, and operation of annealing furnaces are the subject of several key standards. A brief summary of the nature and content of a few of the more relevant standards is included here.

## B.2 Relevant Standards

During the external search, codes and standards were reviewed to determine what the Canadian code standards would be applied to the retrofit designs. For the new designs, the manufacturer of the furnace was responsible for meeting the codes and standards. It was critical for the team to know what the code and standards are so the design can be adjusted. The first code and standard that was important is the safety of the furnace operators. International Labour Organisation (ILO) has specified standards for heat treating processes that ensures the safety of the operators. The standard states, "The work area and the flow of material through it should be designed so as to minimize the possibility of worker contact with hot steel, or to scalding in the case of quenching operations [1]." The ILO has also specified proper handling under their heat treating hazard control standards. The ILO standards for heat treating are listed under section 12 of the Code of practice on safety and health in the iron and steel industry-2005. Section 13 of the code of practice discusses the safety issues in transporting steel internally in the company. These codes will be helpful in finalising the concepts as they will determine whether it is possible to make changes to the existing furnace or not without compromising the safety of the operators.

Environment Canada also has codes and standards that must be met at the minimum for any furnace that operates in Canada. For the annealing furnace doors, it states, "Documented procedures should be developed and implemented for the control of emissions from furnace doors [2]." This standard is listed under section RI109. For the new design consideration, the furnace doors should be designed to minimize heat emission as specified by the standard. Again, the standards from Environment Canada must be met by the new and retrofit design for furnace to be operational in Canada.

American Society of Mechanical Engineers (ASME) has also set minimum codes and standards for an annealing furnace. The code and standard that was the related to the new furnace design was of the welding on the furnace doors and the insulation. Under ASME B31.1 – B31.5 [3] the minimum weld strength standards for the furnace doors and insulation have been mentioned. ASME Code Section 8 also mentions the mandatory requirements and guidance for inspections and testing mechanical devices. These standards will be most likely be incorporated by the manufacture but it was upon the team to point it out to the manufacture. The team in not going to carry out any actual building of a furnace and therefore it was good idea to point it out to the client that ASME standards need to be met to ensure safety of the operators.

Other standards such as the Aerospace Material Specifications (AMS) codes were reviewed. Codes and standards under the AMS cover the mandatory requirements for the temperature sensors, instrumentation, thermal processing equipment, system accuracy test and most importantly temperature uniformity tests. Most of the codes under AMS ensure that the safety of the operator remains a priority. AMS 2750D and AMS 2750E stated that regular inspections need to be carried to check if the thermocouples are giving correct temperature readings. This standard will be important when it comes to the maintenance of the furnace.  CQI-9 is also another standard that is very similar to the AMS 2750E and discusses the mandatory calibrations and inspections for temperature measurement devices such as thermocouples in a furnace.

## B.3 References

[1] Code of Practice on Safety and Health in the Iron and Steel Industry [Online]. International Labour Organisation 2005/8 Section 12-13. Available: http://www.ilo.org/wcmsp5/groups/public/@ed_protect/@protrav/@safework/documents/normatnormativeinst/wcms_112443.pdf [October 24, 2013].

[2] Environmental Code of Practice for Integrated Steel Mills [Online]. Environment Canada Codes of Practice Standard Number RI109. Available: https://www.ec.gc.ca/lcpe-cepa/default.asp?lang=En&n=30360F3C-1&printfullpage=true [October 24, 2013].

[3] Furnace Class and Instrumentation Requirements [Online]. Aerospace Material Specification Standard AMS 2750 E, NADCAP, CQI-9. Available: http://www.nabertherm.com/produkte/thermprozesstechnik/1-ams/1-ams_englisch.pdf [October 24, 2013].