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SENG 490: Directed Studies

Electric Kiln Design Project

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Chapter 1

Introduction

This report describes the learning outcomes of SENG 490, Directed Studies (Electric Kiln Design), at the University of Victoria. The topic of study was proposed by Sonia Rosenberger and carried out as a one-semester project focused on the cross-disciplinary engineering design of a compact electric kiln for hobby ceramics. The work brought together mechanical, electrical, materials, and embedded control design, with emphasis on practical engineering trade-offs involving cost, safety, manufacturability, portability, and performance within the constraints of standard household power.

A central aim of the project was to use the design and prototyping of a kiln as a vehicle for broader engineering learning. In addition to extending existing software and embedded systems experience, the project provided an opportunity to gain hands-on experience in electrical and mechanical design, fabrication, and physical system integration. The project also explored the use of open-source software as a way of reducing implementation complexity in a one-off DIY system, while still allowing for meaningful integration and critical evaluation of the software.

Over the semester, a complete kiln design was developed, materials and components were sourced, and considerable progress was made toward physical prototyping, construction, and subsystem testing. Prototyping and design occurred in parallel, with progress made incrementally as design decisions were refined and materials became available for integration. This report serves as the primary technical documentation of the design, prototype progress, and remaining work. The future work section outlines the steps still required to complete fabrication, integration, testing, and vali-

dation of a fully working kiln. Additional photo and video documentation was produced during the prototyping phase and will be made available upon completion of the kiln.

1.1 Project Overview and Motivation

Hobby electric kilns are compact, electrically heated furnaces designed for small-scale ceramic, glass, and metalworking projects, typically operating from standard household power supplies. They provide controlled temperature ramping and holding capabilities, making them suitable for consistent firing, sintering, and heat-treatment processes in home or studio environments.



Figure 1.1: L&L e23s-3 Easy Fire Electric Pottery Kiln, a representative commercial 120 V hobby kiln retailing at approximately \$7,000 CAD.

The motivation for this project came from a combination of personal and technical interests. An interest in ceramics, combined with an interest in

systems engineering, led to the goal of designing and building a compact, low-cost kiln for personal use. The goal was to create a kiln that would support pottery firing at home while providing experience with the complete engineering design process. The kiln was designed for personal production use rather than mass production, with a focus on portability, household electrical compatibility, and operation in a low- to medium-fire temperature range up to 1220 °C, the maximum temperature needed for cone 6 firing. The project also offered an opportunity to apply existing software and embedded systems knowledge in a broader physical system context, while developing practical skills in electrical and mechanical design and fabrication.

A further motivation was to investigate whether a one-off piece of hobby equipment could be designed and prototyped in a cost-effective and technically sound way, using a home workspace and the UVic ECSS Makerspace. Comparable commercial kilns, such as the Skutt Firebox or the L&L Plug N' Fire, typically retail for a minimum of \$2,000 CAD for the smallest models. The materials required for this design cost approximately \$1,200 CAD, with reclaimed materials used where possible to reduce cost and environmental impact. More broadly, the project was motivated by an interest in using engineering to make specialized equipment more accessible and customizable for individual use.

Throughout the project, the author used a wide variety of physical and online materials to learn about topics in electric kiln design. Materials included manufacturer guides and datasheets, academic references, ceramics technical publications, hobby-kiln forums, and consultation with engineering faculty and technical staff. Large language models (LLMs) were used as research tools to find reputable sources of specific information, as well as to sanity-check design decisions. All LLM output was critically evaluated and used as a tool rather than a source of truth.

The expected learning outcomes of the project included a cross-disciplinary understanding of mechanical and electrical design, materials selection, requirements engineering, information synthesis, technical documentation, embedded control systems, software analysis, ceramics technology, sustainable design, safety and assurance, quality engineering, and hands-on fabrication.

1.2 Project Scope and Constraints

Original Project Scope

The project was originally intended to cover the complete engineering design of a compact top-loading electric kiln for hobby ceramics, suitable for residential use on a standard 120 V, 20 A dedicated circuit, with the kiln intended to support ceramic firing up to cone 6 (approximately 1220 °C). The initial scope included both design work and complete construction, with the goal of producing a fully operational kiln within the directed studies timeline.

Work originally planned within scope included:

- requirements engineering and kiln design space research,
- complete mechanical, thermal, electrical, and control-system design,
- sourcing and selection of refractory, insulation, electrical, and control components,
- fabrication of the firebrick chamber, insulation layer stacks, and modified steel cabinet,
- design, winding, and installation of custom Kanthal A1 heating elements,
- development of the mains power path, SSR-based switching hardware, and safety mechanisms,
- development of a Raspberry-Pi-based controller with thermocouple sensing and web-based control software,
- subsystem testing and staged integration of the controller and heater hardware, and
- preparation of technical documentation describing the design, construction process, testing, and validation work.

Constraints Affecting Scope Completion

Although the project scope remained technically feasible, several practical constraints affected the extent of implementation that could be completed within the course timeline. Key constraints included:

- the one-semester duration of the directed studies course,
- long lead times for specialty refractory, heating, sensing, and high-temperature electrical components in small quantities within Canada,
- delayed supply and tool delivery, which limited confidence in completing construction and tests before the final deadline,
- the need to divide work between home fabrication and UVic ECSS Makerspace resources,
- the need for in-depth safety reviews before any energized mains testing, and
- additional time required to resolve unexpected fabrication issues, particularly in slab assembly and materials integration.

These factors did not change the underlying design objectives, but they did limit the degree of final assembly, integration, and validation completed before submission.

Final Scope of This Submission

The final submitted scope consists of the work completed by the end of the course: a complete kiln design, substantial materials sourcing and component selection, partial physical construction, partial control-system prototyping, and a documented plan for the remaining implementation, testing, and validation required to produce a fully working kiln. Design and safety reviews were performed at incremental stages throughout the project in order to allow construction to proceed according to this design plan after course completion.

Accordingly, this report documents:

- the completed mechanical, thermal, electrical, and control-system design of the kiln,
- the reasoning, calculations, and engineering trade-offs that informed that design,
- sourcing decisions, substitutions, and cost-related considerations,
- physical construction progress made on the firing chamber, shell, insulation, and related fabrication and assembly tasks,
- controller setup and early prototype work, including software configuration and thermocouple interface testing,
- challenges and limitations that affected progress during the semester, and
- a future-work plan describing the remaining fabrication, integration, powered testing, and safety and validation steps required for full operation.

The final submission therefore represents a completed engineering design supported by meaningful prototype progress, rather than a fully integrated kiln. The remaining work is described explicitly so that a clear path is presented from the current prototype state to a finished working system.

1.3 Report Structure

The report is organized to reflect the structure of the project itself: design work is documented first, followed by prototype construction progress, a plan for remaining implementation, lessons learned, and future work.

Chapters 2 through 7 cover the engineering design of the kiln system. These chapters document the functional requirements and design basis, system architecture, and the mechanical, electrical, and control subsystem designs. The design work is substantially more complete than the physical build, and these chapters reflect that: they represent a full engineering design supported by analysis, component selection, and specifications, even where fabrication is still ongoing.

Chapter 8 presents the Bill of Materials and cost summary. Chapters 9 and 10 document prototype construction progress to date and the technical challenges encountered. Chapter 11 outlines the remaining implementation work needed to complete the kiln. Chapter 12 describes the planned testing and validation approach. Chapters 13 and 14 cover future work and conclusions.

Chapter 2

Engineering Requirements and Design Basis

2.1 Functional Requirements

The kiln needed to support small-scale hobby ceramic firing in a residential setting. It needed to reach and hold a maximum temperature of approximately 1220 °C for about 10-15 minutes for a cone-6 firing, while operating from a standard household outlet. The system needed to provide controlled heater switching, temperature measurement, and automatic closed-loop control over the course of one firing. The control system also needed a user interface for real-time temperature display and custom firing cycles with tunable parameters depending on kiln performance upon construction. The project also required a practical physical design. The kiln needed to be buildable with available tools and serviceable after construction. Finally, the design needed to implement physical fail-safe measures to ensure that electrical and thermal hazards were addressed before first operation.

2.2 Non-Functional Constraints

The design was constrained by standard residential electrical service. Heater power had to remain within conservative continuous-use limits for a 120 V, 20 A dedicated circuit. For a 2400 W circuit, the 80% continuous-load rule

allows a maximum draw of 1920 W. Cabinet dimensions, insulation thickness, and total heater power therefore had to be chosen together rather than independently.

The project was also constrained by the one-semester timeline. Specialty refractory, heating, sensing, and high-temperature electrical parts were difficult to source in small quantities within Canada, and shipping delays introduced occasional schedule variability. Work had to be split between a home workspace and the UVic ECSS Makerspace, depending on the tools and safety requirements of each task.

Cost, portability, safety, maintainability, and safety were additional constraints. The kiln needed to remain practical for home use, safe to load and unload, use reclaimed materials where reasonable, and avoid custom fabrication where possible.

2.3 Design Success Criteria

At the design level, success meant producing a complete mechanical, thermal, electrical, and control-system design with justified subsystem choices and a sourceable bill of materials. The design needed to show that the kiln could meet its heating target within residential power limits and that the major safety and integration points had been addressed.

At the prototype level, success meant sourcing the major materials, making meaningful fabrication progress on the kiln body and chamber, advancing the controller from concept to a well-documented implementation, and describing the remaining path to full integration and validation.

2.4 Key Tradeoffs and Assumptions

A lower-power 120 V kiln was chosen instead of a 240 V design because residential compatibility was a core requirement (i.e. operating from a garage outlet on a dedicated circuit). This reduced the available heater power and made insulation performance more important. The design therefore depended on a careful insulation stack and conservative heater sizing.

A top-loading cylindrical kiln was selected instead of a rectangular or front-loading design. The shape reduced shell fabrication complexity by considering the availability of reclaimed cylindrical vessels. Orientation supported safer loading and unloading, because reaching down into a kiln is easier than in through a door. A reclaimed stainless steel keg was preferred initially, but a suitable unit could not be found; an unlined 55-gallon cold-rolled steel barrel with a lockable lid was used instead.

The design assumed that a hand-built kiln would not be perfectly airtight. Passive air leakage was treated as inevitable, and as a ventilation strategy rather than as a defect to eliminate. Ventilation implications are discussed in Section [5.3](#).

Several additional tradeoffs shaped the design. A smaller internal chamber reduces total heat loss, but increases shell surface temperature (a safety and insulation-thickness concern that had to be balanced). Cost and material availability meant that the ideal refractory or heater solution was not always obtainable; reclaimed and locally available materials were used where feasible. The one-semester timeline also constrained validation thoroughness, as only so much time was available to explore the full design space. Where custom fabrication would have improved solution quality, prefabricated or stock parts were substituted; this was acceptable given that the kiln is for personal rather than industrial use.

Chapter 3

Product Design Specification

3.1 Kiln Cabinet, Stand, and Insulation

3.1.1 Design Specifications

Specification	Target Value	Justification
Exterior size	Portable, fits in the cargo space of vehicle: $\leq 2,300$ L (83 ft ³)	The system will be designed to fit within a personal vehicle to enable transport during relocation or off-site firing.
Maximum system mass	≤ 68 kg (150 lb)	The kiln will be designed such that it can be lifted by one person or with minimal assistance. A rolling stand may be added to further improve mobility.
Cabinet material	Cold-rolled steel drum	Steel drums are inexpensive and widely available. A rust-proof, temperature-rated spray paint coating may be applied to increase corrosion resistance.

Specification	Target Value	Justification
Internal hot-face lining material	K23 insulating firebrick (rated to 1200 °C / 2300 °F), 63.5 mm (2.5 in) thickness	K23 firebrick is commonly used in hobby kilns, is cost-effective, and can be cut using hand tools. Thinner walls are suitable for small kilns and allow faster heating and cooling.
Backup insulation layers	Sidewalls: ceramic fiber blanket rated to ≥ 1260 °C. Lid and bottom: rigid insulating board rated to ≥ 650 °C.	Supplemental insulation will reduce heat loss and balance chamber volume reduction and material cost. Each layer must tolerate the temperatures expected at that position in the insulation stack.
Kiln geometry	Cylindrical or near-cylindrical chamber	Cylindrical and cubic shapes provide favorable thermal efficiency and uniform heating characteristics.
Loading orientation	Top-loading design	Top-loading geometry improves visibility during loading, reduces accidental contact between pieces, and is ergonomically safer than front-loading configurations.
Stand	Removable metal barrel dolly	Will raise kiln off the ground for airflow and heat safety.

3.2 Ventilation

3.2.1 Design Specifications

Specification	Target Value	Justification
Room ventilation	Passive window exhaust, small fan	For small kilns, sufficient ventilation can be achieved using open windows or outdoor firing locations. Room ventilation of at least 10-25 times the cubic feet of the kiln per hour is recommended.
Chamber ventilation	Passive, natural leakage	Expected to be sufficient.
Fume isolation	Separation of electronics enclosure airflow from kiln exhaust	Electrical components will be protected from heat and corrosive fumes by maintaining airflow separation.

3.3 Electrical Power System

3.3.1 Design Specifications

Specification	Target Value	Justification
Supply voltage	120 V AC (household)	Standard residential outlets provide 120 V AC supply, simplifying installation in contrast to adding an additional 240 V AC circuit to the operating environment.
Phase configuration	Single-phase	Residential operating environments typically support only single-phase electrical service.

Specification	Target Value	Justification
Power draw	$\leq 1.8 \text{ kW}$	A 20 A 120 V household circuit can provide up to 2400 W ($120\text{V} \times 20\text{A}$), with a maximum continuous load limit of 1920 W (80% of max. power). 1.8 kW is expected to be sufficient for this design (see Section 5.5).
Current draw	$\leq 15 \text{ A}$	15 A will be used to achieve 1.8 kW. This is less than 16 A, the maximum continuous current draw for a 20 A 120 V circuit.
Breaker	$\leq 20 \text{ A}$	A 120V 20A circuit breaker can facilitate the expected load of the kiln, with additional margin for a low-power control device. A dedicated circuit will reduce nuisance breaker trips and prevent interaction with other household loads.
Mains input connector	Grounded 120 V AC plug with three-conductor power cord	Mains connection must match power outlet specifications and connect to power (line), return (neutral), and safety ground (protective earth).
Input power cord rating	$\geq 20 \text{ A}$ continuous duty, workshop-rated insulation, 12-gauge	The kiln will operate as a continuous high-load appliance, requiring a power cord rated for sustained current and elevated ambient temperatures. Length must be sufficient to permit 18-36" clearance between surroundings and all sides of the kiln. Internal insulated wires must be able to be cleanly separated to facilitate connection to the SSR's AC input and return and kiln shell grounding point.

Specification	Target Value	Justification
Ground bonding	Protective earth bonded to kiln shell, lid hardware, stand, and element junction box	Ground bonding will ensure that any internal electrical fault energizing the conductive surfaces of the kiln shell will be safely diverted to earth ground.
Primary disconnect	Manual mains disconnect located upstream of heater switching	A local disconnect (unplugging the mains input connector) will allow safe servicing and provide an immediate physical shutdown independent of software control.
Power path segregation	Isolate high-voltage heater power path and low-voltage control power path	Electrical separation will reduce shock hazards and prevent interference between heater switching and control electronics.
Low-voltage control power supply	Isolated 5V, 2.5A Micro USB power supply with insulated cable for Raspberry Pi	Control electronics require stable low-voltage power independent of heater switching for reliable operation.
Cable entry strain relief	Rated strain relief glands at all enclosure cable entry points	Strain relief will prevent conductor damage and accidental disconnection during transport and operation.
High-temperature wiring near hot zones	High-temperature-rated insulation for wiring adjacent to kiln body	Elevated ambient temperatures near the kiln enclosure require insulation materials that resist thermal degradation.
Power system labeling	Clear labeling of mains input, heater output, and control power connections	Labeling will improve maintenance safety and reduce wiring errors during troubleshooting or upgrades.

3.4 Heating Elements

3.4.1 Design Specifications

Specification	Target Value	Justification
Heating element material	Kanthal A-1 resistance wire, maximum element temperature 1400 °C	Kanthal A-1 is widely used in electric kilns and provides reliable performance up to 1400 °C, well above the 1220 °C cone 6 target.
Wire diameter	1.29 mm (0.0508 in, B&S gauge 16)	Selected standard diameter nearest to the calculated minimum of 1.198 mm; sets the coil geometry and achieves target surface loading.
Element power and current	900 W per element chain at 120 V, 7.5 A per chain; 1800 W and 15 A total (two chains in parallel)	Two elements wired in parallel; combined heater load of 1800 W at 15 A satisfies the power system design constraint and provides margin for fast ramp-up.
Power density	4.83–5.73 kW per cubic foot	Heat loss calculations (see Section 5.5) indicate that for this design with 0.331 cubic ft. chamber, a conservative estimate of 1.6–1.9 kW is needed for cone 6. This gives a power density of 4.83–5.73 kW per cubic foot.

3.5 Power Switching and Relay Hardware

3.5.1 Design Specifications

Specification	Target Value	Justification
Relay type	Zero-cross solid state relay (SSR)	Zero-cross switching reduces electrical noise, minimizes electromagnetic interference, and improves heater element lifespan for resistive loads. SSRs have good longevity and are suitable for low-current kilns.
Control input voltage	3–32 V DC logic compatible	This allows direct low-voltage control input voltage from Raspberry Pi without additional driver circuitry.
Load output rating	≥ 40 A at 120 V AC	Oversizing the SSR improves thermal reliability and provides margin above the maximum heater current draw.
Thermal management	External aluminum heat sink with thermal paste compound	SSRs dissipate heat under load and require proper thermal management to avoid thermal failure modes.
Electrical isolation	Optical isolation internal to SSR	Electrical isolation protects low-voltage control electronics from high-voltage heater circuits.
Power indication	LED pilot light	A pre-integrated pilot light provides a visual indication of power transmission through the relay when it is switched on.

3.6 Thermocouples and Temperature Measurement Hardware

3.6.1 Design Specifications

Specification	Target Value	Justification
Thermocouple type	Type-K ceramic-sheathed thermocouple, rated to $\geq 1300^{\circ}\text{C}$	Type-K sensors provide sufficient temperature range capability for hobby kilns at significantly lower cost than Type-S alternatives.
Thermocouple probe gauge	Heavy-duty, ceramic-insulated, kiln-rated probe (minimum 8-gauge equivalent)	Larger probe diameters improve mechanical durability and long-term stability under repeated thermal cycling. Ceramic insulation is necessary to minimize reaction with kiln fumes and insulate the thermocouple from any potential contact with heating elements.
Thermocouple length	250mm	Thermocouple probe needs to be long enough to extend through the kiln sidewalls (7" thick) and extend 2-3" into the firing chamber for accurate temperature readings.
Interface board	MAX31855 thermocouple amplifier with pin header	These interface boards provide cold-junction compensation, digital SPI output, and compatibility with Raspberry Pi hardware as specified by the controller software.
Signal interface protocol	SPI digital communication	SPI communication reduces noise susceptibility and allows reliable temperature data acquisition.

3.7 Control Hardware Platform

3.7.1 Design Specifications

Specification	Target Value	Justification
Primary controller	Raspberry Pi Zero 2W single-board computer with GPIO header	The open-source kiln controller software is designed for Raspberry Pi platforms and requires only a small number of GPIO pins with SPI capability.
Connectivity	Integrated Wi-Fi networking	Wireless connectivity enables web-based user interface access and remote monitoring without additional display hardware.
GPIO expansion hardware	Breadboard and electrical components kit	Breakout hardware simplifies safe wiring of thermocouple modules, SSR control signals, and auxiliary inputs. Additional components such as resistors, LEDs, jumper wires, and transistors may be needed to explore control system circuitry design and facilitate testing of individual components before mains wiring.
Enclosure separation and containment	Isolated control electronics enclosure	The control hardware must be physically separated from high-temperature zones and corrosive kiln exhaust to improve reliability and safety. The enclosure must provide good airflow around electronics and be robust enough to prevent the circuit from accidental damage or contact with other system components.

3.8 Controller Software and User Interface

3.8.1 Design Specifications

Specification	Target Value	Justification
Control software platform	Open-source kiln-controller application (GitHub project)	The selected open-source platform provides a customizable and low-cost solution with community-reviewed logic and hardware flexibility. Transparent development history and operation is more suitable for safety auditing and exploration of the control system concepts than a closed-source solution. Implementation is also considerably easier than any custom software alternative.
User interface method	Web-based browser interface	A browser-based interface avoids the need for dedicated touchscreen hardware and allows control devices to remain physically distant from heat and fumes.
Offline operation support	Local control without continuous internet access	The controller must remain functional during network outages or weak wireless connectivity common in garage environments.

3.9 Safety Mechanisms

3.9.1 Design Specifications

Specification	Target Value	Justification
Fire safety equipment	Smoke alarm and fire extinguisher present during operation	Residential kiln operation requires additional precautions to mitigate fire risk.
External surface temperature management	Insulation and thermal model validation	Surface temperatures will be minimized using additional insulation to reduce burn risk during operation. The surface temperature of the kiln will be closely monitored during the first firing to validate the thermal model created in the design phase.
Thermal safety cutoff	Dedicated thermal fuse, rated to maximum safe kiln shell temperature	A thermal safety cutoff adds a hardware protection layer to the kiln and operating environment independent of software and the building breaker. Fuse should be placed between the SSR AC output and the heating elements. If the power switch fails on and the kiln exterior exceeds an expected temperature, the fuse must permanently trip the circuit and disconnect power from the elements.
Software safety features	Watchdog timer, fault states, explicit shutdown paths	Software-level safety mechanisms will provide automated fault detection and immediate heater shutdown during abnormal operating conditions or unexpected behaviour of the control feedback loop.

Specification	Target Value	Justification
Safety and hazard documentation	Physical checklists and safety warnings	A checklist must be present in the operating environment that clearly defines acceptable operating conditions, maintenance checks, and steps for safe operation both post- and pre-firing. A safety warning and list of hazards must also be present to reduce the risk of unqualified persons attempting to operate the kiln.
Element power indicators	Panel-mount 120 V AC pilot lights	LED pilot lights rated to mains voltage and kiln cabinet external temperature must be placed in series with each heating element. This provides a visual indication that power is relayed to an element, and will also provide a method of verifying that each elements is being switched as expected by blinking on and off as power is supplied from the SSR.
Over-current protection	Circuit breaker specification	The dedicated circuit upstream of the kiln must be guaranteed to trip on sustained overload or short-circuit.

3.10 Maintenance and Transport

3.10.1 Design Specifications

Specification	Target Value	Justification
Modular components	Replaceable thermocouples and heating elements	Modular replacement reduces long-term maintenance cost and simplifies repairs.
Transport system	Rolling stand with lockable wheels	A wheeled stand will improve mobility while maintaining system stability during operation.

3.11 Additional Considerations

Metric units will be used preferentially throughout the design documentation. Imperial units will be included in parentheses where manufacturer specifications or industry-standard component dimensions are provided using imperial measurements.

Chapter 4

System Architecture Overview

4.1 Overall System Description

The kiln was designed as a set of interacting subsystems. The hot chamber is formed from insulating firebrick. The chamber is housed inside a modified steel barrel, with backup insulation filling the space between the refractory structure and the shell. Two custom-wound Kanthal A1 heating elements provide heat from sidewall grooves.

Electrical power enters through a residential mains path and is switched by a solid-state relay (SSR). Temperature is measured by a thermocouple connected through a MAX31855 thermocouple breakout board. A Raspberry Pi Zero 2 W runs the open-source kiln controller software, provides a web-enabled graphical user interface (GUI), provides cycle control and safety mechanisms, and drives the heater control logic via GPIO pins. A thermal fuse provides an independent hardware safety layer.

4.2 Major Subsystems and Interfaces

Table 4.1: Major system subsystems and key components

Subsystem	Key Components
Mechanical	Steel barrel shell, chamber ring, lid and base slabs, and structural support features
Thermal	Refractory hot-face bricks, backup insulation layers, and the shell surface exposed to the surrounding room
Electrical	Mains input path, SSR switching hardware, heating coil branches, external terminals, and grounding scheme
Sensing	Thermocouple probe and MAX31855 breakout board
Control	Raspberry Pi, GPIO interface, software stack, and web UI

Heat is generated by the elements in their grooves in order to heat the internal firing chamber. Heat is transferred through the chamber walls, end slabs, and backup insulation layers to the steel shell and kiln surroundings. Mains power is routed through the SSR to the heating elements. Temperature data travels from the thermocouple to the breakout board, then to the Pi over SPI. Control signals travel from the Pi to the SSR through GPIO.

4.3 High-Level Design Decisions

Several system-level decisions shaped the design early-on. These were deemed high-level because they had the greatest effect on the rest of the design work that followed.

- The kiln was made top-loading rather than front-loading.
- A reclaimed cylindrical shell was used rather than fabricating a custom cabinet, fixing the available internal diameter and the surface area of the top and bottom of the kiln.
- A maximum power target of 1.8 kW was chosen to add an engineering margin to the maximum continuous operation limit.

- A requirement for shell temperature was introduced and defined so as to not exceed 100°C.
- The heating system was split into two parallel elements rather than one series element.
- The control system was based on an open-source Raspberry Pi controller rather than written from scratch. This significantly reduced software complexity and allowed effort to be focused on hardware selection, integration, and validation. The software choice then dictated the basic control system structure.
- Ventilation was deemed a low priority for the kiln size and construction expectations. A fan-assisted vent option was kept open for later implementation if testing showed it was needed (see Section 5.3).

Chapter 5

Mechanical and Thermal Design

This chapter describes the cabinet construction, insulation strategy, and heat transfer analysis for the kiln. The insulation stack and chamber geometry were selected to allow the internal firing chamber to reach and hold 1220 °C while keeping electrical power demand within the constraints of a residential 120 V circuit and maintaining safe exterior surface temperatures.

5.1 Enclosure and Chamber Geometry

Cabinet design considered internal chamber volume as well as the cost of insulation needed to line the chamber. A reclaimed 55-gallon cold-rolled steel barrel was deemed the most cost-efficient option, with several options available for purchase in good condition from online marketplaces. In order to ensure non-reactivity with temperature and kiln fumes from firing, any coating on the outside of the barrel was to be removed or covered with a secondary heat-resistant coating prior to construction.

A standard 55-gallon barrel measures 23" in outer diameter, 34–35" in height, and radial wall thickness 0.05". Models with a hasp and ring to seal a removable lid are common. A cylindrical section of the barrel was to be cut out and removed such that the lid end-cap section is flush with the top face of the chamber.

The following figure shows a top view of this kiln design with dimensions of interest.

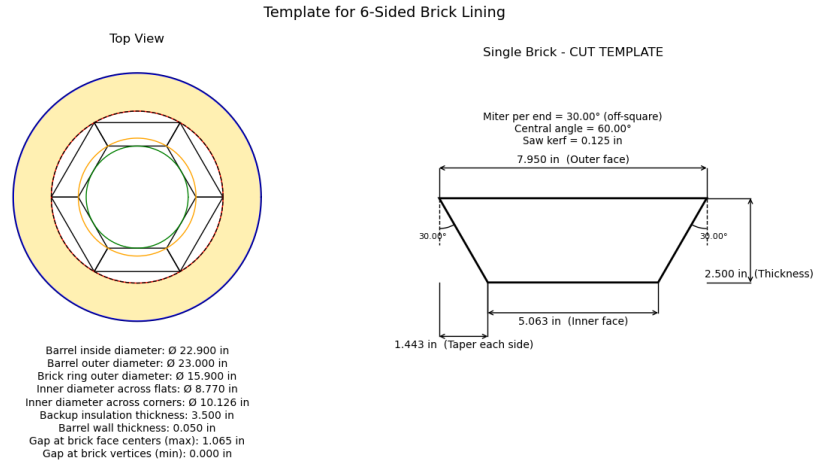


Figure 5.1: 55-Gallon Barrel, 6-sided IFB ring geometry

5.2 Insulation Strategy

The kiln cabinet will be lined with different types of insulation, based on structural and thermal requirements.

The internal refractory hot-face is formed from stacked K-23 insulating fire-brick (IFB) rings, joined with refractory cement. One K-23 IFB measures 9"×4.5"×2.5", and these will be arranged in stacked hexagonal rings of radial thickness 2.5" and height 4.5" per ring. Stacking two rings will give a chamber height of 9".

Backup insulation layers will be used for the sidewalls, bottom, and lid sections, between the IFB layer and the steel cabinet shell. IFB "slab" layers will need to be added to the hot face of the lid and bottom sections of the kiln to act as the end caps of the closed firing chamber. Insulating ceramic fiber wool will be used for the side walls. Insulating board will be used for the lid and bottom to avoid compressing the insulation when an IFB slab is placed on top of the backup layer during end-cap construction.

For heat-transfer modeling, each sidewall insulation layer is approximated as a concentric circular cylinder of equivalent radial thickness and height

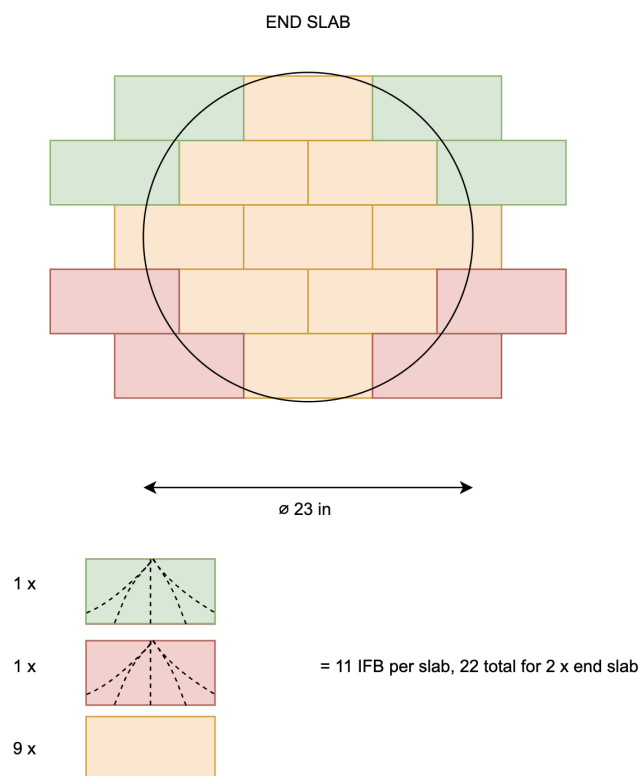


Figure 5.2: Diagram showing how IFBs were cut and assembled to form the end slabs for the kiln lid and bottom hot faces.

equal to that of the chamber. Lid and bottom end-caps are approximated as circular slabs.

The insulation strategy is:

- **Sidewalls:** 2.5 in (63.5 mm) K-23 brick backed by 4.0 in (101.6 mm) ceramic fiber wool.
- **Lid and bottom:** 2.5 in (63.5 mm) K-23 brick backed by 3.0 in (76.2 mm) rigid insulating refractory board.

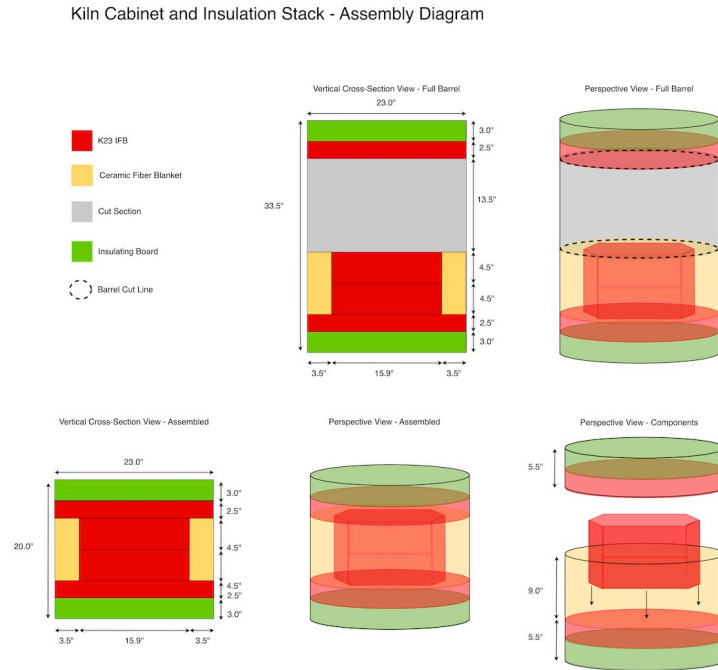


Figure 5.3: Insulation stack layout diagram for the kiln chamber sidewalls, lid, and bottom slabs, with layer thicknesses and material assignments.

Note that in Figure [5.1](#), the yellow-shaded layer of backup insulation is set to 3.5" radial thickness, reduced from the 4" radial thickness assumed in the model. During actual construction, the gaps between the backup insulation and the IFB outer flat face (here, maximum radial thickness 1.065") will be filled with additional ceramic fiber wool. Thus, the average thickness of the fiber layer will roughly match the one used in this thermal model.

Air and moisture are assumed to escape through small natural gaps. This leakage is not explicitly modeled and is treated as part of the uncertainty margin applied to the final power estimate.

The ideal rigid insulation board for the lid and base was difficult to source in small quantities at reasonable cost within Canada. A substitute needed to provide strong insulation, tolerate the expected backup-layer temperatures, present manageable handling hazards, and support a firebrick slab without excessive compression.

This led to the use of PowerWool RigiBoard One, a rigid mineral wool product intended for non-combustible residential insulation. It was available at low cost as a reclaimed leftover from a construction project, in more than the required quantity. It can tolerate temperatures up to 650 °C, which was acceptable because the backup layer is not expected to approach that temperature in normal operation. Its thermal conductivity is comparable to that of the ideal insulation board with respect to the heat loss estimate margins in this thermal model. It is also easy to cut and does not add material safety hazards beyond those already addressed with existing PPE.

Hazardous material handling was considered a priority during design and fabrication planning. Safety practices for IFB, refractory mortar, and similar materials were based on safety data sheets and kiln-specific handling guidance.

5.3 Ventilation and Fume Management

Ventilation requirements were reviewed as part of the overall kiln design. A small kiln built from cut brick and hand-fitted slabs is unlikely to be perfectly airtight. Some passive leakage through masonry gaps and imperfect lid sealing was therefore treated as expected behavior rather than as a defect that had to be completely eliminated.

Dedicated vent holes were not treated as necessary in the initial prototype, provided the surrounding room was well ventilated. If firing behavior or moisture release later showed a need for stronger venting, a fan-assisted exhaust option was identified. A downdraft option could use a hole drilled through the kiln bottom, with a hose and exhaust fan attached and routed outdoors. The two removable ports already present in the barrel lid were also identified

as potential vent ports for gas and moisture release if needed.

Controls electronics were always intended to remain separate from the kiln exhaust path. They are not meant to share any airflow with the hot chamber, and will be physically located at a distance of at least one metre away from the kiln shell.

5.4 Thermal Model and Heat Transfer Approach

This section estimates the steady-state heat loss and external surface temperatures of the kiln during a 1220 °C soak. A 1220 °C soak of approximately 10–15 minutes corresponds to a typical **Cone 6** firing profile for small electric kilns (approximately $< 4 \text{ ft}^3$ internal volume).

The kiln is modeled as a closed cylindrical enclosure with independent heat-flow paths through the **sidewalls**, **lid**, and **bottom**. These paths act in parallel and are evaluated separately. The goal is to estimate (i) minimum electrical power required to hold 1220 °C and (ii) expected external surface temperatures under fan-assisted airflow in an ambient temperature of 15 °C.

5.4.1 Geometry and Insulation Layout

Standard 55-gallon drum outer dimensions:

- Outer diameter: $D_o = 0.584 \text{ m} = 584 \text{ mm} = 23.0 \text{ in}$
- Outer radius: $r_o = 0.292 \text{ m} = 292 \text{ mm} = 11.5 \text{ in}$
- Nominal shell thickness: $t_{steel} = 1.0 \text{ mm} = 0.039 \text{ in}$

Internal diameter. The internal hot-face radius is set by the radial insulation stack:

$$r_i = r_o - (t_{steel} + t_{wool} + t_{brick})$$

$$r_i = 292 - (1.0 + 101.6 + 63.5) \text{ mm} = 125.9 \text{ mm} = 4.96 \text{ in}$$

Thus the internal chamber diameter is:

$$D_i = 2r_i = 251.8 \text{ mm} = 9.92 \text{ in}$$

Internal height (set by cut shell). The usable hot-face chamber height is fixed at:

$$H_i = 9.0 \text{ in} = 228.6 \text{ mm} = 0.2286 \text{ m}$$

Lid and bottom stack thickness.

$$t_{end} = t_{steel} + t_{board} + t_{brick}$$

$$t_{end} = (1.0 + 76.2 + 63.5) \text{ mm} = 140.7 \text{ mm} = 5.54 \text{ in}$$

Thus the trimmed outer shell height becomes:

$$H_o = H_i + 2t_{end}$$

$$H_o = 228.6 + 2(140.7) = 510.0 \text{ mm} = 20.1 \text{ in}$$

5.4.2 Material Properties

Representative thermal conductivities used for steady-state modeling:

- K-23 insulating firebrick: $k_{brick} = 0.24 \text{ W}/(\text{m} \cdot \text{K})$
- Ceramic fiber wool: $k_{wool} = 0.34 \text{ W}/(\text{m} \cdot \text{K})$

- Cold-rolled steel shell: $k_{steel} = 50 \text{ W}/(\text{m} \cdot \text{K})$
- Backup insulation board: $k_{board} = 0.115 \text{ W}/(\text{m} \cdot \text{K})$

5.4.3 Boundary Conditions

- Internal hot-face temperature: $T_i = 1220^\circ\text{C} = 1493 \text{ K}$
- Ambient temperature: $T_\infty = 15^\circ\text{C} = 288 \text{ K}$
- External emissivity (oxidized steel): $\varepsilon = 0.85$
- Forced convection coefficient (fan-assisted): $h = 25 \text{ W}/(\text{m}^2\text{K})$
- Stefan-Boltzmann constant: $\sigma = 5.67 \times 10^{-8} \text{ W}/(\text{m}^2\text{K}^4)$

5.4.4 Heat Transfer Model

At steady state, heat conducted through each surface equals heat rejected at the external shell by convection and radiation:

$$Q = \frac{T_i - T_s}{R_{cond}}$$

$$Q = A [h (T_s - T_\infty) + \varepsilon \sigma (T_s^4 - T_\infty^4)]$$

where T_s is the external surface temperature.

Active hot-gas contact assumption. Hot kiln gases are assumed to contact only the internal chamber walls over height H_i . Sidewall heat transfer is therefore evaluated only over this active band.

5.4.5 Conduction Resistances

Sidewalls (radial conduction). Thermal resistance through concentric cylindrical layers is modeled using:

$$R = \frac{\ln(r_2/r_1)}{2\pi k H_i}$$

Summing steel + wool + brick layers yields:

$$R_{side} \approx 2.06 \text{ K/W}$$

Lid and bottom (axial conduction — bracketed range). Because the end caps involve two-dimensional heat spreading, two bounding cases are evaluated:

- **Lower bound (hot-face area):** $A_i = \pi r_i^2 = 0.0499 \text{ m}^2$
- **Upper bound (full slab area):** $A_o = \pi r_o^2 = 0.2662 \text{ m}^2$

Using 1-D slab conduction:

$$R = \frac{L}{kA}$$

Summing steel + board + brick gives:

$$R_{end,hot} \approx 18.6 \text{ K/W}$$

$$R_{end,cold} \approx 2.61 \text{ K/W}$$

The true resistance lies between these limits.

5.4.6 External Surface Areas

- Sidewall active band:

$$A_{side} = \pi D_o H_o = 0.9360 \text{ m}^2 = 10.0748 \text{ ft}^2$$

- End external surface:

$$A_{end} = \pi r_o^2 = 0.2662 \text{ m}^2 = 2.8655 \text{ ft}^2$$

5.5 Heat Loss, Surface Temperature, and Power Requirement Results

5.5.1 Results: Heat Loss and Surface Temperatures

Sidewalls. Solving the coupled conduction–convection–radiation balance:

$$T_{side} \approx 35^\circ\text{C} \text{ (} 96^\circ\text{F)}$$

$$Q_{side} \approx 0.57 \text{ kW}$$

Lid and bottom (bounded range). Using the two resistance limits:

- **Upper loss case (full-slab area):**

$$T_{end} \approx 68^\circ\text{C}, \text{ (} 155^\circ\text{F)} \quad Q_{end} \approx 0.44 \text{ kW}$$

- **Lower loss case (hot-face area):**

$$T_{end} \approx 23^\circ\text{C}, \text{ (} 74^\circ\text{F)} \quad Q_{end} \approx 0.064 \text{ kW}$$

Total enclosure heat loss. Summing sidewalls plus two end caps:

$$Q_{total,min} \approx 0.57 + 2(0.064) = 0.698 \text{ kW}$$

$$Q_{total,max} \approx 0.57 + 2(0.44) = 1.45 \text{ kW}$$

A realistic operating value is expected to lie between these bounds.

Required holding power. From the thermal model calculations above, the upper limit for required power is:

$$P_{max} \approx 1.5 \text{ kW}$$

This level is compatible with continuous operation limits on a 120 V / 20 A circuit while providing sufficient reserve for non-ideal losses from insulation differences and/or air leakage.

5.5.2 Model Limitations

This analysis is a first-order engineering estimate and includes the following simplifications:

- One-dimensional conduction in each layer
- Representative thermal conductivities at temperatures near 1220 °C
- Uniform internal gas temperature
- Cylindrical approximation of polygonal brick geometry
- End-cap spreading resistance approximated using bounding areas
- Leakage and thermal bridges captured via design margin

Despite these simplifications, the model provides a conservative feasibility check for insulation design, surface temperature safety, and electrical power requirements.

5.6 Maximum Heating Rate Estimate

The steady-state thermal model establishes the power required to hold peak temperature. Combining that result with the available heater power and the kiln's thermal mass gives an estimate of the maximum achievable heating rate at any point during a firing schedule.

Theory: energy balance during heating

During heating at full heater output, the net power delivered to the kiln is the difference between the heater power and the instantaneous heat loss through the insulation:

$$\dot{Q}_{\text{net}}(T) = P_{\text{heater}} - P_{\text{loss}}(T)$$

This net power raises the temperature of the kiln's thermal mass C_{th} (units: J/K):

$$\dot{Q}_{\text{net}} = C_{\text{th}} \frac{dT}{dt}$$

Combining these gives the instantaneous heating rate:

$$\frac{dT}{dt} = \frac{P_{\text{heater}} - P_{\text{loss}}(T)}{C_{\text{th}}}$$

The heating rate decreases as temperature rises because $P_{\text{loss}}(T)$ increases with the hot-face to ambient temperature difference. At the point where $P_{\text{loss}} = P_{\text{heater}}$, the rate reaches zero and the kiln is at steady state.

Thermal mass calculation

The thermal mass is the sum of $m_i c_{p,i}$ over all components that must be heated. The dominant contribution is the refractory firebrick.

K23 IFB. Each standard brick measures $4.5 \times 9 \times 2.5$ in. The volume per brick is:

$$V_{\text{brick}} = 4.5 \times 9 \times 2.5 = 101.25 \text{ in}^3 \quad \times \quad 1.639 \times 10^{-5} \text{ m}^3/\text{in}^3 = 1.66 \times 10^{-3} \text{ m}^3$$

Using a bulk density of $\rho_{\text{IFB}} \approx 550 \text{ kg/m}^3$ and specific heat $c_{p,\text{IFB}} \approx 1.0 \text{ kJ}/(\text{kg}\cdot\text{K})$:

$$m_{\text{brick}} = \rho_{\text{IFB}} \times V_{\text{brick}} = 550 \times 1.66 \times 10^{-3} \approx 0.91 \text{ kg}$$

$$m_{\text{IFB}} = 34 \times 0.91 = 31 \text{ kg} \quad C_{\text{IFB}} = 31 \times 1.0 = 31 \text{ kJ/K}$$

Ceramic fiber blanket. The blanket occupies the cylindrical annulus between the outer face of the IFB and the inner face of the steel shell. Using the radii from the thermal model geometry (Section 5.5), with $r_1 = 0.291 \text{ m}$ (inner face of shell), $r_2 = 0.1894 \text{ m}$ (outer face of IFB), and sidewall height $H = 0.2286 \text{ m}$:

$$V_{\text{wool}} = \pi (r_1^2 - r_2^2) H = \pi (0.291^2 - 0.1894^2) (0.2286) \approx 0.0350 \text{ m}^3$$

Using $\rho_{\text{wool}} \approx 96 \text{ kg/m}^3$ and $c_{p,\text{wool}} \approx 1.0 \text{ kJ/(kg}\cdot\text{K)}$:

$$m_{\text{blanket}} = 96 \times 0.0350 \approx 3.4 \text{ kg} \quad C_{\text{blanket}} \approx 3 \text{ kJ/K}$$

Rigid insulation board (lid and base). The backup insulation board forms two circular discs (one above the lid slab and one under the base slab) each with radius $r_1 = 0.291 \text{ m}$ and thickness $t_{\text{board}} = 76.2 \text{ mm}$:

$$V_{\text{board}} = 2 \times \pi r_1^2 \times t_{\text{board}} = 2 \times \pi (0.291)^2 (0.0762) \approx 0.0405 \text{ m}^3$$

Using $\rho_{\text{board}} = 140 \text{ kg/m}^3$ and $c_{p,\text{board}} = 0.85 \text{ kJ/(kg}\cdot\text{K)}$ (from PowerWool RigiBoard ONE product data):

$$m_{\text{board}} = 140 \times 0.0405 \approx 5.7 \text{ kg} \quad C_{\text{board}} = 5.7 \times 0.85 \approx 5 \text{ kJ/K}$$

The steel shell contributes negligible thermal mass relative to the refractory layers. Summing all three components:

$$C_{\text{th}} = C_{\text{IFB}} + C_{\text{blanket}} + C_{\text{board}} = 31 + 3 + 5 = 39 \text{ kJ/K}$$

Evaluated cases

Using $P_{\text{heater}} = 1800 \text{ W}$ and heat loss bounds from Section [5.5](#):

- **Cold start, negligible heat loss:**

$$P_{\text{net}} = 1800 - 0 = 1800 \text{ W} \quad \frac{dT}{dt} = \frac{1800}{39,000} = 0.046 \text{ }^\circ\text{C/s} \approx \mathbf{166 \text{ }^\circ\text{C/hr}}$$

- **Near peak (1220°C), lower heat loss bound:**

$$P_{\text{net}} = 1800 - 698 = 1102 \text{ W} \quad \frac{dT}{dt} = \frac{1102}{39,000} = 0.028 \text{ }^\circ\text{C/s} \approx \mathbf{102 \text{ }^\circ\text{C/hr}}$$

- **Near peak (1220°C), upper heat loss bound:**

$$P_{\text{net}} = 1800 - 1450 = 350 \text{ W} \quad \frac{dT}{dt} = \frac{350}{39,000} = 0.009 \text{ }^\circ\text{C/s} \approx \mathbf{32 \text{ }^\circ\text{C/hr}}$$

Implications for firing schedules

Typical ceramic firing schedules use ramp rates of 60–150 °C/hr during main heating phases, with slower rates at critical transitions such as quartz inversion ($\approx 573 \text{ }^\circ\text{C}$) and during early moisture release. The estimated range of 32–102 °C/hr near peak is compatible with controlled ceramic firing. The upper heat loss bound leaves only 350 W of net power near 1220 °C, which is why the heater should be sized greater than the 1500 W holding-power estimate. The 300 W margin corresponds to an additional:

$$\frac{300}{39,000} \times 3600 \approx 28 \text{ }^\circ\text{C/hr}$$

of ramp headroom at peak, confirming the margin is meaningful but not large.

These estimates assume the kiln is fully sealed and the heater is running at 100% duty cycle. Actual heating rates will depend on real insulation performance, lid seal quality, and ambient conditions. Empirical ramp rates will be characterised from the thermal decay logs produced by `kiln-tuner.py`

during the first firing. If firing cycles are running excessively long to reach peak temperatures, elements may be replaced with larger diameter coils to provide extra resistive length. This would require widening the grooves, and should only be done if absolutely necessary, to reach the final upper continuous operation power limit of the heater (1920W).

5.7 Mechanical Integration Considerations

Mechanical integration required coordinating the shell, chamber, slabs, insulation, and future through-holes for seating and/or mounting components. A lift and support design concept for the lid was developed to allow the kiln lid to be lifted up via a cool-touch handle after firing and propped open for cooling and loading/unloading. A cut template for the lid and base slabs was designed to minimize brick waste during construction. The barrel modification strategy included cutting the barrel into top and bottom sections according to insulation stack and chamber height, and forming inward tabs to support the lid and chamber edges at the correct height.

A wood-stove-grade gasket was investigated for the lid opening. This was not treated as necessary for the initial build, but remained a later option if testing showed the bare metal edge seal leaked too much heat.

A reclaimed barrel dolly with locking casters was investigated as a possible stand to keep the kiln off the ground and improve portability. It has not yet been sourced at the time of writing, but remains the preferred low-cost solution.

Several fabrication jigs were designed to support construction. A bevel-cutting jig was developed for the chamber firebricks. A winding jig for the heating elements was also designed and 3D-printed.

5.8 Mechanical and Thermal Design Limitations

Several mechanical and thermal details still depend on physical validation. The lid and base slab approach needs to be proven in practice. The backup



Figure 5.4: Example of bent metal tab lid support design of the chamber edge. The lid section edge will also use this strategy to retain the brick slab.

Cutting Jig - Kiln Chamber IFB

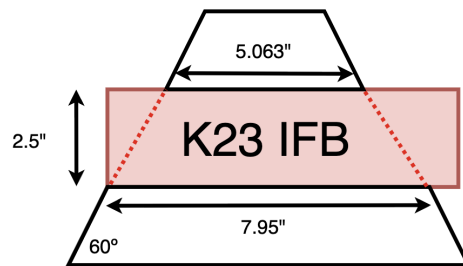


Figure 5.5: Diagram of the bevel-cutting jig used to guide hacksaw cuts on IFBs for the chamber sidewall ring.

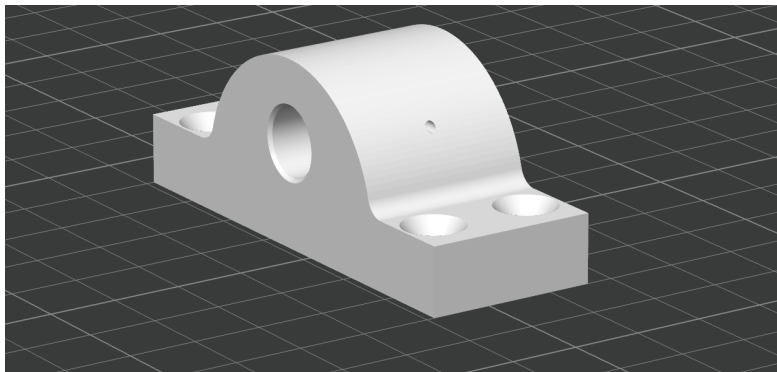


Figure 5.6: 3D-printed winding jig designed to support consistent coil geometry when winding the Kanthal A-1 heating elements.

insulation under those slabs needs to be checked for compression under load, and the final support-tab heights in the shell depend on these results.

The lid seal strategy also remains partly provisional. The design assumes some passive leakage; whether that leakage is acceptable will only be confirmed after assembly and heating tests. The thermal model is sufficient for design selection, but final assembly still needs practical validation.

Chapter 6

Electrical Power and Heater Design

6.1 Electrical Power Architecture

The heater system was designed around a standard 120 V, 20 A household power circuit. Current and power limits were treated as hard constraints from the beginning. The electrical design therefore started from the available residential supply rather than from the largest heater that could physically fit in the chamber.

Major components including the SSR, heatsink, thermal fuse, mains cable, terminal blocks for the elements, and the thermocouple were specified to match the selected voltage, current, and power targets. The mains and control paths were reviewed as a system rather than as isolated components. Full electrical specifications are listed in the Product Design Specification (Chapter [3](#)).

6.2 Heating Element Design Objectives

Element design calculations were performed in order to find the dimensions of element coils that would satisfy power requirements for fast heating, with the total stretched length of the heating coils constrained by the firing chamber

dimensions. Since the kiln cabinet was designed before the elements, the IFB chamber sidewalls had both finite volume of insulation, and finite surface area available for the element grooves. The Kanthal Element Design Guide was a valuable resource for finding a solution under physical constraints.

Elements were designed with the goal of providing 1.5 kW, enough power to hold the kiln at its maximum operating temperature according to the thermal model (Chapter 5.5). An additional 0.3 kW was added to ensure that the kiln would not struggle to ramp up to the maximum temperature. This resulted in a power requirement of 1.8 kW for the heater. Sufficient heater power is desirable, as small kilns with less thermal mass and a relatively large surface area lose heat more quickly than commercial kilns. This can lead to long firing times and increase firing costs from excessive power consumption.

The heating elements for this kiln will be wound in-house from Kanthal A-1 resistance wire. The finished elements will be installed into machined undercut grooves in the hot-face IFB sidewalls of the kiln, with the undercut helping to retain the coils. Where necessary, element pins made from the same wire may be used to further secure the elements within the grooves.

Minimizing coil diameter was identified as a design objective in order to avoid loss of insulation with the IFB volume removed from the chamber in order to house the elements. Additionally, minimizing the element wire diameter (maximizing the gauge) was desired in order to make elements easier to wind.

6.2.1 Element Wiring Configuration

The kiln heating system consists of two individual heating element coils, wired in parallel with each other. This configuration divides the total coil length into two, simplifying installation and allowing one element to be replaced, modified, or serviced independently.

By dividing the total heating power across two parallel branches, the current and power dissipation per chain are reduced. This results in lower surface loading on each individual element. The lower surface loading corresponds to a lower element surface temperature, which improves element longevity and reduces mechanical deformation during firing cycles. Reduced deformation helps ensure that the elements remain properly seated within their grooves over repeated thermal cycles.

6.3 Element Sizing Calculations

6.3.1 Design Parameters

Total length of grooves:

$$l_{grooves} = 3 \text{ m}$$

The groove pattern is cut such that the first five bricks will have 2 channels in the hot face, and there is a step up to the next parallel over the 6th brick. Available length of the element grooves will eventually depend on their total measured length from the assembled chamber. An estimate was obtained by calculating the approximate length available from two channels per brick for five bricks, plus the length available from the two entry/exit/transfer bricks.

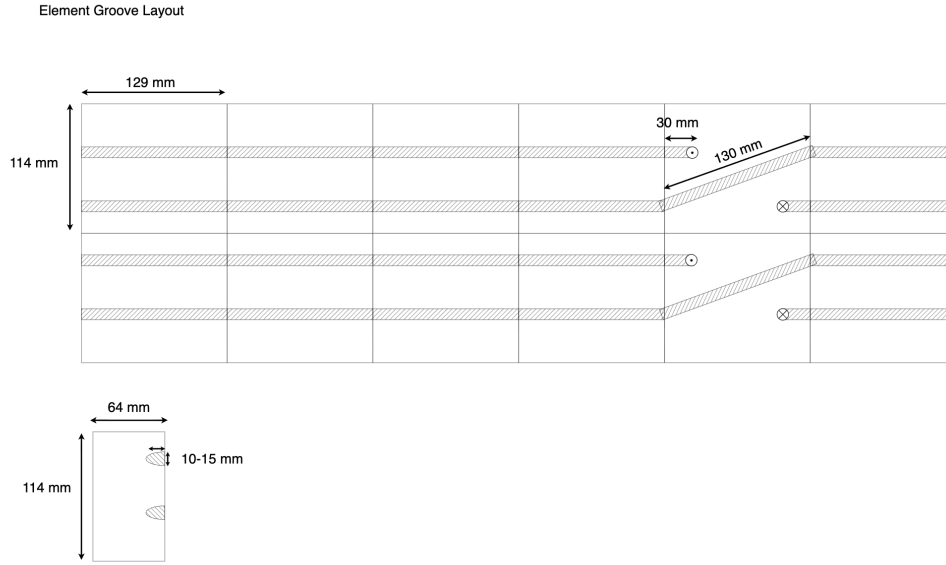


Figure 6.1: Groove pattern and dimensions

Figure [6.1](#) shows the hexagonal hot-face sidewalls of the kiln, laid flat to illustrate the element grooved channels. Channel depth is shown as an estimate on a single brick, expected 10-15 mm. Entry and exit through-holes are shown for reference, diameter (not to scale) and will be drilled to the diameter of pigtailed ends.

Number of element chains in parallel:

$$n_{elements} = 2$$

Power:

$$P_{total} = 1800 \text{ W}$$

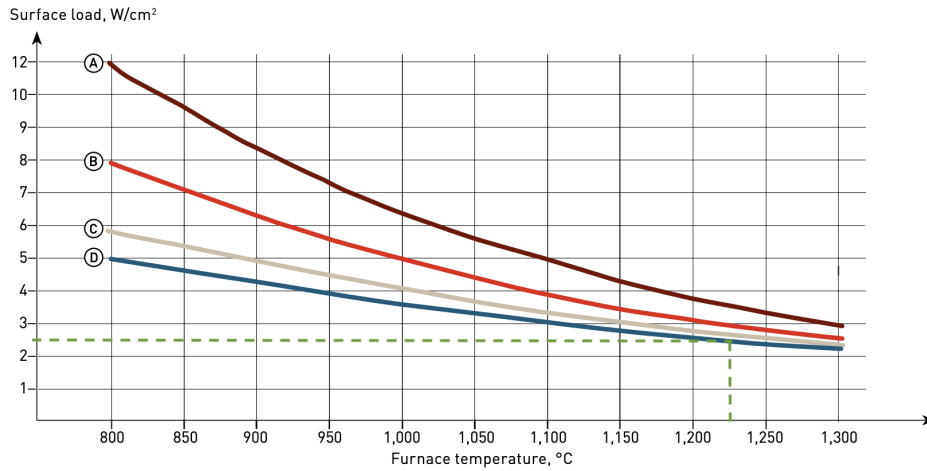
$$P_{element} = \frac{P_{total}}{n_{elements}} = 900 \text{ W}$$

Voltage:

$$U = 120 \text{ V}$$

Target surface load: The Kanthal A-1 element design calculation guide includes recommendations for maximum surface loads for elements in grooves, as a function of furnace temperature. Figure 6.2 indicates that the target value for 1220 °C is 2.5 W/cm², multiplied by a factor of 0.8 (80%) for on-off control.

**MAXIMUM RECOMMENDED SURFACE LOADS FOR KANTHAL® A-1,
KANTHAL® AF AND KANTHAL® APM ALLOYS IN INDUSTRIAL FURNACES**



Note: The diagrams are valid for thyristor control. For on-off control lower surface loads should be chosen (about - 20%).

Figure 6.2: Surface loading, Kanthal A-1 element design calculation guide

Surface loading:

$$p_s = 2.5 \times 0.8 = 2.0 \text{ W/cm}^2, \text{ from Kanthal A-1 Property Datasheet}$$

Resistivity at operating temperature:

$$\rho = 1.45 \text{ } \Omega \text{ mm}^2/\text{m}, 20^\circ\text{C}, \text{ from Kanthal A-1 Property Datasheet}$$

Temperature factor:

$$C_t = 1.04, 1220^\circ\text{C}, \text{ from Kanthal A-1 Property Datasheet}$$

Wire diameter form factor (metric units):

$$k_d = 2.91, \text{ from Kanthal A-1 Property Datasheet}$$

6.3.2 Current and Resistance

Element current is calculated from:

$$I = \frac{P}{U} = \frac{900 \text{ W}}{120 \text{ V}} = 7.5 \text{ A}$$

Element resistance is calculated from:

$$R = \frac{U}{I} = \frac{120}{7.5} = 16.0 \text{ } \Omega$$

6.3.3 Wire Diameter

The wire diameter required to achieve the target surface load is:

$$d = \frac{1}{k_d} \sqrt{\frac{I^2 \rho C_t}{p_s}} = \frac{1}{2.91} \sqrt{\frac{(7.5)^2 \times 1.45 \times 1.04}{2.0}} = 1.198 \text{ mm}$$

Selected standard wire diameter:

$$d_{\text{sel}} = 1.29032 \text{ mm (0.0508 in, B\&S gauge 16)}$$

Actual surface loading:

$$\rho_{s, \text{ actual}} = \frac{I^2 \rho C_t}{(k_d d_{\text{sel}})^3} = \frac{7.5^2 \times 1.45 \times 1.04}{(2.91 \times 1.29032)^3} = 1.602 \text{ W/cm}^2$$

6.3.4 Hot and Cold Resistance

Hot resistance:

$$R_T = 16.0 \ \Omega$$

Cold resistance:

$$R_{20} = \frac{R_T}{C_t} = \frac{16.0}{1.04} = 15.3846 \ \Omega$$

6.3.5 Resistance per Unit Length

$$R_{20/m} = 1.0866 \ \Omega/\text{m, from Kanthal A-1 Property Datasheet}$$

6.3.6 Uncoiled Wire Length

The length of wire for a single element comes from the required resistance.

$$\ell = \frac{R_{20}}{R_{20/m}} = \frac{15.3846}{1.0866} = 14.1583 \text{ m} = 14158.3 \text{ mm}$$

6.4 Coil Geometry and Groove Layout

For heating elements in grooves, the Kanthal A-1 alloy element design calculation guide recommends a coil diameter, D , of $5\text{--}8\times$ the wire diameter d , and a pitch, s , of $2\text{--}3\times d$. This is illustrated in Figure [6.3](#).

④ ■ Heating elements in grooves

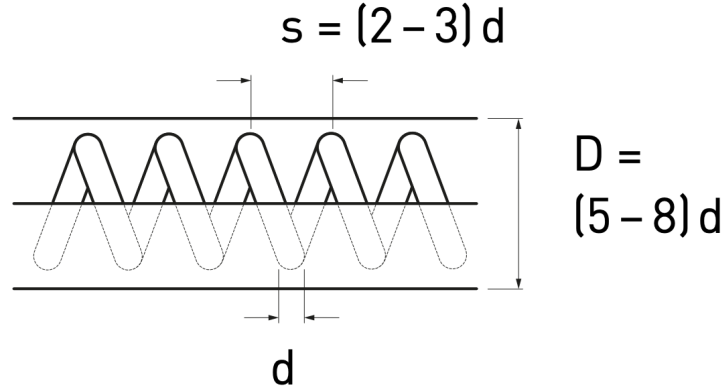


Figure 6.3: Element coil diagram, Kanthal A-1 element design calculation guide

Recommended coil outer diameter:

$$D = [5 \times d, 8 \times d] = [5 \times 1.29032, 8 \times 1.29032] = [6.4516, 10.3226] \text{ mm}$$

Recommended pitch:

$$s = [2 \times d, 3 \times d] = [2 \times 1.29032, 3 \times 1.29032] = [2.5806, 3.8712] \text{ mm}$$

Number of turns:

$$w = \frac{\ell}{\pi(D - d)}$$

Close-wound coil length:

$$L_w = wd$$

Stretched coil length:

$$L = \frac{s}{d}L_w$$

Combining the above three equations:

$$L = \frac{\ell \times s}{\pi(D - d)}$$

Maximum channel length available for each element chain:

$$L_{element} = \frac{L_{grooves}}{2} = \frac{3000}{2} = 1500 \text{ mm}$$

Substituting values for L , ℓ , and d yields a relation between s and D :

$$1500 = \frac{14158.3 \times s}{\pi(D - 1.29032)}$$

Coil inner diameter:

$$D_i = D - 2d = D - 2 \times 1.29032 = D - 2.58064 \text{ mm}$$

Plotting s as a function of D within the recommended domain and range, a minimum D is chosen such that s falls within the acceptable range and D_i is an exact mm increment. Since groove depth depends on outer coil diameter D , choosing a minimum value allows for as shallow a groove as possible, minimizing the amount of insulating brick removed to house the elements. Choosing D_i to the nearest mm facilitates use of a standard-diameter mandrel around which the elements are wound.

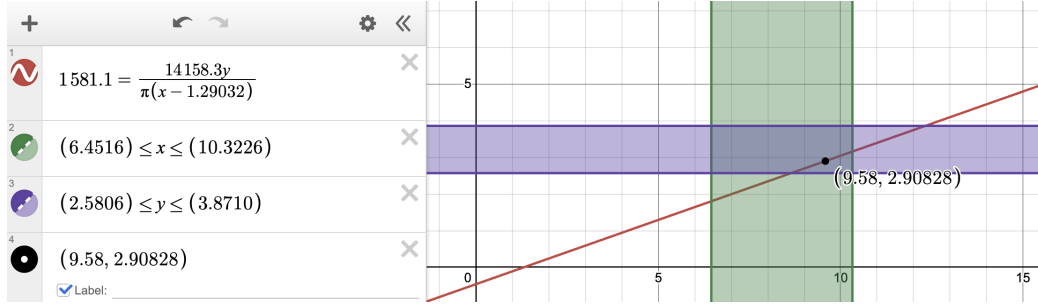


Figure 6.4: Choosing D , s

Figure 6.4 shows the relationship between D and s . Choosing $D = 9.58$ mm gives $s = 2.91$ mm, which falls in the recommended range for both values, and gives $D_i = D - 2.58 = 7$ mm.

Substituting the chosen values back, we can obtain our number of turns per coil, and the close-wound length of each coil:

$$w = 544 \text{ turns}$$

$$L_w = 701.9 \text{ mm}$$

After winding, cold resistance of each element will be measured and compared with the target cold resistance per element.

6.5 Element Routing, Exits, and Cold-End Strategy

The positive and negative ends of each element are routed from their hot-face grooves, through holes drilled in the sidewalls of the kiln, to the outside of the kiln enclosure. Each end will be connected to its own ceramic terminal block, mounted on the outside of the steel enclosure. High-temperature jumper cables will then connect each ceramic terminal to either the SSR output or the neutral return.

To reduce the temperature of the end sections of each element routed through the kiln sidewall, these sections are pigtailed: the uncoiled end of the wire is folded back on itself and twisted into a double helix shape. This doubles

the effective cross-sectional area of the section, thus halving the effective resistance. An example of this is shown in the figure below.



Figure 6.5: An unstretched (close-wound) element coil with 'pigtailed' ends

The distance to be covered by each pigtailed section is approximately equal to the radial thickness of the sidewall plus the distance to the ceramic terminal.

The maximum radial thickness from the hot brick face to the outside of the kiln:

$$t_{sidewall} = t_{steel} + t_{backup\ insulation} + t_{brick} = 0.05 + (3.5 + 1.065) + 2.5 = 7.115 \text{ in} = 180.7 \text{ mm}$$

The ceramic terminals are placed near the cold-face exit of the element wire. Assuming a generous distance of 80 mm from the exit face to the end of the housed section:

$$L_{pigtail} = 260 \text{ mm}$$

The length of wire needed for each pigtailed section:

$$L_{wire} = 2 \frac{L_{pigtail}}{s} \sqrt{(\pi D)^2 + s^2}$$

For a double helix twist of Kanthal 16-gauge A-1, using $D = 2d$ and $s = 4d$ where $d = 1.29 \text{ mm}$:

$$L_{wire} = 2 \times \frac{260}{5.16} \sqrt{(2 \times \pi \times 1.29)^2 + 5.16^2} = 968.28 \text{ mm}$$

Multiplying by 4 for four pigtailed ends:

$$L_{additional} = 4 \times 968.28 = 3873.2 \text{ mm}$$

Total wire length for the design:

$$L_{total} = 2\ell + L_{additional} = 2 \times 14158.3 + 3873.2 = 32189.8 \text{ mm} = 32.1898 \text{ m}$$

One pound of 16-gauge Kanthal A-1 wire measures approximately 160.5 ft in length. This quantity is expected to be a sufficient allowance for the project.

The pigtailed sections are also protected with ceramic beads threaded over the wire as they pass through the insulation. Running the Kanthal through the wall also gives the wire distance to cool before it reaches the outer terminal connections.

External ceramic terminal blocks will be used to join the ends of each element to mains wiring.

6.5.1 Summary of Element Design

Wire diameter	$d = 1.3 \text{ mm (0.058 in)}$
Wire length (per coil)	$\ell = 14.1583 \text{ m (46.4511 ft)}$
Number of turns	$w = 544$
Coil outer diameter	$D = 9.6 \text{ mm (0.377 in)}$
Coil inner diameter	$D_i = 7.0 \text{ mm (0.2756 in)}$
Coil pitch	$s = 2.9 \text{ mm (0.1145 in)}$
Close-wound coil length (per coil)	$L_w = 0.75484 \text{ m (2.4765 ft)}$
Stretched coil length (per coil)	$L = 1.5811 \text{ m (5.1873 ft)}$
Length of pigtails (per end)	$L_{pigtail} = 260 \text{ mm (10.263 in)}$
Total wire length	$L_{total} = 32.1898 \text{ m (105.6096 ft)}$

6.6 Wiring Architecture and Junction Design

The intended wiring layout was documented in an electrical drawing for review. The heater branches, external terminals, switching hardware, and control components were treated as part of one integrated system rather than as separate sketches.

ECE technical staff reviewed the design and provided feedback that helped refine how the high-temperature element terminations transition into the rest of the electrical system. Full outcomes of that review are described in Section [9.4](#).

6.7 Relay and Power Switching Hardware

6.7.1 Solid State Relay Selection

Heater power modulation is achieved using an AC solid state relay (SSR) configured for zero-cross switching. The SSR is selected with voltage and current ratings well above the maximum kiln load to ensure reliable operation. For single-phase kilns, a single-phase SSR module giving one switching channel is

sufficient. Zero-cross switching minimizes electrical noise and reduces stress on both the relay and heating elements during repetitive switching.

A 40DA SSR (40 A) is used for this design. This SSR is rated to control high-current AC loads (24–380 V AC) using a low-voltage DC input (3–32 V DC).

6.7.2 SSR Thermal Management

Due to internal conduction losses, the SSR dissipates heat during operation and therefore requires heatsinking. The reference design explicitly notes that high-current SSR devices must be mounted to an appropriate heatsink to maintain safe junction temperatures. The control enclosure for this design includes provisions for heatsink mounting and passive airflow to prevent excessive temperature rise during firing cycles.

The switching strategy was reviewed with ECE technical staff. Their recommendation affected the interface between the controller and the heater power hardware but did not change the main decision to use SSR-based mains switching for the heating load. The revised drive implementation is described in Section [7.4](#).

6.8 Electrical Safety Provisions

Electrical protection is achieved through appropriate upstream overcurrent protection and adherence to safe wiring practices for high-voltage and high-current operation. The controller enclosure functions as an intermediary power device, with mains input supplied to the controller and the kiln load connected downstream. Isolation between low-voltage control circuitry and mains wiring is maintained through the use of the SSR and careful enclosure layout.

A thermal fuse was incorporated as an independent hardware safety mechanism in the heater power path, providing a shutdown capability that does not depend on the controller software. Grounding recommendations, isolation considerations, conductor temperature ratings, and a staged testing strategy were also reviewed with technical staff.

A particularly useful recommendation was to test mains switching first with a representative resistive indicator load rather than with the heating elements connected. This allows line-voltage switching behavior to be verified before full heater integration.

The panel-mount pilot lights specified for each element chain serve this role directly. Each pilot light is a low-current, mains-rated resistive load. With the heating elements not yet wired, the pilot lights can be connected in place of the element ends at the ceramic terminal blocks. The full switching path (GPIO output, MOSFET, SSR control side, SSR load side) can then be exercised under live mains conditions. When the controller commands heat, each pilot light should blink on and off at the SSR switching rate, providing immediate visual confirmation that the end-to-end control path is working. Because pilot lights draw only a few watts rather than the full 900 W element load, a wiring error at this stage presents significantly less hazard than the same error would under element load. Any fault such as continuous-on, no switching, or asymmetric channel behaviour becomes visible before the high-current heater path is introduced. This test corresponds to the Stage 2 SSR switching check in the testing plan (see Section [12.2](#)).

Chapter 7

Control System Design

This chapter describes the hardware architecture and design decisions associated with the kiln control system. The control system provides temperature measurement, heater power modulation, safety shutdown capability, and embedded control via a single-board computer. Software platform selection, user interface, and connectivity are also described in this chapter.

The control system diagram shown in Figure [7.1](#) illustrates the high-level heater control system circuitry.

This control system design is based on the open-source project “kiln-controller” by Jason Bruce (GitHub: [jbruce12000](#)), the code from which is used as the software controller.

7.1 Control Requirements and Operating Concept

The control system needed to measure kiln temperature, provide heater switching commands, and expose a usable interface for setup and monitoring. It also needed to remain practical for a one-off DIY system and work within the hardware limitations of a small single-board computer.

The intended operating concept was a Raspberry Pi controller running existing kiln-control software, using a thermocouple interface over SPI and issuing

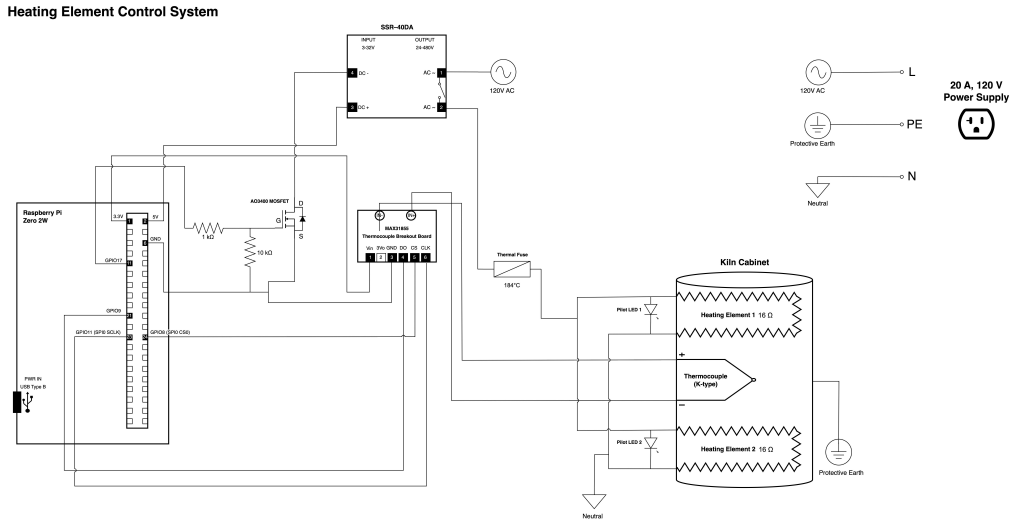


Figure 7.1: Control system diagram showing Raspberry Pi and GPIO pinout labels, SSR control circuitry, temperature measurement module, heating elements, pilot lights for heating elements, and representative connections to mains L, N, and PE.

heater commands through a GPIO-controlled switching path.

7.2 Controller Platform Selection

The kiln controller is implemented using a Raspberry Pi Zero 2 W single-board computer, which provides sufficient processing capability, network connectivity, and GPIO access for system operation. Only four GPIO pins are required, and the integrated wireless networking enables remote monitoring and control via network-connected devices.

The Raspberry Pi Zero 2 W was selected because it provides a full Linux environment at low cost while meeting all hardware requirements. It supports Wi-Fi for remote access, SPI for thermocouple communication, GPIO for control output, and has sufficient processing capability to run the controller software (Python) and a web-based interface concurrently.

The choice of a Pi rather than a more minimal microcontroller was deliberate. The project required a web server, background software dependencies, and a

flexible development environment. These requirements are better suited to a Linux-based platform than to a bare microcontroller, such as a Raspberry Pi Pico.

7.3 Temperature Measurement Hardware

7.3.1 Thermocouple Selection and Placement

Temperature measurement within the kiln is performed using a ceramic-sheathed thermocouple probe rated to measure temperatures up to 1300 °C. The controller software supports multiple thermocouple types, including K, J, N, R, S, T, E, and B types, but a K-type was chosen for this design as specified in Section 3.6. The model chosen uses Chromium-Nickel (Cr-Ni), and Silicon-Nickel (Si-Ni) conductors to measure temperature. The thermocouple probe is 250 mm long and is positioned within the kiln chamber so that it protrudes about 2.5 in deep into the chamber. This provides a representative measurement of the thermal environment, and the ceramic-sheathed probe remains mechanically protected from direct contact with heating elements and workpieces. This is shown in Figure 7.2.

7.3.2 Thermocouple Interface Board

The thermocouple signal is conditioned and digitized using an SPI-based thermocouple interface board. The reference design supports Adafruit MAX31855 and MAX31856 breakout boards, which provide cold-junction compensation, thermocouple linearization, and digital temperature output. The MAX31855 is used for this design, since it is a simpler and more cost-effective option that exclusively supports K-type thermocouples. The interface board communicates with the kiln controller Raspberry Pi via SPI. The MAX31855 pins chip select (CS), clock (CLK), and data output (DO) are used for communication with the controller.

The MAX31855 breakout board arrived without the 6-pin header required for GPIO connection. The header was soldered onto the board before the breadboarded thermocouple-reading circuit could be assembled.



Figure 7.2: Example photo showing ideal thermocouple placement in a kiln firing chamber.

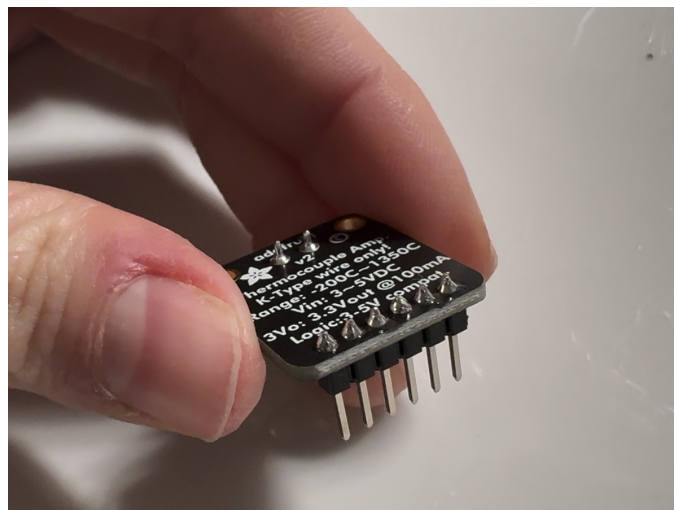


Figure 7.3: 6-pin header soldered onto the MAX31855 breakout board to enable connection to the Raspberry Pi GPIO pins.

7.3.3 Thermocouple Wiring and Noise Mitigation

Thermocouple wiring employs stainless-steel insulated conductors, physically insulated from mains heater wiring to minimize electromagnetic interference. The use of digital SPI communication between the thermocouple interface board and controller further reduces susceptibility to analog noise. Mechanical strain relief and thermal protection of cabling near the kiln body will be implemented to ensure long-term measurement reliability under high-temperature operating conditions.

7.4 SSR Drive and GPIO Interface

7.4.1 Switching Strategy

Heater control is implemented using time-proportioning control, in which the SSR is periodically switched on and off within a fixed control interval. The default system duty cycle is two seconds, meaning that control decisions are evaluated at two-second intervals to determine relay activation duration. The duty cycle will be further evaluated upon first firing of the assembled kiln, and may be adjusted if needed. This approach enables effective power modulation while maintaining compatibility with zero-cross SSR devices. The controller software determines switching behavior based on closed-loop temperature control algorithms.

7.4.2 Hardware Interfaces

The controller interfaces with peripheral hardware through GPIO connections. Three GPIO pins are used to communicate with the thermocouple interface board via SPI, while an additional Pi-driven GPIO output controls heater switching from the low-end side of the SSR. Because the Raspberry Pi GPIO cannot reliably source sufficient current (~ 25 mA) to drive the SSR directly, a low-side switching stage was employed to provide the required drive current, while the input voltage is provided to the SSR by the Pi's 5 V pin. Initially, a PN2222 bipolar transistor was used to accomplish this. After a safety and design review with ECE staff, a logic-level N-channel AO3400 MOSFET was recommended over a bipolar transistor because it is

voltage-controlled rather than current-controlled, allowing it to switch the SSR input from a 3.3 V GPIO signal with negligible steady-state gate current. This reduces loading on the Raspberry Pi output and provides a lower on-state voltage drop.

Early controller work included GPIO sanity checks and enabling SPI communication. A simple blinky-style test with onlt the Pi and an LED was used to confirm that the Pi environment and GPIO access were functioning correctly.

The intended heater-control output pin also had to be corrected in the software configuration. Without that change, the thermocouple could read correctly while the controller still attempted to switch the wrong pin when calling for heat. The interface between the Pi and the switching hardware therefore required both software configuration work and hardware review.

The pin assignment and hardware connections shown in Section 7.1 are listed and described in Table 7.1.

Table 7.1: Control system pin assignments

Device	Pin / Terminal	Connected To	Function
Raspberry Pi Zero 2 W	Physical Pin 1 (3.3V)	MAX31855 VIN	Supplies 3.3 V power to the thermocouple interface board.
Raspberry Pi Zero 2 W	Physical Pin 2 or 4 (5V)	SSR input positive terminal	Supplies the SSR input drive voltage.
Raspberry Pi Zero 2 W	Physical Pin 6 (GND)	MAX31855 GND, MOSFET source, common control ground	Provides the common ground reference for the low-voltage control system.
Raspberry Pi Zero 2 W	Physical Pin 11 (GPIO17)	MOSFET gate through 100 Ω series resistor	Heater control output; drives the MOSFET gate to switch the SSR input.

Device	Pin / Terminal	Connected To	Function
Raspberry Pi Zero 2 W	Physical Pin 21 (GPIO9 / MISO)	MAX31855 DO	Receives thermocouple temperature data from the MAX31855 over SPI.
Raspberry Pi Zero 2 W	Physical Pin 23 (GPIO11 / SCLK)	MAX31855 CLK	Provides the SPI clock for thermocouple data transfer.
Raspberry Pi Zero 2 W	Physical Pin 24 (GPIO8 / CE0)	MAX31855 CS	Chip-select line for the MAX31855 SPI interface.
MAX31855 breakout	VIN	Raspberry Pi Pin 1 (3.3V)	Power input for the thermocouple interface.
MAX31855 breakout	GND	Raspberry Pi Pin 6 (GND)	Ground reference for the thermocouple interface.
MAX31855 breakout	CLK	Raspberry Pi Pin 23 (GPIO11 / SCLK)	SPI clock input.
MAX31855 breakout	DO	Raspberry Pi Pin 21 (GPIO9 / MISO)	SPI data output to the Raspberry Pi.
MAX31855 breakout	CS	Raspberry Pi Pin 24 (GPIO8 / CE0)	SPI chip-select input.
MAX31855 breakout	3Vo	Not connected	Not required in this configuration.
MAX31855 breakout	T+	Thermocouple positive lead	Positive thermocouple input.
MAX31855 breakout	T-	Thermocouple negative lead	Negative thermocouple input.
K-type thermocouple	Positive lead	MAX31855 T+	Thermocouple positive signal connection.
K-type thermocouple	Negative lead	MAX31855 T-	Thermocouple negative signal connection.

Device	Pin / Terminal	Connected To	Function
Logic-level N-channel MOSFET	Gate	Raspberry Pi GPIO17 through $100\,\Omega$ resistor; $10\,\text{k}\Omega$ pull-down to ground	Low-side switching control input for the SSR drive path.
Logic-level N-channel MOSFET	Source	Common ground	Ground reference for low-side switching.
Logic-level N-channel MOSFET	Drain	SSR input negative terminal	Switches the SSR input current path to ground.
SSR (control side)	Input positive (+)	Raspberry Pi 5 V	Positive control-side supply for the SSR input LED/opto-isolator.
SSR (control side)	Input negative (-)	MOSFET drain	Returns SSR input current through the MOSFET when the GPIO is asserted.

7.5 Software Platform

The control software was based on an open-source kiln-controller project (GitHub: jbruce12000/kiln-controller). It was evaluated before adoption and judged to be current, stable, and transparent enough to serve as a practical foundation for the system.

The codebase was installed on the Pi and tested in simulation mode, confirming that the software could run on the selected hardware and that the web interface could be reached from a laptop. The main adaptation work so far has involved hardware-specific configuration rather than rewriting the controller logic itself.

Temperature sensing is handled by a dedicated daemon thread (`TempSensorReal`)

that runs concurrently with the control loop. During each duty cycle the thread takes `temperature_average_samples` (default: 10) successive readings from the thermocouple board, spaced evenly across the two-second period. A sliding window (`TempTracker`) retains the most recent N readings; the reported temperature is the median of those values, which suppresses the effect of occasional outlier readings without discarding the full sample set. The MAX31855 driver reads the `temperature_NIST` attribute, which returns the thermocouple temperature after the hardware has applied cold-junction compensation and NIST linearization.

The `Oven` class operates as a daemon thread with a three-state machine: `IDLE`, `RUNNING`, and `PAUSED`. In the `RUNNING` state, the thread executes one control cycle per `sensor_time_wait` seconds (default: 2 s). Each cycle reads the current temperature, computes a PID output value in $[0, 1]$, and divides the duty cycle into a heating interval and an idle interval. The GPIO output is asserted for `time_step` $\times$ `pid_output` seconds and then deasserted for the remainder, realizing time-proportional power modulation over the SSR.

The PID algorithm operates within a configurable control window (`pid_control_window`, default: 5 degrees). When the measured temperature is more than this margin below the setpoint, the output is held at 100% (maximum heating). When it exceeds the setpoint by more than the margin, the output is 0% (no heating, no active cooling). Within the window, the standard PID equation is applied; the combined output is clamped to $[-100, +100]$ and normalized to $[0, 1]$ as a fractional duty cycle. Integral accumulation is suspended outside the window, preventing windup. A separate low-temperature throttle limits output to `throttle_percent` (default: 20%) whenever the setpoint is below `throttle_below_temp` (default: 300 degrees) and the controller would otherwise demand full heat. This reduces element overshoot during the cold-start phase before the kiln's thermal mass has stabilized.

Firing schedules are stored as JSON files, each containing a sorted list of (elapsed-time, temperature) waypoints. The `Profile` class interpolates linearly between surrounding waypoints to compute the target temperature at any given runtime. If `seek_start` is enabled and the kiln is already warmer than the schedule's initial point when a run is started, the controller locates the corresponding point on the profile curve and begins execution from there, avoiding unnecessary re-heating. During operation, `kiln_must_catch_up` compares actual temperature to the current setpoint; if the deviation exceeds the control window in either direction, the schedule's reference start time is shifted forward by one `time_step`, pausing advancement until the

kiln temperature returns to within the acceptable band.

The oven state, comprising temperature, setpoint, runtime, profile name, accumulated energy cost, and PID statistics, is serialized to a JSON file every `sensor_time_wait` seconds during a run. On startup, the controller checks whether this state file is present and no older than `automatic_restart_window` minutes (default: 15 minutes). If both conditions are met and the saved state was `RUNNING`, the profile is reloaded and execution resumes from the recorded runtime without operator intervention, providing recovery from transient power outages during unattended firings.

The web server runs on the Bottle framework with `gevent` for concurrent connection handling. An `OvenWatcher` daemon thread polls the oven state every `time_step` seconds and broadcasts a JSON message to all connected Web-Socket clients. When a new browser client connects mid-run, `OvenWatcher` first sends a backlog of up to 50 historical state snapshots from the current run before joining the live stream. Current PID statistics are also available at the `/api/stats` REST endpoint during any run.

7.5.1 Software Configuration

Three values in `config.py` must be set to match the hardware connections described in Section [7.4.2](#). The default configuration uses software SPI with a different set of GPIO pins and a different heater output line; both must be corrected before the controller will operate correctly with this wiring.

Hardware SPI. The design uses the hardware SPI0 peripheral (GPIO8/CE0, GPIO9/MISO, GPIO11/SCLK). The controller auto-selects hardware SPI when no software SPI pins are defined in `config.py`. The four software SPI pin assignments in the default configuration must therefore be removed or commented out:

```
# Remove or comment out these lines to use hardware SPI:
# spi_sclk = board.D17
# spi_miso = board.D27
# spi_cs   = board.D22
# spi_mosi = board.D10
```

Heater output pin. The heater control signal is connected to GPIO17 (Physical Pin 11). The default configuration assigns the heater output to GPIO23, which must be corrected:

```
gpio_heat = board.D17    # Physical Pin 11 (GPIO17) -> MOSFET gate
```

Thermocouple board selection. The MAX31855 breakout is used. The configuration must reflect this explicitly, as the default in some versions of the software selects the MAX31856:

```
max31855 = 1
max31856 = 0
```

These three corrections were identified and applied during controller prototyping. With hardware SPI selected and the correct GPIO assignments in place, the thermocouple was read successfully from the Raspberry Pi without further modification to the controller software.

SPI mode is selected automatically at startup: if software SPI pins are defined in `config.py`, bit-bang SPI is used via `bitbangio`; otherwise the hardware SPI peripheral is selected. The `config.py` file was edited to ensure hardware SPI was selected during initial temperature sensor testing.

7.6 UI, Logging, and Connectivity

The Pi was flashed with Raspberry Pi OS, connected to the network, and configured for remote shell access through PiConnect. The controller software's web UI was then tested over the network from a laptop.

These steps established that the selected hardware and software stack could support remote access and browser-based interaction. At this stage, the work focused on connectivity and basic controller usability rather than on full data logging or long-duration kiln runs.

The controls UI for the kiln software is shown in Figure [7.4](#). The interface is simple in design, but has the necessary functionality needed to reliably



Figure 7.4: Example image of the Web UI of the kiln controller software, as accessed over the local network.

interact with the control system as designed for this project. The UI provides a real-time dashboard showing current kiln temperature, target setpoint, heater on/off state, heating rate, and accumulated energy cost, alongside a live chart of the actual vs. scheduled temperature curve. It also allows the operator to select, create, and start firing profiles, monitor schedule progress, and stop a run remotely from any network-connected device.

7.7 Fault Handling

7.7.1 Thermal Fuse Implementation

An independent thermal cutoff device is incorporated to provide hardware-level over-temperature protection. The thermal fuse is installed in series with the heater power path such that activation permanently removes power from the heating elements. This mechanism provides a fail-safe shutdown independent of controller software, preventing uncontrolled heating in the event of sensing, control, or switching failures.

7.7.2 Controller-Side Power Failure

The control system incorporates multiple layers of fail-safe behavior. Loss of controller power results in cessation of heater switching via the MOSFET switch circuit, preventing continued heating without feedback.

7.7.3 Software Failsafes

Software-level monitoring mechanisms support automatic recovery following power interruptions and detection of abnormal operating conditions. State is serialized to `state.json` every `sensor_time_wait` seconds during a run; on startup, `should_i_automatic_restart()` checks whether this file is present and no older than `automatic_restart_window` (default: 15 minutes). If the saved state was `RUNNING`, the profile is reloaded and execution resumes from the recorded runtime via `automatic_restart()`. This allows the kiln to recover from transient power outages without operator intervention, provided power returns within the restart window.

Abnormal conditions during a run are handled by `reset_if_emergency()`, which is called every control cycle. If the measured temperature meets or exceeds `emergency_shutoff_temp` (configured to cone 7, above the cone 6 target), `abort_run()` is called immediately, halting the firing schedule and cutting heater output to zero. The same abort path is triggered if the thermocouple board accumulates faults beyond a configurable error-rate threshold (`over_error_limit()`), treating loss of reliable measurement as a fault condition equivalent to an over-temperature event. In both cases, `abort_run()` resets the oven state to `IDLE` and writes a final state file.

Schedule integrity is maintained by `kiln_must_catch_up()`, which runs each control cycle and compares measured temperature against the current set-point. If the deviation exceeds `pid_control_window` in either direction (the kiln is too cold to keep pace, or too hot to proceed) the schedule's reference start time is shifted forward by one `time_step`, pausing profile advancement until the kiln returns to within the acceptable band. This prevents both thermal shock from advancing the schedule too quickly and runaway overshoot from advancing into a hold segment while temperature is still rising.

External monitoring is supported by `watcher.py`, a separate process that polls the controller's REST API every `sleepfor` seconds. If the temperature error exceeds `temp_error_limit` (default: 10 °C) for `bad_check_limit` (default: 6) consecutive checks, a Slack alert is dispatched via webhook, providing a notification path for unattended firings where software fault mechanisms alone may not be sufficient to alert the operator. This Slack channel must be specified in the code once it is set up.

7.7.4 Boot and Default States

During system startup and reboot events, heater switching remains disabled until the controller software is fully operational and valid temperature measurements are available. Automatic restart functionality following power interruptions is supported at the software level, allowing kiln operation to resume in a controlled manner after transient faults.

The control system was developed in a way that separated low-voltage verification from mains testing, reducing risk during early setup and debugging (see Section [6.8](#) for the staged testing strategy).

Full fail-safe behavior under heating faults, sensor faults, or controller faults

remains to be thoroughly validated in the integrated system. That work depends on final controller-to-heater integration and powered testing, and will be a necessary step before multi-hour firing schedules can be run.

7.8 Control Enclosure and Integration Constraints

7.8.1 Physical Layout

The control enclosure houses the Raspberry Pi, thermocouple interface board, SSR, and associated wiring. This will be a 3D-printed enclosure located away from the kiln. High-voltage switching components are physically segregated from low-voltage control electronics and will be enclosed in a grounded metal junction box to improve safety and reduce electromagnetic coupling. The metal junction box functions as an intermediary module between mains supply and kiln load.

7.8.2 Wiring Architecture

System wiring connects mains input to the SSR switching stage and subsequently to the kiln heating elements. Low-voltage wiring connects the Raspberry Pi to the thermocouple interface board and SSR driver circuitry. Connectorized GPIO connections and structured cable routing facilitate assembly, maintenance, and debugging.

7.8.3 Thermal and Environmental Considerations

Thermal management within the enclosure focuses primarily on SSR heat dissipation and maintaining suitable operating temperatures for embedded electronics. Heatsinking and passive airflow are used to mitigate temperature rise during extended kiln operation. Mechanical protection and strain relief are incorporated to ensure long-term reliability under workshop operating conditions.

The electrical drawing for the control and mains path was reviewed with ECE technical staff, which helped refine the integration constraints before final wiring began.

Final enclosure mounting, wire routing, and physical separation from the shell still remain to be implemented. The enclosure plan includes a metal junction box mounted to the shell with electrical contact between the box and barrel, with the box grounded to protective earth. This prevents against electrical discharge hazards if the elements were ever to come into accidental contact with the kiln shell.

Chapter 8

Bill of Materials, Cost, and Sourcing

8.1 Hardware Bill of Materials

Item	Qty	Unit (CAD)	Line (CAD)
55 gallon steel drum (reclaimed)	1	150.00	0.00
K23 insulating firebrick (4.5×9×2.5 in)	34	7.39	251.17
Kanthal A-1 wire 16-gauge, 1 lb (160.5 ft)	1	70.00	70.00
PowerWool RigiBoard One Mineral Wool Insulation 2-ft x 4-ft, 2" thick (reclaimed)	2	105.59	50.00
METRE WIRE 10G SEW-2 (200C), Red/Black	2	14.17	28.34
Cerablanket Insulating Ceramic Fiber Blanket,(12×12×1 in)	18	7.60	136.80
Room exhaust fan (reclaimed)	1	29.52	0.00
Type-K thermocouple, 12", ceramic sheath	1	13.57	16.56

Item	Qty	Unit (CAD)	Line (CAD)
MAX31855 thermocouple amplifier breakout	1	34.74	40.04
Raspberry Pi Zero 2 WH - with Pre-Soldered Headers	1	36.95	36.95
Electronics prototyping kit (breadboard, jumper wires, resistors)	1	37.50	37.50
Single-phase SSR-40DA solid state relay	1	12.41	12.41
Aluminum Heat Sink	1	26.10	26.10
2 Way Ceramic Terminal Blocks, 20A 250V High Temp Porcelain	4	17.30	13.84
32GB Micro SDHC Class 10 Memory Card	1	13.99	13.99
USB-A Port Wall Charger (18W)	1	31.44	31.44
USB 2.0 A to Micro B Charger Cable, 6 Feet	1	11.81	11.81
No.36 High Strength 3200°F - Refractory Mortar 2-Pint	1	59.99	91.70
7mm diameter, 3' Aluminum Rod	1		
PPE (respirator and safety glasses)	1	97.12	97.12
Sanding block, masonry trowel, and Rust-Oleum spray paint	1	35.33	35.33
High-temperature mortar, lower-grade (additional quantities)	1	127.38	127.38
Ceramic insulating beads	1	36.24	36.24
Thermal fuses	1	11.41	11.41
Hardware Subtotal (CAD)			1,176.13

Note: "Reclaimed" indicates sourced secondhand.

8.2 Software and Tools

Item	Qty	Unit (CAD)	Line (CAD)
Kiln controller software (open-source)	1	0.00	0.00
BrickCalculator (open-source)	1	0.00	0.00
Raspberry Pi OS (open-source)	1	0.00	0.00
Software Subtotal (CAD)			0.00

Grand Total (CAD) at time of writing: \$ 1,176.13

8.3 Components Pending Procurement

The following components are required by the design but had not been purchased at the time of writing. Each is identified in the design specification, remaining work plan, or construction notes. Costs are not listed here; they will need to be confirmed at the time of purchase.

Item	Notes
Rolling dolly stand with locking casters	Removable metal barrel dolly for raising the kiln off the ground. Reclaimed preferred. Not yet sourced.
Heavy-duty hinge	Required for lid attachment. Remaining work includes mounting the hinge and lid support hardware.
Angle-iron lid supports (×2)	Structural supports for the lid resting on the barrel rim. Listed in future sourcing plans.
Cool-touch lid handle	Required for safe lid handling during and after firing. Design specifies wood or equivalent heat-resistant material.

Item	Notes
Metal junction box	Control electronics enclosure to be mounted on the kiln shell, grounded to protective earth. Covers the ceramic terminal blocks and thermocouple feedthrough.
Mains power cord with grounded plug	3-conductor, 12 AWG, ≥ 20 A continuous duty, workshop-rated insulation. PDS specifies sufficient length for 18–36 in clearance around the kiln.
Panel-mount 120 V AC pilot lights ($\times 2$)	One per element chain, mains-rated. PDS specifies pilot lights in series with each element to visually confirm heater switching.
AO3400 logic-level N-channel MOSFET	Recommended by ECE technical review to replace the PN2222 BJT in the SSR drive circuit. Required to complete the switching stage before mains-power testing.
Strain relief cable glands	PDS specifies rated strain relief glands at all control enclosure cable entry points to prevent conductor damage during operation and transport.
Mains-path connectors and mechanical junctions	Terminal hardware needed to connect the power cord, SSR output, and heating element ends. Remaining work explicitly lists procurement of mains-path connectors.

8.4 Budget Status

The major materials were sourced with cost in mind, and reclaimed materials were used where practical. The barrel was reclaimed rather than purchased new. Additional final-build items have not yet been purchased at the time of writing, but are not expected to add more than approximately \$200 CAD to the total cost.

The initial budget estimate of approximately \$600 CAD was largely a rough guess made early in the project. The actual materials cost was closer to \$1,200 CAD — approximately twice the original estimate. A collaboration

grant from The Matrix Institute at the University of Victoria provided a significant portion of this funding and facilitated the purchase of higher-quality components. Whether the resulting budget–quality tradeoff proves durable will not be fully known until the kiln has operated through enough firing cycles to reveal any failure or degradation in components that may have been sub-optimal choices.

8.5 Sourcing Decisions and Substitutions

Most materials and components were sourced from online suppliers. Kiln-specific materials remained difficult to obtain in small quantities, and Canadian suppliers were used where possible. These included firebricks, fiber insulation, refractory mortar, Kanthal wire, the Raspberry Pi, the MAX31855 breakout, the SSR, the thermocouple, and supporting electrical components.

Construction consumables were purchased as needed from local suppliers. These included sandpaper, PPE, rustproof paint, angle-grinder discs, and similar items that were not fixed early in the design.

Materials were reclaimed where possible to reduce cost and environmental impact. The barrel shell and backup insulation board were both reclaimed. Future work includes plans to source additional generic components in a similar way, such as a rolling dolly stand, a heavy-duty hinge, angle-iron lid supports, and a wooden cool-touch handle.

Custom fabrication jigs were also part of the implementation strategy. A bevel-cutting jig was designed for the chamber bricks. An element-winding jig was designed and 3D-printed, which required the special order of a 7 mm diameter rod from McMaster-Carr. 3D printing proved a practical method for manufacturing custom jigs and small parts needed for assembly. Material substitutions for the backup insulation board and shell are described in Section [5.2](#).

Chapter 9

Prototype Construction Progress

9.1 Build Status Overview

At the time of submission, the full kiln design had been completed and the major materials had been sourced. Physical construction had begun on the refractory components and shell. The controller had progressed to a working low-voltage prototype, including simulation-mode testing and successful thermocouple reading on a breadboard.

The kiln has not yet reached full physical integration or powered heating validation. Final assembly remains blocked by unresolved slab construction details, pending insulation compression checks, and the remaining wiring and safety-review work.

9.2 Fabrication and Mechanical Build Progress

Firebricks for the chamber ring were cut using a jig. Lid and base slab pieces were cut from paper templates scaled to the final design and transferred to the bricks with marker lines. Most brick cutting was done with an older large-tooth wood saw, as refractory brick dulls blades quickly and the saw was already near end-of-life. Bricks were wetted before cutting or grinding

to reduce dust. A large-tooth hacksaw was used for some insulation cuts and finer edge work. A sanding block was used to clean up jagged brick edges.



Figure 9.1: Bevel-cutting jig clamped around a cut IFB chamber brick during sidewall fabrication.

Once the element grooves were marked on the actual bricks, the original groove path was simplified. The full-size layout showed that some runs were too close to one another and too close to the kiln lid. The revised path shortened the channels somewhat, but the elements could still be stretched to the required installed length.

The grooves were cut with a die grinder using a spherical bit matched to the channel diameter. This made depth control easier because the bit profile visually indicated the intended groove depth. Hand tools were preferred over larger stationary tools because they were available at home, easier to use cautiously, and easier to manage from a dust-control standpoint. Through-holes for the element exits were then drilled in the sidewall bricks.

Work also began on the lid and base slabs. Initial mortar joints cracked and did not hold adequately. The failed joints were removed, and the bottom slab was redone with a longer drying period. At that point, effort shifted toward finalizing the design and advancing the control system rather than forcing the masonry forward before the slab problem was resolved.

The barrel was cut into lid and lower chamber sections using an angle grinder and cut-off discs. Sharp edges were deburred with a sanding disc.



Figure 9.2: Hacksaw used with the bevel-cutting jig for IFB cuts; the large-tooth wood saw used for the majority of cuts is also visible.



Figure 9.3: Dry-fit chamber assembly with element groove channel paths marked on the brick faces prior to cutting.



Figure 9.4: Die grinder with spherical bit used to cut the undercut element grooves into the IFB sidewall bricks.



Figure 9.5: End slab masonry in progress, showing IFB pieces assembled to form the kiln lid and bottom hot faces.



Figure 9.6: Barrel after cutting, showing the separated lid and chamber sections sized to match the insulation stack and chamber heights.

Rapid surface rusting was observed shortly after the barrel was obtained. The shell was sanded, cleaned, dried, and coated inside and out with two layers of corrosion-resistant high-temperature paint. The coating appeared effective in an informal water-exposure check.



Figure 9.7: Lid section of the barrel being spray-coated with high-temperature rust-resistant paint; ports are taped off to protect against accidental sealant coverage.

Where hardware will later be mounted, the paint will need to be removed locally so the grounding connection bonds directly to bare steel.

Further shell work was deferred until the slab dimensions and insulation stack could be test-fit more confidently. Backup insulation pieces were cut to size and test-fit in the barrel sections. Final cabinet assembly was deferred until compression under slab load can be checked. Remaining shell tasks include cutting the inward support tabs, drilling the hardware openings, and finalizing the support heights based on the actual slab and insulation stack.

9.3 Component Procurement and Readiness

By March 2026, all major materials had been ordered and many had already arrived, while the thermocouple was expected to be delayed until April. The

kiln body, heating hardware, and controller could all advance without the thermocouple, but closed-loop heating validation depended on that part arriving in time. The thermocouple did arrive in time to test it, but similar occurrences with other supplies led to fluctuations in the project timeline that made it difficult to work in a strictly linear fashion. Design and prototyping therefore occurred in parallel throughout the project.

9.4 Control-System Prototyping Progress

The following steps were completed during controller prototyping:

- Raspberry Pi flashed with Raspberry Pi OS, connected to the network, and configured for remote shell access via PiConnect.
- GPIO verified with a blinky-style LED test; SPI enabled and confirmed working.
- Controller software installed and run in simulation mode; web UI confirmed accessible from a laptop over the network.
- Breadboarded thermocouple-reading setup built with the Pi, MAX31855 breakout, and thermocouple; ambient temperature read accurately.
- Three configuration corrections applied: software SPI switched to hardware SPI pins; MAX31855 selected explicitly in place of the default MAX31856 setting; heater output GPIO reassigned to the intended control line.
- Control-system electrical drawing produced and reviewed with ECE technical staff; outcomes included improvements to the switching-stage design, conductor specifications, grounding recommendations, isolation approach, and staged test plan.
- Raspberry Pi enclosure 3D-printed from an open-source model.

9.5 Partial Testing and Dry-Run Work

Testing completed so far has been limited to low-risk verification work:

- Raspberry Pi setup and network configuration
- GPIO output check (blinky-style LED test)
- SPI interface enablement and confirmation
- Web UI access through the controller software in simulation mode
- Breadboarded thermocouple reading at ambient temperature

Dry-run controller testing without the kiln heating load was also part of the planned validation strategy. That dry run was intended to demonstrate GPIO control of the switching circuit, software operation, and simulation-mode control behavior without requiring the fully assembled kiln.

9.6 Current Prototype State at Submission

At submission, the project consists of a complete kiln design, a sourceable material set, partial physical construction of the chamber and shell, and a partially validated controller prototype. The refractory chamber components have been cut, groove layout has been revised and implemented, barrel preparation has begun, and insulation pieces have been cut and test-fit. The low-voltage control path has been proven to the point of reading thermocouple data on the Pi.

The project does not yet include a fully assembled kiln, completed element winding and installation, final mains wiring, a safety review of the integrated physical system, or powered heating tests of the integrated system. These remaining steps are described in the future work plan.

Chapter 10

Challenges, Limitations, and Design Revisions

10.1 Schedule and Procurement Constraints

The original milestone schedule assumed that kiln materials could be sourced quickly. In practice, refractory materials, heating wire, insulation products, and high-temperature electrical components took significantly longer to source in small quantities within Canada than expected. Shipping delays introduced schedule variability that was difficult to plan around, and work had to be reordered as materials arrived out of sequence. This meant that design and prototyping occurred in parallel rather than in a clean sequential progression.

10.2 Technical Uncertainties and Unvalidated Areas

Several design decisions are justified analytically but still require physical confirmation, as summarised in Table [10.1](#).

Table 10.1: Technical uncertainties and unvalidated areas

Unvalidated Area	Notes
Lid and base slab construction	Two mortar attempts resulted in joint cracking under ideal drying conditions; physical validation of the final approach is still required.
Backup insulation compression	Rigid insulation under the slabs requires compression testing under load; shell support-tab heights depend on the result.
Lid seal performance	Functional adequacy under firing conditions has not been confirmed; see Section 5.8.
Integrated heater-switching path	Controller validated at low voltage; the full path through the MOSFET and SSR has not yet been tested under line-powered conditions.
Shell surface temperature	Predicted by the thermal model; not yet measured during operation.
Heat loss	Analytically estimated; requires validation against measured power draw and temperature data from a first firing.
Element resistance after installation	Cold resistance of the wound elements has not yet been measured in their final installed configuration.
Control-system noise sensitivity	Electromagnetic environment near the mains switching path has not been characterised; sensor behaviour under operating conditions is unknown.
Safety Warnings and Operation Manual	Documentation, as described in the PDS, will need to be created for the final assembly. This will also need to detail maintenance checkup recommendations specific to the final build.

10.3 Design Changes and Revisions from the Original Plan

Table 10.2 summarises the principal changes made relative to the original design plan.

Table 10.2: Design changes and revisions from the original plan

Item Changed	Reason
Shell material (stainless steel keg → cold-rolled steel barrel)	A suitable secondhand stainless steel keg could not be found; a 55-gallon unlined cold-rolled steel barrel was used instead.
Backup insulation for lid and base → PowerWool RigiBoard One	The preferred rigid high-temperature board was not economical or practical to source in small quantities.
Insulation stack thickness (increased)	Feedback indicated the estimated shell surface temperature was too high for residential garage use; thicker backup layers were added.
Element groove layout (revised and simplified)	Full-scale marking on the actual bricks revealed spacing issues not apparent in earlier drawings; groove paths were shortened.
End-slab masonry approach (under review)	Repeated mortar joint cracking has not been resolved; the construction method may change before final assembly.
Heater switching stage (BJT → MOSFET)	ECE technical review recommended a logic-level N-channel MOSFET in place of the PN2222 BJT; see Section 9.4 for details.

10.4 Limitations of the Prototype at Submission

The main limitation at submission is not the completeness of the design, but the incompleteness of the integrated prototype. Specifically:

- The kiln has not yet been fully assembled as a physical unit.
- Element installation is not complete.
- Final shell modifications depend on slab and insulation verification still in progress.
- The electrical system has been reviewed in principle but has not yet undergone a safety review in its final assembled form.
- No energized heater tests have been performed on the finished system.

The project therefore reaches submission as a complete engineering design with meaningful fabrication and control-system progress, but not as a fully integrated and validated kiln.

Chapter 11

Plan for Remaining Implementation

11.1 Remaining Mechanical Construction

- Resolve and validate the lid and base slab construction approach.
- Confirm that the rigid backup insulation does not compress excessively under slab load.
- Complete remaining shell modifications once slab and insulation heights are confirmed.
- Cut the inward support tabs and finalize their heights based on the confirmed slab and insulation stack.
- Drill the remaining hardware openings in the shell.
- Mount the hinge and lid support hardware.
- Source and install the rolling dolly stand.

11.2 Remaining Electrical Integration

- Wind and install the final heating elements.

- Route the pigtailed cold ends through the sidewall and connect to the ceramic terminal blocks.
- Complete junction hardware and procure mains-path connectors and mechanical junctions.
- Procure and install two 120 V LED pilot lights across the heating element branches (positions shown in Figure 7.1), mounted on the junction box exterior as power indicators.
- Verify protective-earth bonding on the finished shell and metal junction box.
- Finalize conductor selection and heater-branch implementation to reflect ECE technical review recommendations on temperature ratings and layout.

11.3 Remaining Control-System Integration

- Implement the final SSR drive circuit with MOSFET low-side switching.
- Source and install junctions, hot lines, and connectors to specification.
- Integrate the controller with the finished kiln hardware and finalize `config.py` settings for the actual installed wiring.
- Design and 3D-print a final enclosure for the control hardware once the physical layout is confirmed.
- Mount a metal junction box on the side of the steel shell to cover the ceramic terminal blocks and thermocouple mount; ground the box to protective earth.
- Electrically isolate the thermocouple from the junction box grounding points, as it connects to the MAX31855 and must not carry mains current back to the control hardware.

11.4 Safety Review and Pre-Power Checks

Before the kiln is connected to line power, a final safety review of the physical assembly will be performed by an electrical professional, following up on the design review conducted prior to submission. The review scope includes:

- Inspection of mains wiring and grounding
- SSR installation and heatsink adequacy
- Thermal fuse placement and rating
- Separation between high-voltage and low-voltage control wiring

No energized testing of heating elements shall occur before that review is complete. Pre-power electrical checks include:

- Continuity checks across all wiring paths
- Insulation resistance checks between conductors and ground
- Verification that the shell and junction hardware are electrically bonded to protective earth as intended

Chapter 12

Testing and Validation

12.1 Validation Criteria

A fully working kiln, in the context of this project, is not just a completed physical assembly. It is a system that satisfies all of the following criteria:

- Finished chamber and shell with installed refractory components
- Wound and installed heating elements
- Verified mains wiring, grounding, and thermal fuse placement
- Working temperature measurement through the full thermocouple-to-Pi chain
- Functional controller integration with closed-loop heater control confirmed in operation
- Completed safety review by an electrical professional
- Staged heating tests demonstrating safe and intended operation

The current project has reached the point where the remaining path is clear. The design is complete, major materials have been sourced, key fabrication steps have begun, and the controller has been partially validated. The remaining work is concentrated in final assembly, integration, safety review, and powered validation.

12.2 Testing Plan

The testing sequence proceeds in stages, from low-risk software verification through to full heating validation.

Table [12.1](#) describes the three stages of the planned validation sequence.

Table 12.1: Staged testing and validation plan

Stage	Key Verification Tasks
Stage 1: Controller verification — no kiln load	• Pi bootup, software installation, and Wi-Fi connectivity checks • Run built-in simulation mode; verify web UI controls in simulation • GPIO pin tests using <code>test-output.py</code>
Stage 2: Subsystem verification — hardware connected	• SSR switching tests (manual first, then via <code>test-output.py</code>) • Mains switching verification using pilot lights as indicator load: with heating elements not yet connected, wire the panel-mount pilot lights at the SSR output terminals and apply mains power. Trigger switching via <code>test-output.py</code>. Confirm both pilot lights blink in response to each command, then confirm asymmetric or continuous-on behaviour is absent on each channel. See Section 6.8 for rationale. • Thermocouple reading verification (manual first, then via <code>test-thermocouple.py</code>) • Watcher script and alert behaviour checks • Electrical resistivity checks of installed elements

Stage	Key Verification Tasks
Stage 3: Integrated closed-loop operation	• PID tuning using <code>kiln-tuner.py</code>; results reviewed via <code>kiln-logger.py</code> CSV output • Power-interruption restart check • Representative custom heating schedule run • Full validation: successful bisque and glaze firing schedule execution • Ramp rate verification confirming required heating rates within available power budget

The controller codebase includes standalone scripts that support staged hardware verification independently of the full control loop. `test-thermocouple.py` initializes the SPI interface using the same pin settings as `config.py`, prints the detected board type and thermocouple model, and outputs a timestamped temperature reading once per second. It selects hardware or software SPI by the same auto-detection logic used in normal operation, so a successful run confirms the exact SPI path the controller relies on. `test-output.py` configures the `gpio_heat` pin as a digital output and toggles it on and off in five-second intervals, printing the state and timestamp each cycle. This allows the GPIO-to-MOSFET-to-SSR switching path to be exercised without running the controller. The output state can be observed concurrently using the included `gporeadall.py` utility. These two scripts allow thermocouple reading and GPIO switching to be confirmed in isolation before any integration work begins.

The `kiln-tuner.py` script provides the PID autotuner referenced in Stage 3 above. It drives the kiln at maximum heat until a configurable target temperature is reached, then cuts power and logs the natural thermal decay back to that temperature, recording time and temperature to a CSV file at each `sensor_time_wait` interval. From the logged step response, the script fits a tangent line to the temperature curve, extracts the apparent process delay (L) and time constant (T), and computes initial PID gains using the Ziegler–Nichols open-loop method. The computed K_p , K_i , and K_d values are printed in the exact format expected by `config.py`. An optional Matplotlib plot of the fitted tangent can be displayed to assess the quality of the fit before accepting the results. The `kiln-logger.py` script connects to the controller’s WebSocket status endpoint and writes a timestamped CSV log of state fields (temperature, setpoint, runtime, heat output, profile name) and, when invoked with `--pidstats`, a full breakdown of proportional, integral,

and derivative terms each cycle. Both tools support offline analysis and can be used to refine PID parameters between firings.

Chapter 13

Future Work

13.1 Failure Detection Subsystem

One of the risks identified in this project was the possibility that the SSR could fail 'ON', causing heating elements to be separated from control logic and posing a safety hazard. The present design implements a thermal fuse to protect against excessive power generation if the SSR fails in this way. However, there are multiple possible points of failure in the system and it may be desirable to have a more intelligent and reactive method of both detecting and reacting to component failures. As a potential future improvement, a separate software-enabled safety control subsystem could be implemented in physical and logical isolation from the heater control system. The basic idea for this is described below.

An isolated current transformer (CT) clamp could be added to the SSR AC output path, providing non-invasive current monitoring. The CT senses current magnetically, allowing detection of whether the heating elements are drawing power without any direct electrical connection to the mains circuit. A small and inexpensive device, such as a Raspberry Pi Pico, could be set up in physical isolation from the main control system to read current from the CT. In addition to CT readings, the Pico would receive periodic SSR command data from the heater control system, relayed over a wireless side channel such as Wi-Fi, Bluetooth, or radio frequency (possible by way of additional peripherals).

If the safety subsystem detects a sustained discrepancy between SSR com-

manded state and detected current, it can infer that the SSR has failed. Furthermore, failure of the heater control could be detected by a timeout condition if the heater control system should fail to relay SSR command data or system status. Upon failure detection, the safety subsystem would trigger a separate mechanical contactor placed in series with the heater power path. The contactor would then physically open the circuit and disconnect power to the elements, providing a true fail-safe shutdown mechanism.

Although fairly straightforward, this subsystem was deemed beyond the scope of the project implementation. The requirement for custom software and integration with the open-source controller was not expected to provide value far greater than that of the existing safety mechanisms. However, this subsystem will be a topic of exploration in the future.

13.2 Video Documentation

Another way to communicate the results of this project is the production of a detailed video series and/or blog post documenting the design and construction process. This project would have been significantly more difficult without the online community that shares DIY kiln, refractory, and foundry builds through forums, YouTube, and similar platforms. Most existing DIY builds either focus on adding digital controls to an existing physical product, or on integrating a prefabricated control system into a hand-built enclosure. This project synthesized techniques from both approaches and represents a combination that is not well-documented at the time of writing. An archive of photos and videos is in progress and will be used to produce content for the community, with particular emphasis on pitfalls, unexpected issues, and their workarounds.

13.3 Controls PCB

The current design uses a breadboarded control system housed in a plastic enclosure separate from the kiln cabinet. A future improvement would be to design a custom Raspberry Pi pHAT (a compact add-on board) to consolidate the low-voltage control hardware into a single PCB. This would replace breadboarded connections with a more reliable solution and allow the

board to be fabricated with materials suited to the thermal and environmental conditions of the application. PCB design is a skill that aligns with the project's cross-disciplinary engineering goals, but is better deferred until the kiln is fully assembled and validated with the current controls layout.

13.4 Open-Source Software Contribution

The open-source kiln-controller software used in this project is still actively maintained and open for contributions. As testing and operation progresses, the software will be evaluated closely for its ability to meet the controller objectives. Issues or limitations identified during operation will be documented in a personal fork of the repository, and any potential fixes will be posed as contributions. Electrical safety considerations and more detailed implementation guidelines will also be contributed to the project documentation, as these were not part of the original upstream project.

Chapter 14

Conclusion

14.1 Final Project Outcome

At the time of writing, the electric kiln design is considered complete as described in this report. Significant progress has been made on construction, and the plan for remaining implementation is described in detail sufficient to continue from the current prototype state. Additional specifications may need to be made as construction progresses in order to further refine design decisions down to the level of physical implementation. These decisions will be documented in any further written or photo/video materials produced from this project. Testing and validation activities have been described in detail in the preceding sections and will be at least as extensive as what is described there.

Overall, this project was a highly valuable learning experience, and was an extremely interesting of many of the engineering skills that the author has been fortunate enough to develop throughout her degree. The opportunity to collaborate with other engineering disciplines was a unique experience and helped to shape the learning process for all concepts covered by this report.

14.2 Key Engineering Outcomes

The project was largely successful in accomplishing its objectives, despite the gap between the original expectations and the prototype state at submission. Key engineering outcomes included developing a deeper understanding of the following:

- Sourcing specialty materials from local and international marketplaces, including consequences of shipping delays, minimum quantity requirements, cost–performance tradeoffs, and the value of developing a flexible high-level design before committing to suppliers.
- Safety best practices for powered hand tools, PPE, hazardous materials handling, high-temperature equipment, and high-voltage power systems, in the context of working without a dedicated fabrication facility.
- Environmental and logistical constraints as first-class factors in requirements engineering.
- The utility and wide availability of open-source software solutions, and the practical benefits of adopting an existing community solution rather than designing custom software from scratch.
- How design choices in one subsystem propagate as constraints into others across mechanical, thermal, electrical, and control domains.
- The difficulties of working across multiple engineering trades simultaneously, and the real cost (in time and effort) of attempting to produce quality work in areas outside one’s primary expertise (such as bricklaying).
- The value of manufacturer design guides; specifically, the Kanthal element design guide was a significant resource for heater sizing and geometry decisions.
- The flexibility of the Raspberry Pi platform for embedded control applications, and the accessibility of breadboarding and hardware interfacing for software practitioners new to physical systems.
- How to communicate a technically complex build to domain specialists through electrical diagrams and written documentation in order to support a safety review outside the primary area of expertise.

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