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Mark II 500 °C Oven Build Instructions

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Summary

This report provides details of the construction of the Mark II, a second-generation compact oven designed to test prototype silicon carbide devices at temperatures up to 500 °C. Improvements made to the original Mark I oven in the Mark II design include the ability to ramp the temperature gradually to a setpoint and to contain active cooling inside the oven.

Introduction

This report provides instructions on the Computer Numerical Control (CNC) milling process for several Mark II oven components, a wiring diagram, Computer-Aided Design (CAD) drawings, and assembly instructions. The appendices include illustrations of the assembly and a list of components.

Note the following information regarding Mark II ovens:

1. The PID controller software described is capable of monitoring up to eight ovens at once. To do this, each oven should be wired to one serial (RS-485) converter and the converter connected to the computer.
2. The PID controller for the original Mark I included a precalibrated thermocouple. In contrast, the Mark II oven's thermocouple is purchased separately; therefore, calibration is recommended to reduce errors in measurement.

Step 1: Computer Numerical Control (CNC) Process

SOLIDWORKS® 3-D modeling software (Dassault Systemes Solidworks Corporation) (Version 2003 or 2001) and the Bantam Tools Desktop CNC Milling Machine can be used for fabricating the enclosures for the Mark II ovens. However, several preliminary steps are required in order to fabricate a SOLIDWORKS® design using the Bantam Tools Milling Machine. Because SOLIDWORKS is a design application, an additional computer-aided manufacturing (CAM) application or plugin is needed to generate toolpaths and G-code that the milling machine can follow to mill the design. Detailed instructions for working with the Bantam Tools milling machine are included in the following steps.

To begin construction of the Mark II oven, refer to the drawings in Appendix A, and model these drawings in a software program with CAD capabilities, such as SOLIDWORKS®. These components represent the final parts resulting from the bill of materials (BOM) item numbers 2.1, 2.2, and 2.4. After modeling all 10 parts shown in Appendix A, transfer the model to a Computer Aided Manufacturing (CAM) software application. Three-dimensional modeling software often includes integrated CAM capabilities (e.g., SOLIDWORKS, Creo). Figure 1 shows a SOLIDWORKS interface with the SOLIDWORKS CAM ribbon highlighted.

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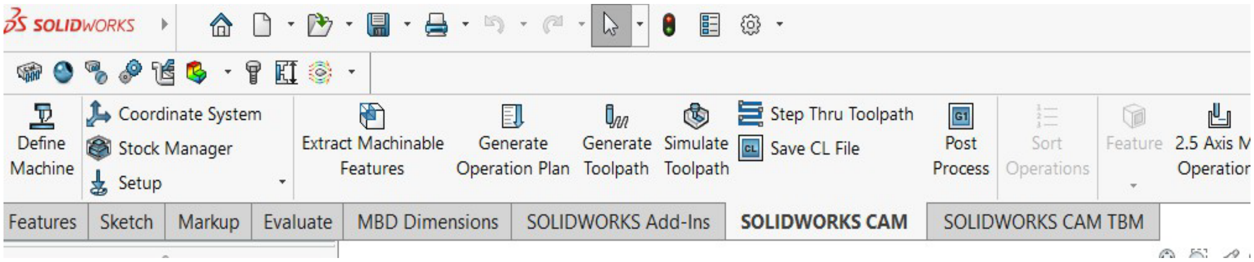

Figure 1.—SOLIDWORKS® CAM interface.

1. Download and install either the Macintosh or the Windows version of the Bantam Tools Milling Machine Software (also known as "post-processor" software) on to the computer controller. This software can be downloaded from the Bantam website.[1] Import the CNC machine's control (.CTL) file into the SOLIDWORKS® application using the Define Machine icon.
2. In the SOLIDWORKS® CAM ribbon (Figure 1):
    a. Use the Coordinate System icon to set up the coordinate system to be on the top-left corner of the model. The z-axis should be positive upwards, and the x-axis should be positive to the right.
    b. Select the "Stock Manager" icon to define the stock being machined. For most parts, an auto-generated stock will be accurate.
    c. Create a 2.5-mill operation with the Stock Manager icon. Choose the Contour Mill method of machining. Finally, follow the steps provided to select the desired feature to create the operation.
    d. Generate a toolpath (Generate Toolpath icon) and simulate its operation (Simulate Toolpath icon) to ensure it performs as expected.
    e. Select the Post Process icon to create the G-code. Import the G-code file produced into the Bantam Tools Milling Machine software application.
3. Power up the Bantam Tools Desktop CNC Milling Machine and connect it to the computer controller using the USB cable provided.
4. Home the device. (A pop-up dialog will appear to handle this when the Bantam software application is opened, but it can also be completed using the upper-left control button in the Bantam software).
5. Secure the bed into the Bantam Tools Desktop CNC Milling Machine by screwing in the six or four floor bolts provided.
6. Place extra stock beneath the desired material and screw both down onto the chosen bed.
7. Install the milling tool desired. Use two wrenches to loosen any previously installed tool, then twist, then loosen it one more time. Install the new tool and repeat the removal process in reverse. Then select the tool in the CNC milling machine software.
    a. Note: Once milling has begun, if the chips generated by the milling process slow the spindle or feed rate, the tool can break. To prevent this, adjust the spindle speed, feed rate, and other values in real time to determine the proper values. If the milling process is running smoothly, it may be possible to increase the spindle speed.
    b. To select a custom tool that is not listed in the software, go to Settings → Open tool library → Add → Fill out the information requested → Confirm. Select the custom tool, which should now appear in the tool drop-down menu.
8. Click Next in the window, then confirm that the tool has moved to an empty spot on the bed (that is, not above the stock piece or desired material).

[1] https://support.bantamtools.com/hc/en-us/articles/29471852026131-Bantam-Tools-Milling-Machine-Software

9. Select the material size and continue on with options to select the bed being used.
10. After securing the stock, begin the milling operation. When milling, always secure the stock properly and lubricate the bit often to extend its cutting life and avoid friction damage to the machine.
    a. Two options are available for material offset probing routines: automatic and manual. Note: The manual option must be used if the material is nonconductive (such as plastic).
        - Click Manual → Next → (origin is front left) Select right edge and back edge. → Move tool to be in that area via software; when close, change the scale to step (rather than jog) in the software. → Keep changing the scale when getting closer. → When ready, click “set x zero” and do a +z operation.→ Repeat the same steps to “set y zero.” There is no need to do ’z’ zero due to previous settings.
        - Insert a sheet of paper between the tool and the stock to gauge how close the bit is to the material. Tug on the paper and adjust the distance accordingly. If the bit is too close to the material, it runs the risk of breaking the bit. If the bit is too far away, then the z-axis movements won’t actually engage the bit with the stock.
    b. Within the SOLIDWORKS application, export the code for editing the stock piece as an .nc (Mastercam numerical control) file and in the Bantam software: file tab → G-code. Or use the Pro version of the Bantam Tools software, which supports conversational CAM, a feature that offers a simple way to program toolpaths without the need to rely on external CAD/CAM programs, for each hole and to generate G-code.
    c. Note: If a summary run job appears grayed out on the screen, make sure the CNC machine’s lid is closed properly.
    d. It is possible to “mill all” or select/deselect individual holes to pick and choose.
    e. If a “Tighten Drive Belt” pop-up window opens, follow the video link provided for instructions on proper tightening of the drive belt.
    f. It is possible to save profile selections between each part for version control and to archive all the current settings.
    g. When the work is complete, clean all machined part(s) and the CNC machine.

Refer to Appendix A to compare the drawings with the finished pieces.

Step 2: Wiring

Consult Table B.2 in Appendix B for a list of the electrical components needed. Additional necessary components, such as wire crimps and thread sealant, are listed in this appendix as well. Cut the wires to the lengths specified in the following list. All wires are 16 AWG stranded.

- **USB:** Red and blue, 138 mm
- **Inlet:** White, black, and green, 75 mm
- **Power Supply**: Yellow, 150 mm; green, 130 mm; black, 100 mm; white, 110 mm
- **Pneumatic**: Red 110 mm and black 200 mm
- **Terminal Strip**: White, 225 mm
- **Solid State Relay**: Black, 215 mm; blue, 70 mm and 270 mm; red, 280 mm

Use the wiring diagram in Figure 2 as a guide. Use wire crimps on all stripped ends. Red spade crimps can be used for single wire ends; blue spade crimps can be used for a double wire.

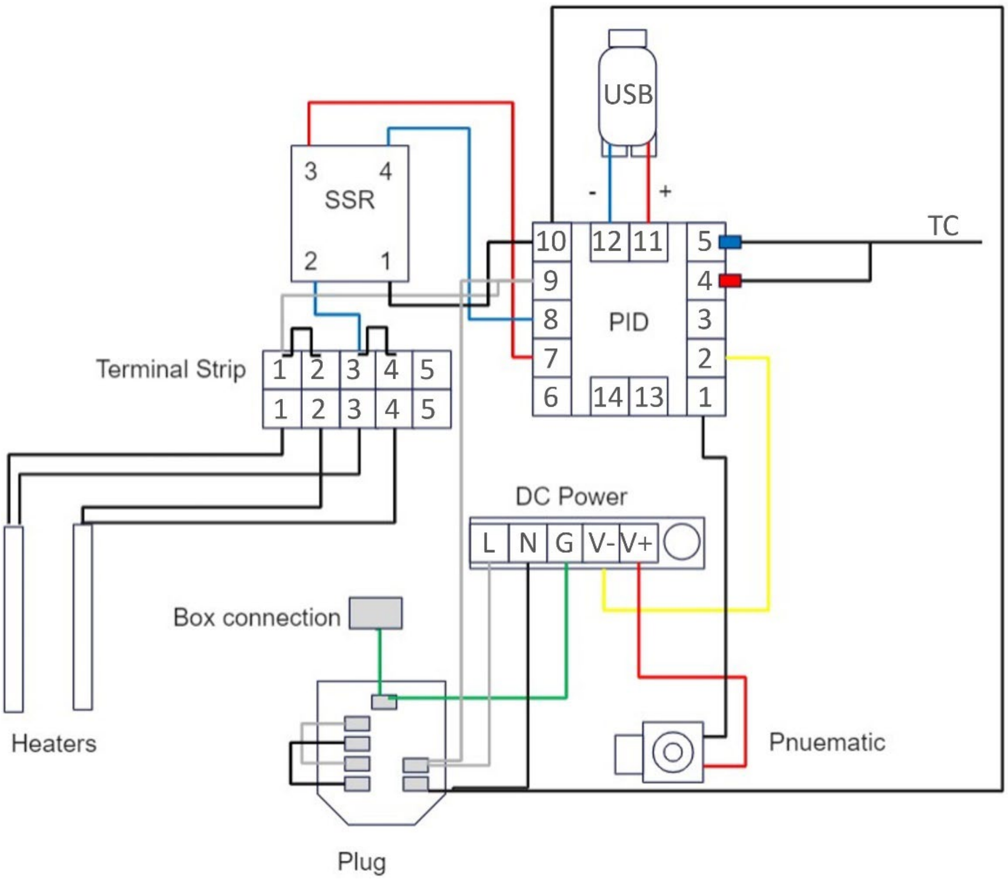

Figure 2.—Mark II oven wiring diagram.

The terminal strip contains two shorts between Terminals 1 and 2 and Terminals 3 and 4. If not available, form the shorts from small wires. Do not shorten the heater and thermocouple (TC) component wires.

Step 3: Assembly

Step 3a: Electrical Box Assembly

Once the wiring and component fabrication are complete, the components can be assembled. First, assemble the electrical box (using parts from Appendix A with Figure A.3 to Figure A.7).

Start with box components from Figure A.3, Figure A.5, and Figure A.6, with the plate part from Figure A.7.

1. Take four 4/40 × 5/16 bolts (BOM 3.13) and insert them into the four central holes with the threated ends of the bolts pointing out of the box. Secure them with the nuts (BOM 3.13). Then screw on four standoffs (BOM 3.12), using one standoff per bolt.
2. Screw in all the electrical components into the corresponding slots. See Figure 3 for the component layout and the fasteners needed for each part.
   a. Screw in the USB hub slot (BOM 3.1) next to the solid state relay (SSR).
   b. Apply thermal paste to the area where the SSR (BOM 3.2) will be installed. Use M4 bolts, nuts, and washer to screw it in. (BOM 3.11)

   c. Using M3 bolts, nuts, and washers (BOM 3.14), secure the terminal strip (BOM 3.8) in its designated spot.
   d. Apply thermal paste to the area where the power supply will be. Using 4/40 × 5/16 button socket caps, secure the power supply (BOM 3.5).
   e. Slide in the PID controller (BOM 3.10). No fasteners are needed.
   f. Wrap a layer of thread sealant (BOM 3.17) on the brass male elbow (BOM 3.9) and screw it into the solenoid as shown in Figure 3. Apply thermal paste (BOM 3.16) beneath the solenoid and use M4 bolts (BOM 3.11) as fasteners. Then wrap a layer of thread sealant on the air flow control valve (BOM 3.3) and twist it into place.
3. Using the 4/40 × 5/16 button socket caps (BOM 3.13), secure the inlet plug.
4. Take the plate from Figure A.7, and match holes with Figure A.3 and the standoffs (BOM 3.12). Add eight more standoffs, two per standoff to secure the plate to the top of the electronics box part. (See Figure 4 for a visual reference.)
5. Feed the TC through the middle 0.5-in. hole (by the inlet and PID controller). Use zip-ties and wind the TC into a tight circle; be certain to keep enough out for the measurement end of the TC to reach the middle of the top oven location and ensure the extra cable does not touch the inlet terminals.
6. Feed the heater wires through both 0.5-in. holes (one heater per hole). Be certain to keep enough out for the heater element to reach the top oven block.

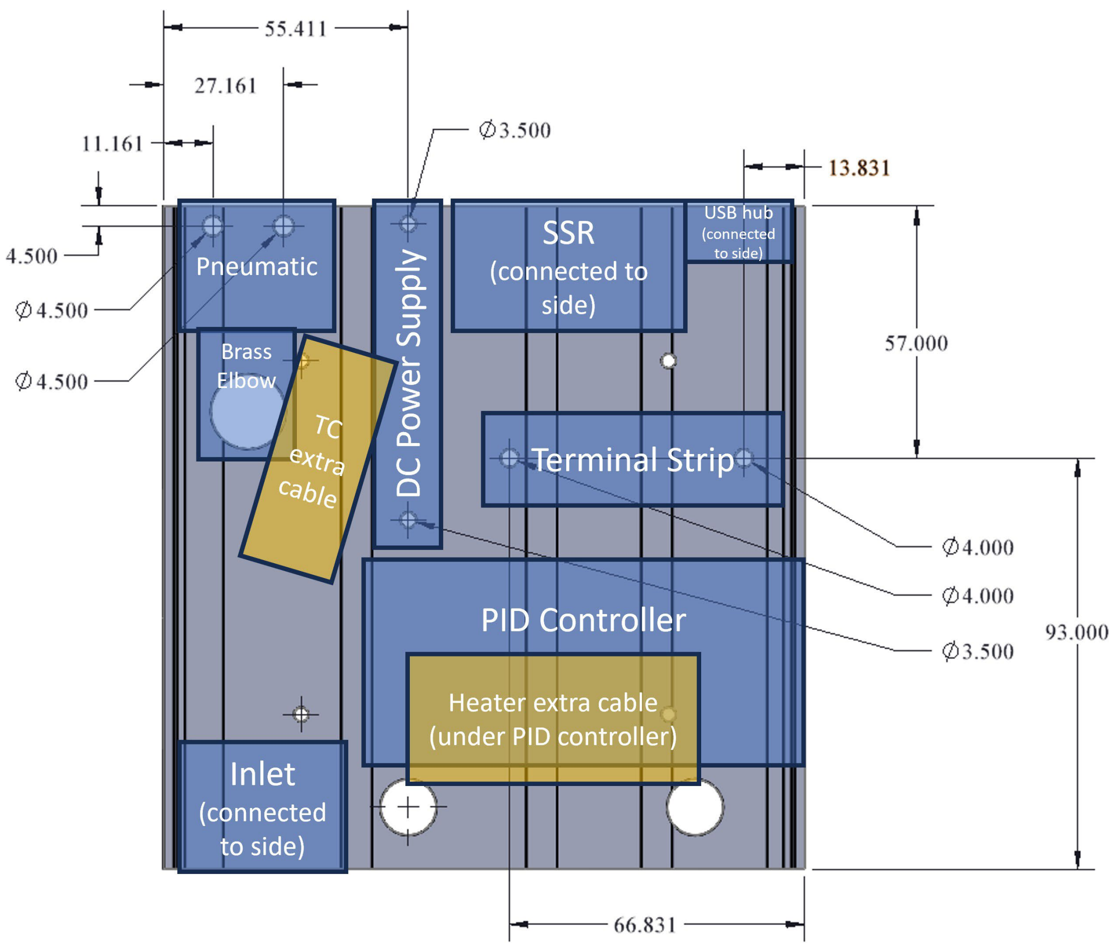

Figure 3.—Mark II oven component layout. All measurements are in millimeters.

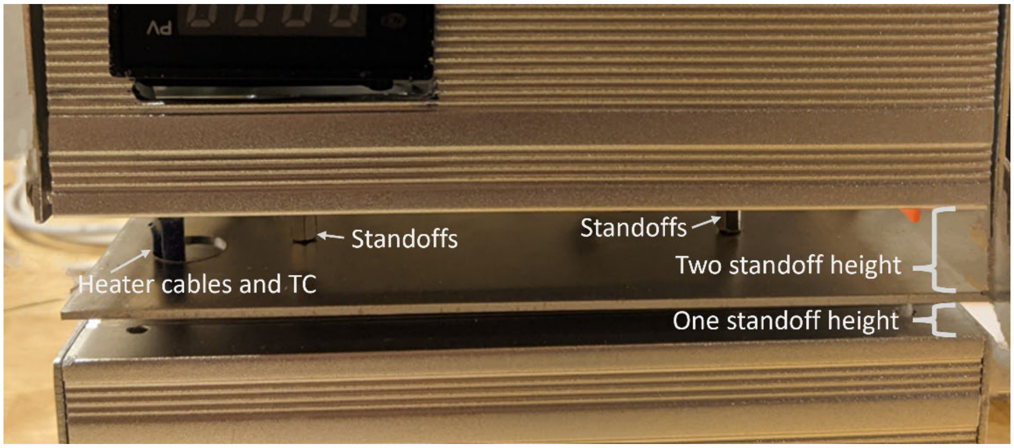

Figure 4.—Standoff spacing.

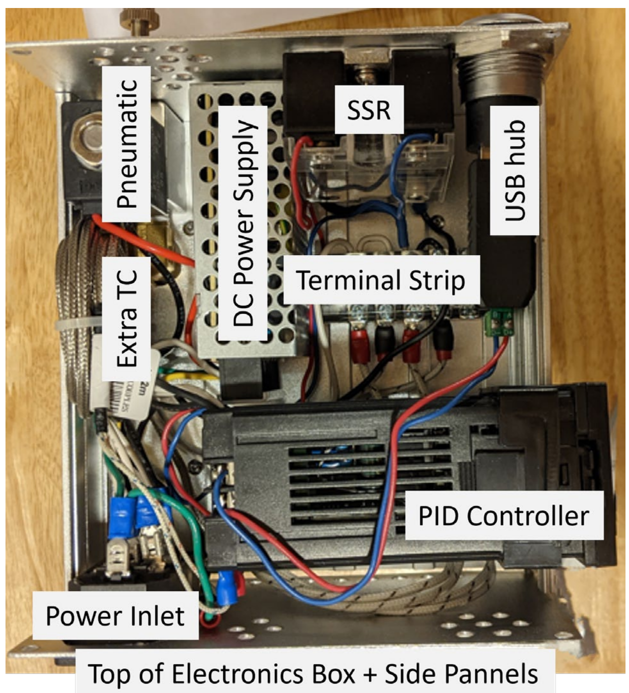

Figure 5.—Top of electronics box component and wiring view.

See Figure 7 for reference on how the electronics box should look at this point in the assembly process. After securing all the components, work on the piece shown in Figure A.4, using a 4/40 × 5/16 bolt with thread sealant, two washers, rubber feet, and a 4/40 nut, in that order, to create each of the four legs for the bottom of the electrical box (BOM 3.13, 3.17, 3.18). Finally, screw in the side plates (Figure A.5 and Figure A.6)and snap the top and bottom together to complete the electrical box. Be sure to tighten the PID controller tabs to secure the controller within the side of the box before installing the side panel containing the inlet plug.

Step 3b: Oven Box Assembly

Once the electronics box is fully assembled, flip it over, showing the plate from Figure A.7, containing the male side of the standoffs.

1. Take the copper piping (BOM 4.2) and cut a 24-mm piece. Swage the piece into the brass male elbow.
2. Place the bottom oven box (Figure A.7) matched with the holes on top of the standoff bolts and secure with four 4/40 nuts (BOM 3.13).
3. Prepare the heater block. This block is shown in Figure A.10. It can be milled down from a piece of solid aluminum stock, 3D aluminum printed, or purchased through BOM 2.3 and 2.4 (middle of 80/20 removed and tapped, then bolted together with some 4/40 bolts). Consult the Mark I Silicon Carbide Integrated Circuit Test Oven Assembly and Programming Guide at https://ntrs.nasa.gov/citations/20230014821 for more information). Once the heater block is ready:
   a. Tap one of the top right holes with a ¼-in. tap.
   b. Put the two heater rods into the bottom two holes.
   c. Screw the thermocouple into the tapped hole.
4. Bend the copper pipe (BOM 4.2) to enter the opposite hole as the thermocouple.
5. Place insulation around the heater block to align it with the slits on the side panels.
   a. Use sharp, heavy-duty scissors to cut the 0.5-in. thick ceramic insulation blanket (BOM 4.4) into pieces of the following dimensions (there are five layers of insulation):
      – (1) Top piece, layer 1 (133.35 by 152.4 by 31.75 mm)
      – (1) Top piece, layer 2 (141.2 by 152.4 by 25.4 mm)
      – (2) Middle piece, openings (76.2 by 25.4 by 25.4 mm)
      – (1) Middle piece, larger side (38.1 by 139.7 by 19.05 mm)
      – (0) Middle piece, heater block
      – (1) Middle piece, smaller side (31.75 by 146.1 by 15.24 mm)
      – (1) Bottom piece, layer 1 (152.4 by 152.4 by 31.75 mm). Contains two slits at the heater and TC wires.
      – (1) Bottom piece, layer 2 (152.4 by 152.4 by 25.4 mm). Contains two slits at the heater and TC wires.
   b. Place insulation around the heater block as shown in Figure 6.
6. Close up the top and bottom oven box and secure with the side plates to finish the oven box.

The oven opening side panels (Figure A.8 and Figure A.9) are for a double-sided oven. If this is not needed, the center large square can be omitted, but the vent holes should still be drilled. When the Mark II oven construction is complete, it should look similar to Figure 7; the back should look like Figure 8(a) if a single-sided oven or Figure 8(b) if a double-sided oven.

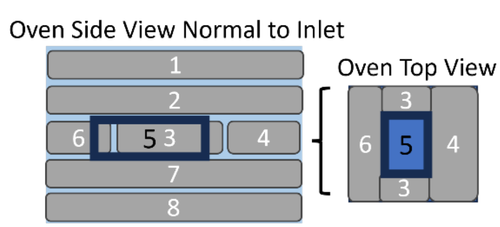

Figure 6.—Insulation layout for oven box.

Figure 7.—Completed Mark II oven.

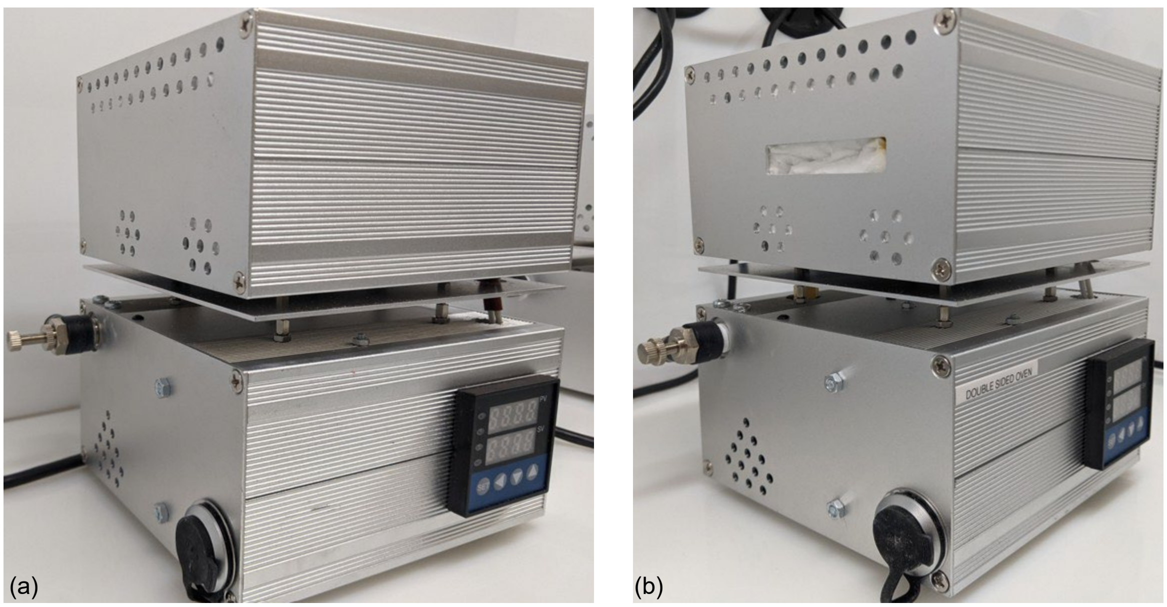

Figure 8.—Back of Mark II oven. (a) Single-sided version. (b) Double-sided version.

Step 4: Programming Proportional-Integral-Derivative (PID) Controller

For 500 °C operation, see the controller values listed in Table 1. This includes the oven's active cooling mechanism if the setpoint and actual value are 20 °C off. The table does not include setting a recipe for the oven to follow. These values will give just the steady-state temperature of 10 °C shown as its setpoint in Table 1. If a recipe is inputted, consider setting LOOP to 1 for continuous operation of the recipe. To set these values, use the manufacturer software available (consult the USB PID Time & Temperature Programmable Controller website at https://www.thermomart.com/Temperature-Controller-Ramp-Soak-Programmable/PID-Temperature-controller-Ramp-Soak-USB-PC) or set them manually with the PID front-facing controls.

TABLE 1.—PID CONTROLLER INPUTS

PID Abbreviation	Description	Value
SP	Set Value	10
AL-1	Alarm Set 1	20
AL-2	Alarm Set 2	0
Pb	PV Bias	0
P	Proportional Band	185
I	Calculus Time	1,866
d	Differential Time	73
T	PID Control Cycle	4
FILT	Digital Filter	20
Hy	Differential Gap	0.5
dp	Decimal Point Position Selection	1
outH	Output Limiter High	200
outL	Output Limiter Low	0
AT	Auto Tuning	0
LocK	Set Data Lock	0
Sn	Input Type	K
OP-A	Main Output Opt.	1
C F	Measured Value (PV) Unit Select	0
ALP	Alarm Output Opt.	4
COOL	System Function Opt.	0
P-SH	Range High	525
P-SL	Range Low	0
SEC	Set Time Unit	0
LOOP	Cycles	0
PED	Power Down	2
AL P	Wait Zone	10
run	Program Control Mode Setting	0
Pro	Program Segment	1

If further details on the controller inputs are required, consult the USB PID Time & Temperature Programmable Controller Manual, available online at: https://www.thermomart.com/download/PID-RS-USB-N.pdf.

Appendix A.—Drawings

Figure A.1 to Figure A.10 illustrate the aluminum components needed to build the Mark II oven. All measurements in this appendix are in millimeters.

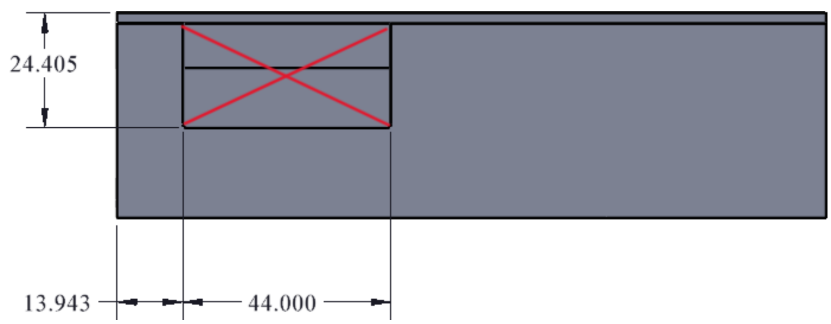

Figure A.1.—PID slit in top electrical box.

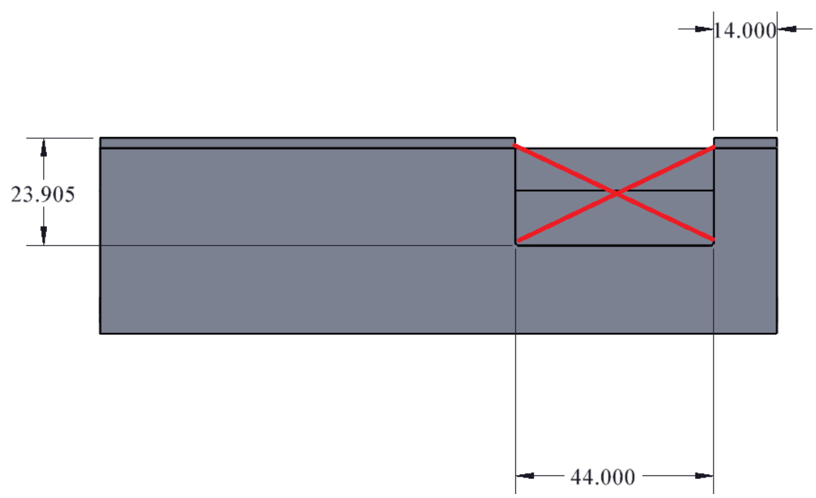

Figure A.2.—PID slit in bottom electrical box.

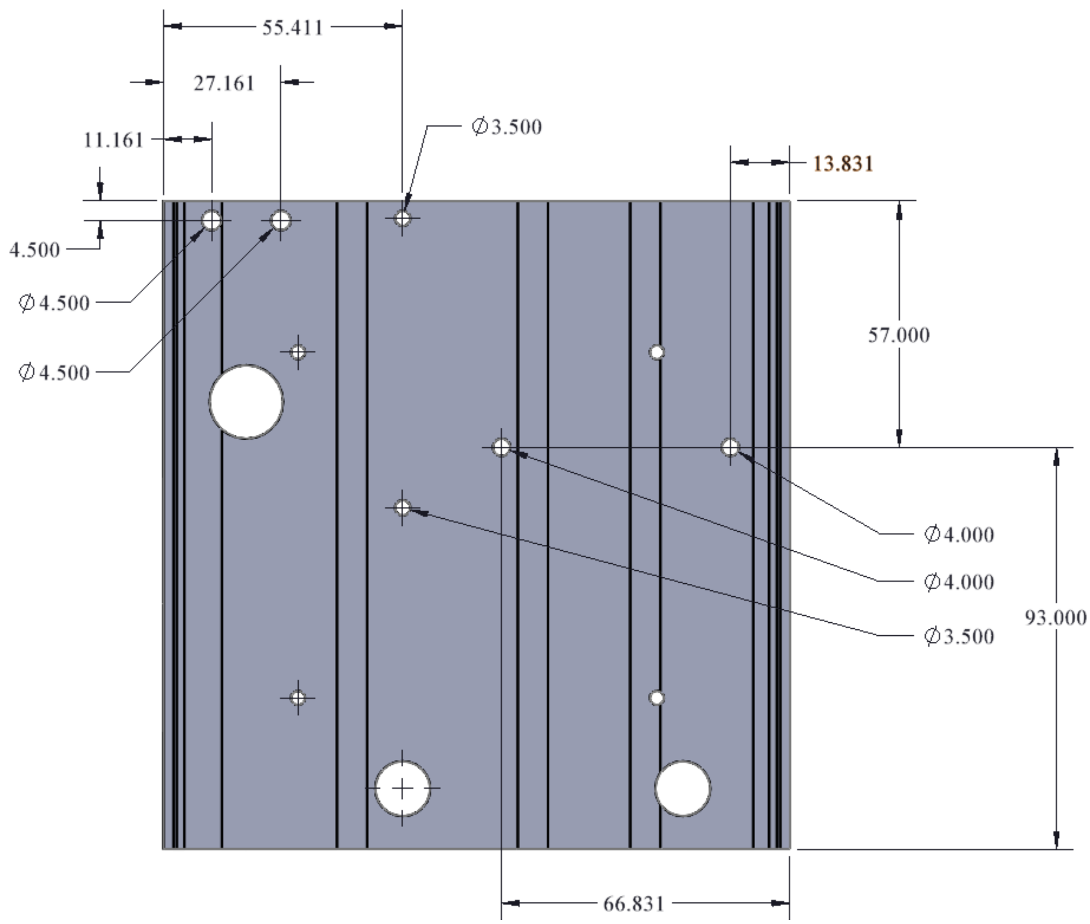

Figure A.3.—Top of electrical box. PID slot is bottom right and flanges are pointed up. Four central holes are the same as in Figure A.7.

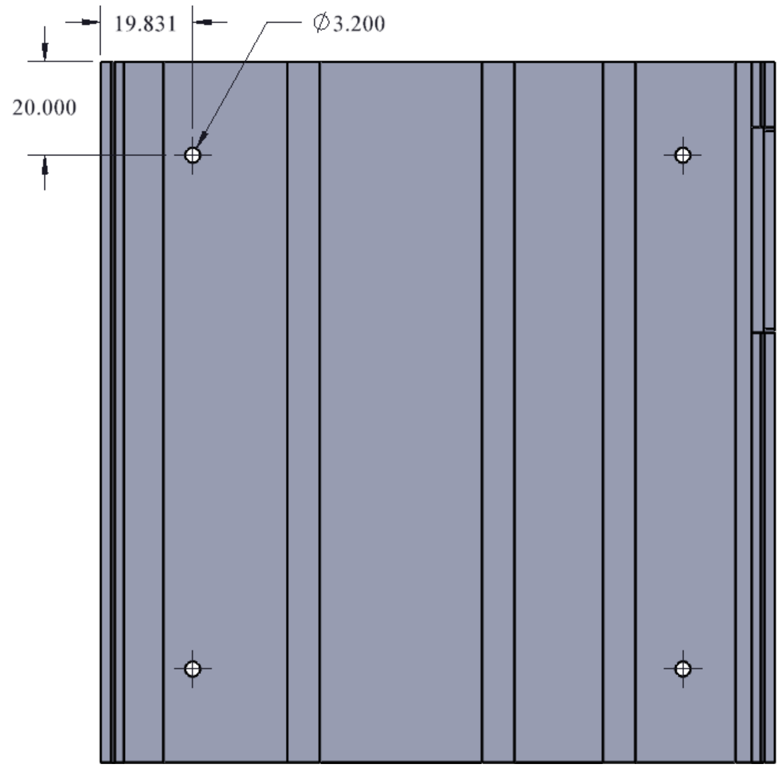

Figure A.4.—Bottom of electrical box.

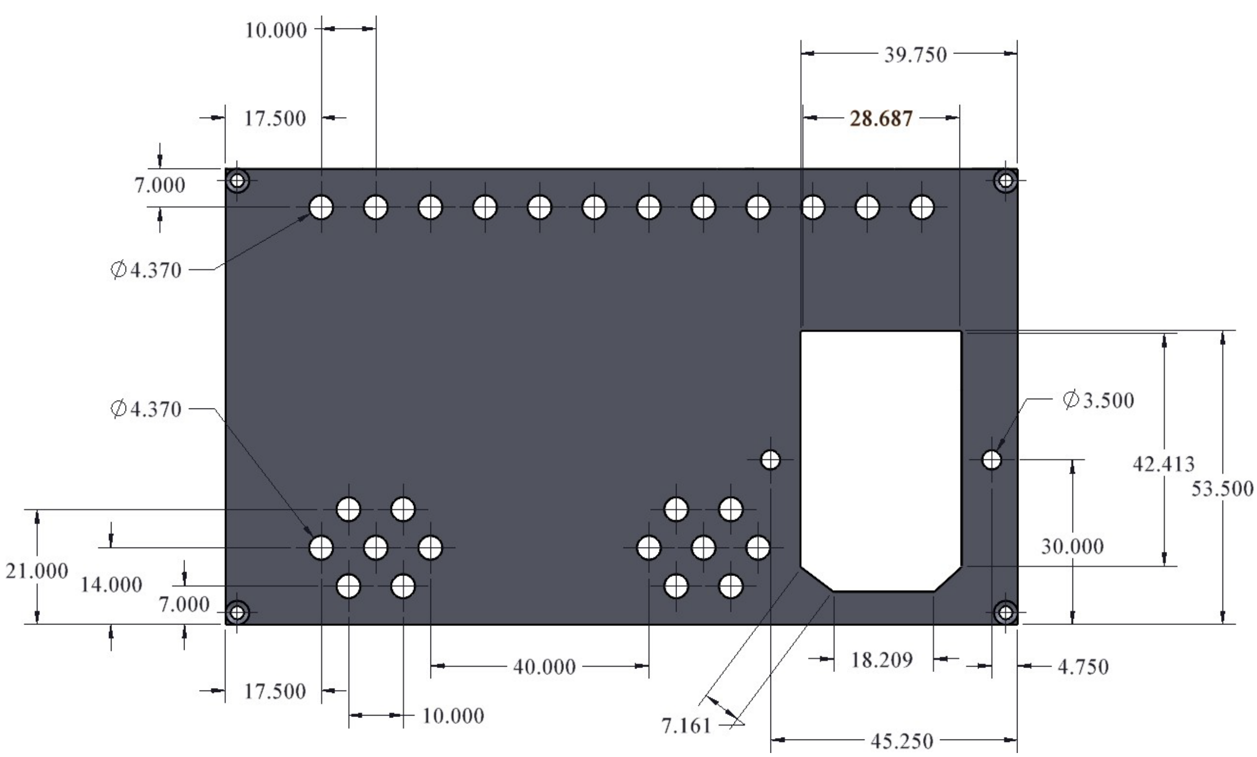

Figure A.5.—Side panel with plug slot. All holes are equidistant. Plug slot is symmetrical.

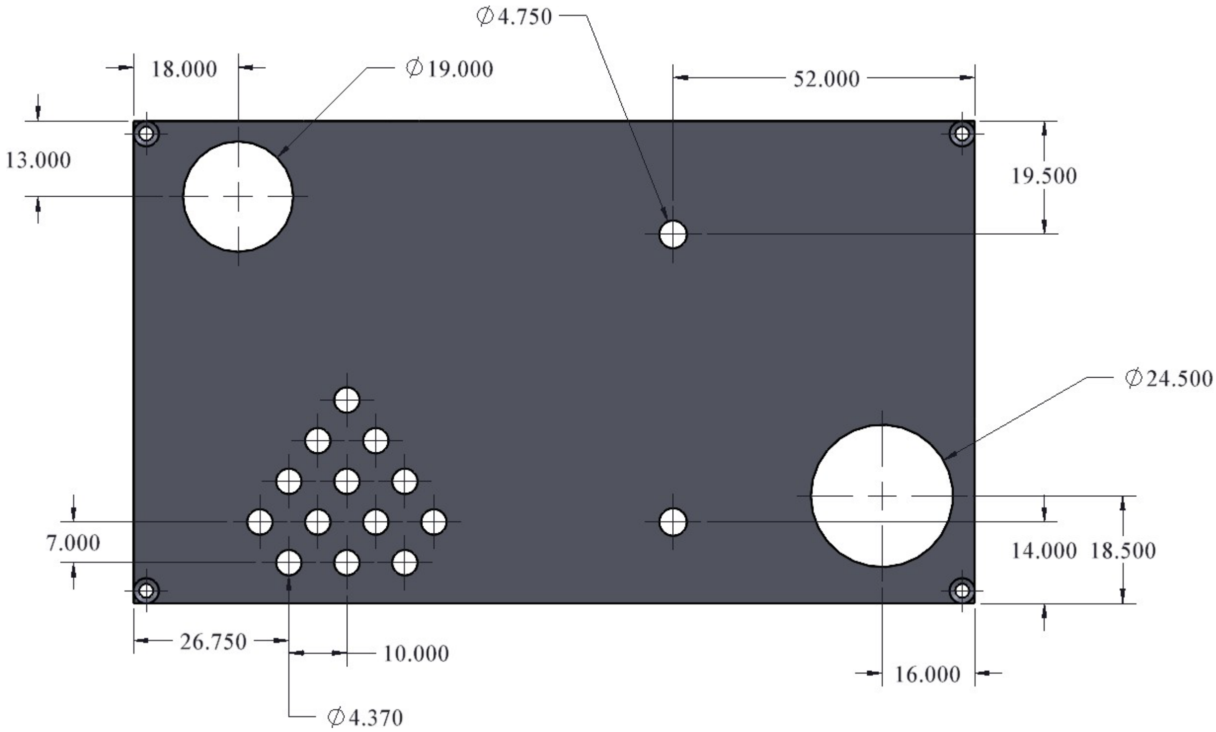

Figure A.6.—Side panel with push valve and solenoid. All holes are equidistant.

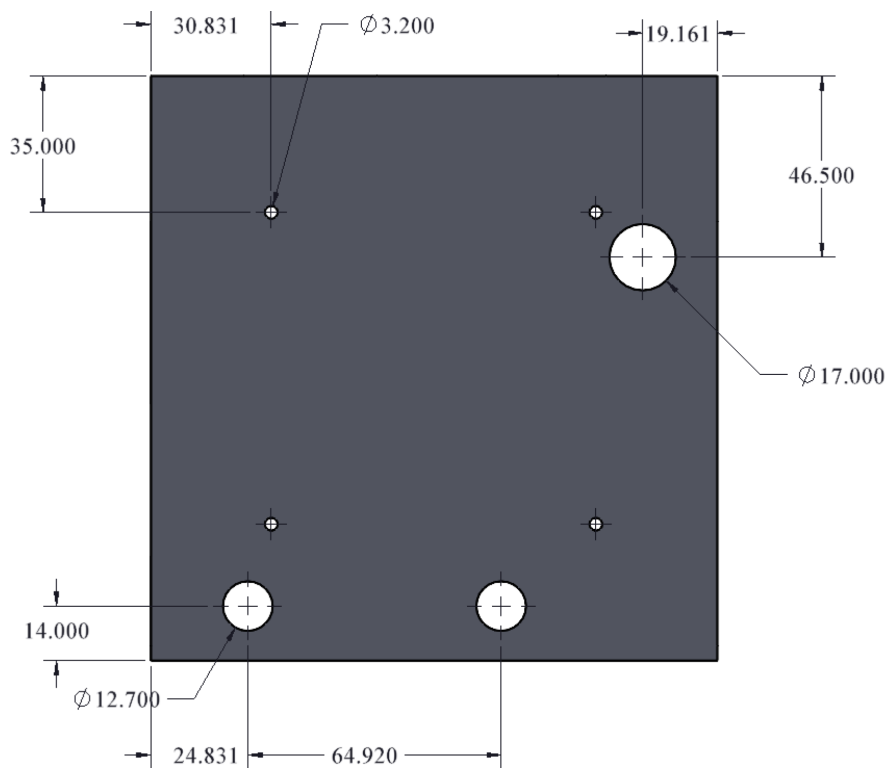

Figure A.7.—Middle separation plate. Bottom of oven box. Central holes are symmetrical.

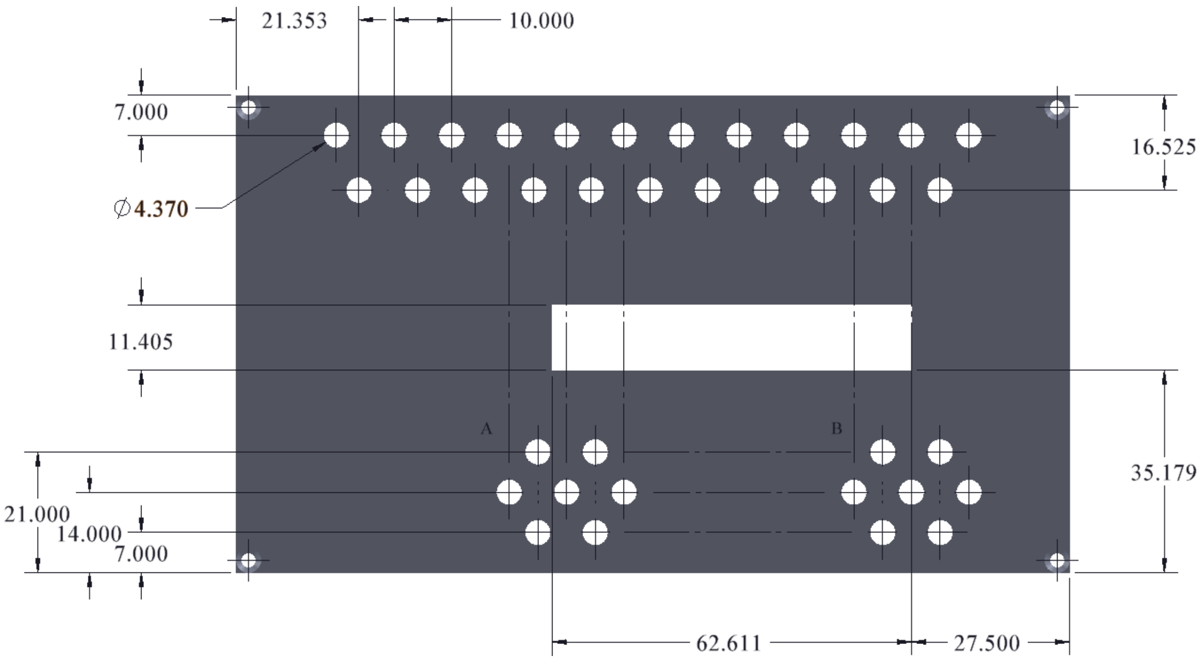

Figure A.8.—Oven side panel, version 1.

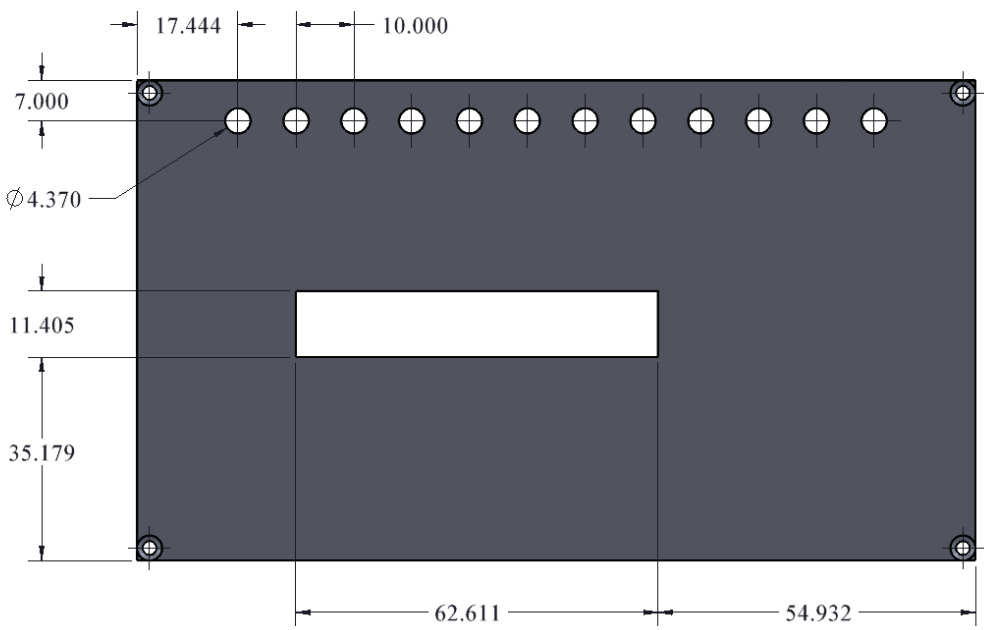

Figure A.9.—Oven side panel, version 2.

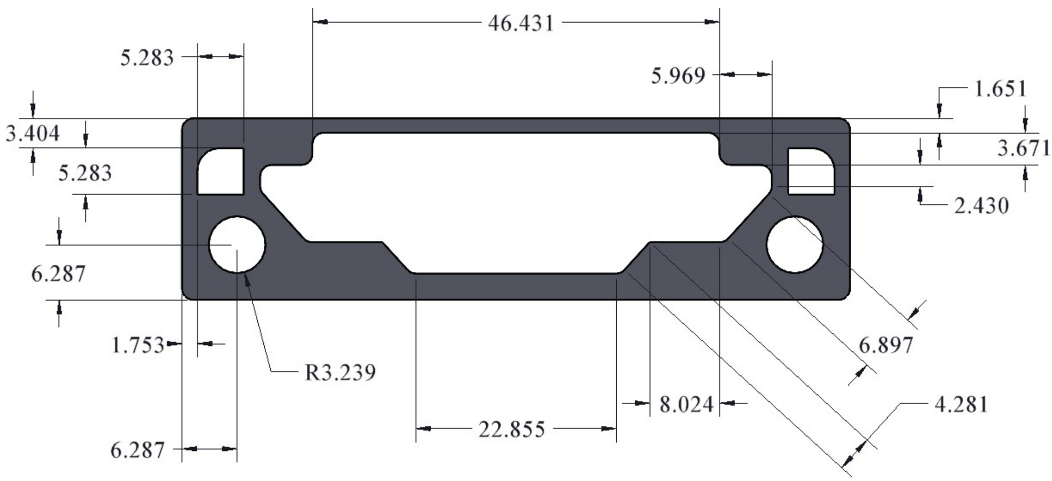

Figure A.10.—Heater block, 100-mm-long, symmetrical.

Appendix B.—Component List

Table B.1, Table B.2, and Table B.3 list the aluminum, electronic, and oven components of the Mark II oven.

TABLE B.1.—STOCK ALUMINUM OVEN COMPONENTS

BOM item number	Description	Manufacturer	Quantity
2.1	Aluminum enclosure, 3.2 by 5.7 by 5.9 in.	Vikye	2
2.2	Aluminum plate, 5.9 by 5.7 by 1/16 in.	2TwentyTwo	1
2.3	Aluminum plate, 4 by 3 by 1/16 in.	2TwentyTwo	1
2.4	Light T-slotted profile, 3034-Lite, 15 series, 3 by 0.75 in., 4 in. long	80/20	1

TABLE B.2.—ELECTRONIC COMPONENTS

BOM item number	Description	Manufacturer
3.1	USB 3.0 panel mount coupler	Penglin
3.2	Single-phase SSR solid state relay 25 A	Twidec
3.3	Push to connect air line fitting air flow control valve ¼-in., OD ¼-in.	Tailonz Pneumatic
3.4	DC 24 V electric solenoid air valve ¼-in. NPT	Beduan
3.5	RS-25-24 AC to DC power supply, single output, 24 V, 1.1 A, 26.4 W, 1.5-in.	Mean Well
3.6	Inlet module plug male power socket with 5 A fuse switch 10 A 250 V, 3-pin	Antrader
3.7	3A, 250 V, 0.2 by 0.78-in. glass tube time-delay fuses	Bojack
3.8	Terminal block set, 5 pieces, 5 positions, 600 V, 15 A	Glarks
3.9	Male elbow, 90°: brass, for ¼-in. tube OD, 1/8-in. pipe size	Grainger
3.10	High resolution temperature controller PID-RS-USB	Thermomart
3.11	M4 screws, nuts, and washers	N/A
3.12	#4-40 6 and 6 mm F/M brass hex standoff spacer screws PCB pillar nickel-plated	N/A
3.13	4/40 by 5/16 screws, nuts, and washers	N/A
3.14	M3 screws, nuts, and washers	N/A
3.15	Blue and red wire crimps	N/A
3.16	Thermal paste	N/A
3.17	Thread sealant	N/A
3.18	Small round rubber feet with screws, Part no. X00207UXD1	Otrestodyl

TABLE B.3.—OVEN COMPONENTS

BOM item number	Description	Manufacturer	Quantity
4.1	¼-in screw probe temperature sensor, K-Type thermocouple, 2-m cable	Twidec	1
4.2	Copper pipe 1/8-in. OD by 5/64-in. ID, 8 in., Part no. TC-75-9	JB Industries	1
4.3	6 by 100 mm tubular heating element, mould cartridge heater AC 110 V, 150 W	XJSXZC	2
4.4	Ceramic insulation blanket, PO810013, 19 by 14 by 1/2 in., Model no. 2675E, density 96 kg/m^3, heat capacity 840 J/kgK, and thermal conductivity 0.019 W/mK	Lynn Manufacturing	1