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USB-C Outlets for Plug Loads in 350V DC Buildings

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***Abstract*—USB-C has become the universal plug standard for charging consumer electronics, typically through AC/DC wall adapters. As new standards in USB power distribution allow USB-C ports to provide up to 240W at 48V, many discuss the possibility of USB-C emerging as a plug-load standard, especially in DC buildings. This work proposes the use of USB-C wall outlets to power the emerging USB-C ecosystem without need for a wall adapter. We first study the market feasibility of USB-C outlets through a series of customer discovery interviews. We then perform several experiments to evaluate the technical feasibility. These include a comparative evaluation of efficiency and a thermal experiment to study how the heat from outlet's conversion loss can be dissipated through an exterior wall section.**

***Index Terms*—USB-C, USB-PD, Outlet, DC Microgrids, DC Buildings, DC Plug Loads, Power Electronics**

I. Introduction

Today, electronics are everywhere. The average American home has 24 pieces of electronics [1], all of which comprise a $1028 billion consumer electronics market [2]. USB is easily the most popular DC plug standard for charging electronic devices. While electronic loads operate internally on direct current (DC), power from wall outlets is alternating current (AC). Nearly all electronic devices and many other types of low-power loads are powered through USB wall adapters, which perform the AC/DC conversion. Wall adapters are bulky, heavy, and inconvenient. Those permitted in the USA may operate with as low as 88% efficiency and up to 0.2 W of standby power [3]. In addition, a large fraction of electronic waste can be attributed to the 500,000 wall adapters discarded every year [4]. USB outlets have the potential to solve many of the inconveniences in wall adapters. USB-enabled wall outlets have been on the market for years, though each port is generally limited to the 5 V 3 A USB-A standard, which is sufficient only for charging small consumer electronics.

Today, USB-C is emerging as the single standard and connector for consumer electronics. Its point-to-point power delivery architecture allows for simultaneous power and communications [5]. Power over USB-C strictly adheres to the USB power delivery (USB-PD) protocol. USB-PD has generally become the standard by which a power source such as a charger can communicate with and transfer power to an attached load. As of 2021, the USB-PD 3.1 standard now allows for Extended Power Range (EPR) Mode, enabling up to 240 W at 48 V [6]. 240 W is high enough to power many types of plug loads beyond electronics (e.g. refrigeration, lighting, displays), thus increasing the overall utility of USB-C outlets. As the USB-ready device ecosystem expands, it may well make sense to move the AC/DC conversion from the wall adapter to the outlet.

DC microgrid systems or subsystems are emerging in many off-grid or lightly grid-tied applications. The potential benefits of DC power distribution networks have been studied and validated in academic research, including efficiency [7]–[9], cost [10], power quality [11], [12], resilience [13], safety, and potential to combine power and data onto the same line. Other conveniences such as its ability to mitigate the pains of permitting and interconnection agreements have allowed DC power to establish itself in niche applications [14]. Nonetheless DC power has stalled in its transition to the buildings industry due to the infamous "chicken and egg" problem: a lack of DC-ready buildings discourages the production of DC loads and vice-versa. As such, DC systems have thus far been developed as subsystems in AC buildings. These buildings use small DC systems that address or optimize specific load networks, the most common being low-voltage lighting.

The greatest barrier to DC buildings is the lack of an accepted plug and receptacle standard. The most common receptacle standard in the US is NEMA 5-15, the ubiquitous three-pronged outlet for 120 V AC power, used throughout residential and commercial buildings. A standard DC receptacle as prevalent as NEMA 5-15 would allow manufacturers to develop DC loads, pushing the DC industry past the "chicken and egg" problem. While many institutions have united around the 350 V DC Current/OS standard [15] for buildings, such a high voltage is not necessarily appropriate for low-power plug loads, especially given all the benefits of touch-safe low-voltage plugs. With the advent of the 240 W USB-PD 3.1, USB-C may well be a promising candidate for a universal DC plug-load standard in the low-voltage range. As the set of USB-ready devices widens to include loads such as lighting, refrigeration, and displays, DC buildings could be enabled with an increasingly large set of mature plug loads. AC circuits could even be retrofitted as DC with little inconvenience to the occupants. Thus the DC industry may greatly benefit from a transition to USB-C outlets within AC buildings. One possible concern is that the power conversion losses generate heat, which is dissipated into the wall. Part of our research evaluates the ability for a wall section to dissipate the outlet's conversion loss.

Several past works investigate the potential of DC distribution via USB-C. Much of this research investigates the role of individual USB hubs [16]–[19] or workstations [20], though some works propose the connection of multiple hubs to form a USB-driven DC nanogrid [21], [22]. While some works propose the scope of loads that could be powered by USB [19], only few non-electronic loads such as lighting [8] have been prototyped. Several works also describe the use of USB wall outlets [23], [24]. In general, USB does improve the possibility of smart outlets, which can regulate their power based on limits provided by a centralized controller [25], [26]. Several works detail the standby consumption concerns present in outlets that contain electronics. GFCI outlets [27], [28] may draw up to 1 W in standby; these works show how the standby consumption of outlets with electronics can quickly add up over an entire building. Finally, several other works describe the security concerns present with USB, particularly in the scenario that a clean USB hub or outlet were swapped with a malicious one [29], [30].

This work describes our study in scoping the market and technical feasibility of a high-power USB-C outlet with 350 V DC input. We first evaluate the market feasibility of such a product through a series of customer discovery interviews, described in Section II. Our technical feasibility analysis studies the electrical and thermal characteristics of a 140 W prototype USB-C outlet from Power Integrations. In Section III, we show how the outlet's efficiency compares with other 140 W USB-C wall adapters on the market. In Section IV we describe a thermal experiment that studies whether the losses from the outlet can be adequately dissipated within a typical wall section.

II. Market Feasibility Study

Our market feasibility study consists of a series of customer discovery interviews. Our customer discovery interviews include the following professionals:

- DC system designer
- DC developer
- DC microgrid academic
- Network system developer
- Electrician
- Electrical designer
- Electrical safety officer
- USB R&D engineer
- USB applications engineer

The interview questions were similar, but varied slightly based on the interviewee's background.

A. General Trends in Response

In general, all interviewees approved of using USB-PD outlet to enable the USB ecosystem and ultimately promote DC distribution. USB outlets are already gaining traction in the market, and high-power USB-C outlets would expand the options for user-friendly touch-safe DC plug loads. The interviewees generally recommended bringing the outlet to market as soon as possible, even if it means reducing the project scope or quality of the product. 140 W should be sufficient to power most small loads and it may be fine to sacrifice performance and efficiency in order to reduce time to market.

The interviewees all agreed that most plug loads could be powered by a 240 W USB-C outlet. The best loads for USB-C are battery-based. Opinions were split on whether this outlet would be appropriate for lighting. The interviewees all noted that high-power AC outlets are still be needed for many types of loads. As expected, the kitchen would require the most AC outlets. Occupants may need high power in other rooms for vacuum cleaners, power tools, hair dryers, or irons.

The interviewees generally could not think of any reason the outlet would fail to achieve UL certification. However, they mentioned that the USB-C outlets could not completely replace AC outlets unless they also contained an AC outlet. The National Electrical Code (NEC) requires an AC outlet every twelve feet. Since plug load cords are standardized to six feet, the load can connect from anywhere along the perimeter of the room. Similarly, kitchen counters have an AC outlet every six feet, and kitchen appliances have three-foot cords. These rules are intended to limit the use of extension cords, which can cause fire and trip hazards. AC outlets are fixed at 18 inches off the ground to make them compliant with the American Disabilities Act. Ideally, new USB outlets would have space for an AC outlet. While dedicated USB-C outlets could never replace AC outlets in accordance with the current NEC, they could certainly take a complementary role. The interviewees recommended placing new complementary USB outlets at desk level so as to facilitate charging devices on a desk or table.

B. Interesting Points

Currently, there is little standardization among DC plugs, cords, connectors, and outlets. Several of the interviewees are developing high-voltage (350 V DC) plug loads and outlets with the Anderson Safe-D-Grid or Fujitsu connectors. Some DC companies have opted to use Molex or other types of connectors for behind-the-wall connections until a standard is formed. In the EU, the developers aligned with Current/OS have opted primarily to use USB-C (and very rarely PoE) as their standard DC plug-load connector. The applications engineers also approve of the eventual standardization around USB-C. They mention plug-load manufacturer would save a lot of money using a standardized connector compatible with a generic and interchangeable USB-C power supply.

The electricians and electrical designers estimate the outlets to cost $20 based on the cost of USB outlets today. While this is ten times the cost of standard AC outlets, it is equivalent to the cost of GFCI or AFCI outlets. Although the USB-C outlet can interrupt faults, such is unnecessary in outlets; homes typically use a single AFCI breaker that covers all outlets on a circuit. The electrical designer mentioned that contractors always try to limit the number of USB outlets per site. In addition, USB outlets may initially suffer a lower life span due to the 400 V electrolytic capacitors, which are the weakest link in most power supply designs.

Power supply efficiency can be an issue for the internal temperature, as electrical losses are dissipated as heat. The R&D engineer noted that gallium nitride (GaN) technology could greatly improve the efficiency and power density of USB-C power supplies. His team designed a prototype USB-C power supply reference design with two USB-C outputs that could power share up to 240W at 96% efficiency. Both the R&D and applications engineers mentioned that wall adapters typically have thermal epoxy and potting to transfer the heat outside the enclosure. This may be necessary for the USB-C outlet's front face plate. The DC developer also noted that 48 V DC microgrids can have substantial voltage drop on the lines; USB-C outlets may need a buck-boost converter to output 48 V 240 W. Finally, the DC academic suggested being aware that the standby consumption of these outlets can add up.

The proposed USB-C outlet would greatly reduce electrical shock. The electrical safety officer explained that half of all electrical shocks in the US happen when fingers touch the contacts while disconnecting NEMA 5-15 plugs. Newer flat plugs are even worse in this regard. While the EU solved this problem over multiple iterations by insulating the base of their contacts, the US continues to use the dangerously uninsulated NEMA plug standard. USB plug loads would be a huge improvement in electrical safety. Not only is 48V below the touch-safe limit, but the USB plugs themselves are completely finger safe. The electrical safety officer said that the proposed outlet would not even need to interrupt faults, since 48V DC is non-fatal even in wet conditions.

There were several other interesting points related to building codes. First, the electrician insisted that an outlets must be UL listed for most electricians to even consider them. The electrical designer suggested working within the existing NEC guidelines as much as possible. Many electrical inspectors use checklists that are a decade outdated. The DC developer pointed out that NEC class 2 wiring has a 100 W limit. As such, the outlet could not be used as a 240 W behind-the-wall power supply with class 2 cables, though this would rarely ever be its intended use or application. Finally, while not relevant to the US, the DC academic believes that there would be no problem using the proposed outlet as a retrofit component in Germany, the Netherlands, France, Belgium, and likely most other EU markets. In general, each EU country has their own specific electrical rules, all of which are derived from the IEC standard 60664 for electrical installation in buildings. The IEC sets minimum safety compliance, but allows each country to specify how to wire a building. Some countries, such as Belgium, have many specific rules with the intent of simplifying procedures for installers. The DC academic expects localized rules to be more flexible and quick to update.

III. Electrical Efficiency Study

We studied and compared the loss and efficiency of the 140 W prototype DC USB-C outlet with several competitive AC USB-C wall adapters on the market today. The results are as follows.

A. DC Outlet Prototype

We derive the set of efficiency curves for the DC prototype, parametrically sweeping the input voltage (320 V to 420 V DC), output voltage (5 V to 28 V DC), and output current (0-5 A). At 28 V DC output, the outlet's efficiency is greater than 96% at full load as shown in Figure 1. Lower output voltages result in lower efficiency due to a higher voltage conversion ratio. Likewise, a lower input voltage results in higher efficiency. It is thus natural that a 320:28 V ratio would have the highest performance, and a 420:5 V ratio would have the lowest.

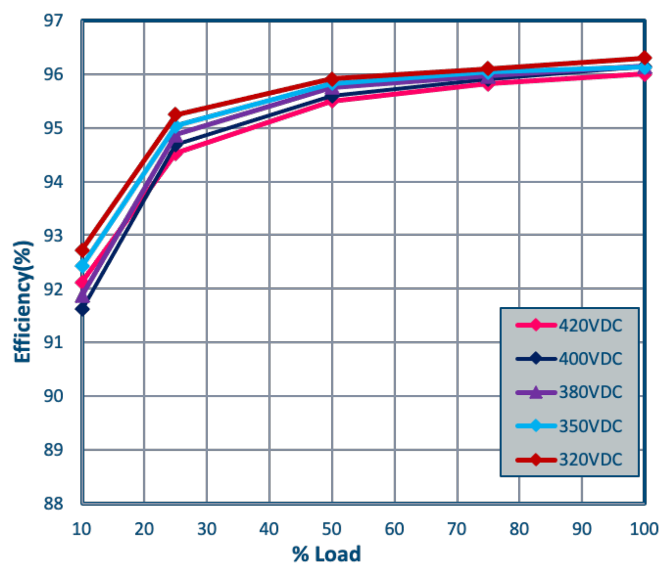

Fig. 1. Efficiency curves for the USB-C outlet prototype set to 28 V output.

Power converters always perform poorly at light load. For many converters, the efficiency at peak load is slightly lower than the peak efficiency, though this varies depending on what operating load the power converter is optimized for. In this case, we optimize the power converter for peak load so as to reduce heat.

B. AC Wall Adapters

We benchmark the proposed 140 W DC USB-C outlet against today's USB-C standard solution: 140 W AC wall adapters. We measure the efficiency of the following 140 W wall adapters:

- Anker 717 Charger

- Rocoren GaN Charger
- Kovol Sprint
- Dongguan Mizhi IF140-1
- Apple USB-C Power Adapter

The measurements are conducted using two ports of a Chroma 66204 power meter, one for 120 V AC input and one for DC USB output. The output current is set and selected using a Chroma 63802 electronic load. The USB output voltages are selected and programmed using a ChargerLab Power-Z KM002C USB tester. This programmer allows the user to program and send USB-PD messages to the power supply. In this way, the USB tester can set the wall adapter's output voltage, while the electronic load can set its output current.

We measure the efficiency at USB output voltages of 28 V, 20 V, 15 V, and 9 V, and output currents of 1-5 A. The measurement results at 28 V are shown in Figure 2.

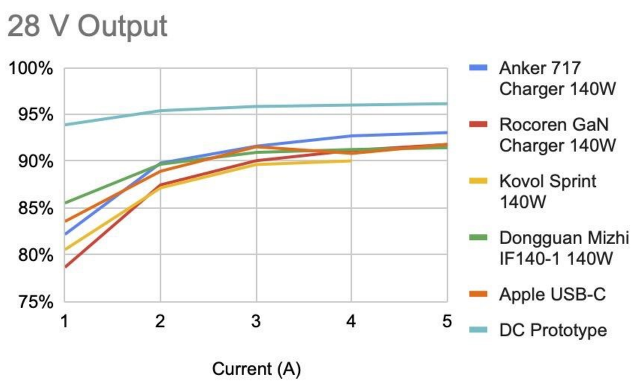

Fig. 2. Efficiency curve comparison at 28 V output of the DC USB-PD outlet prototype and a set of market-ready 140 W wall adapters.

C. Efficiency Comparison

Figure 2 shows how the efficiency of the AC wall adapters compare to the prototype DC outlet. In every case, the DC outlet has the highest efficiency over the full curve. The average difference in efficiency between the DC outlet and AC wall adapters weighted equally over all operating voltages and currents is 10.97%.

We use NREL's ResStock tool [31] to determine how the efficiency savings may impact the national residential energy consumption. Plug loads account for approximately 8.5% of the total energy consumption in homes today (includes electricity, natural gas, oil, and propane). We estimate that approximately 75% of plug load energy consumption could technically come from a 240 W USB-C wall adapter or outlet. Thus the outlet may impact 6.4% of the 3363 TWh of annual residential consumption (in 2018). Given the 10.97% difference in efficiency, we expect the outlet could save 0.7% of residential energy, or 23.6 TWh annually.

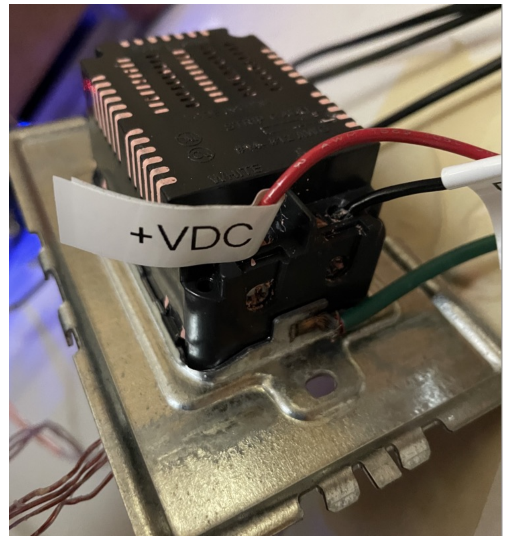

Fig. 3. The 140 W USB-C outlet prototype and Legrand Adorne faceplate.

IV. Thermal Experiment

The objective of the thermal experiment is to study the internal temperature and thermal dissipation caused by a 140 W USB-C outlet in a realistic exterior wall section. Success metrics relate to the internal temperatures at steady state and how they compare with the temperature ratings of the outlet's electronic components and the surrounding insulation. The results will indicate whether the heat due to losses in the outlet can be sufficiently transferred out of the wall. They also have general implications on the acceptable losses of wall outlets and other in-wall power electronics.

A. Experimental Setup

The study includes three experiments, each repeated with different types of outlets:

- The 140 W USB-C prototype
- A mock-up outlet, heatsinked to the faceplate
- A mock-up, heatsinked and vented

The first experiment uses the actual 140 W USB-C outlet prototype in Figures 3 and 4, and monitors the temperature of four of its internal components with thermocouples. The internal circuit boards are thermally coupled to the plastic housing via a potting compound. The housing is fastened to a Legrand Adorne metal frame and plastic faceplate, but its thermal coupling to the faceplate is weak.

The other two experiments test whether thermal dissipation can be improved if (a) the power electronics are heat-sinked directly to a metal face plate, and (b) the junction box is vented into the conditioned space. These experiments use a representative outlet, shown in Figures 5 and 6, simulated by a power resistor (250 ohms) whose dissipation is equal to the losses of the USB-C outlet. The power resistor is thermally bonded to a metal cube, which in turn is bonded to the face plate. In one experiment, the face plate is flush against the wall. In the other, it is separated from the wall by a 1 cm gap.

Fig. 4. The outlet mounted in a wall section with a PowerZ USB tester plugged into it.

Fig. 6. The mock-up mounted in the wall section, with a 1 cm gap between the faceplate and wall.

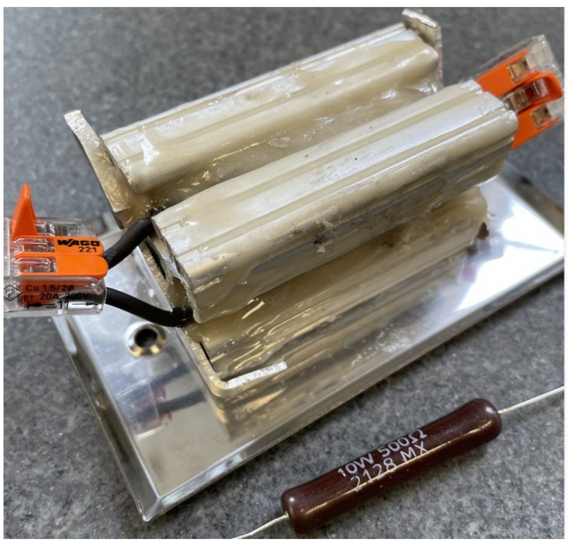

Fig. 5. Representative outlet mock-up, consisting of a metal block with power resistors thermally bonded to a metal face plate.

The outlets and mock-ups are powered by a Chroma 62012P-600-8 power supply. The USB-C prototype is operated with an input of 350 V. The mock-up outlets are operated up to 40 V, depending on the desired power dissipation. The USB-C prototype's output is controlled by a ChargerLAB Power-Z KM003C tester, which communicates with the outlet and requests a 28 V output. The tester's output is connected through a break-out board to a BK Precision 8502B electronic load set to draw up to 5 A (140 W) in constant current mode.

In this experiment, the outlet is powered at a certain level for four hours while the test chambers reach steady state. The output levels are 1.25 A (35 W), 2.5 A (70 W), and 3.75 A (105 W), each of which generates losses of 1.83 W, 3.05 W, and 4.57 W, respectively. For testing the mock-up outlets, the input current is controlled so as to mimic these loss values in the power resistors within the mock-up.

The thermal experiment uses a representative code compliant external wall section, shown in Figure 7. Its wooden 2x6 frame is packaged with six inches of fiberglass batt insulation (R-19). The interior (cold) side is covered in 0.5" of sheetrock. The exterior (hot) side has a plywood shear tie, 1.5" poly-iso foam board (R-9). In a realistic environment, it would then be clad in exterior siding. For the experiment, the foam board is left unclad; such should have minimal impact on thermal conductance.

The outlet resides within a blue PVC plastic junction box, surrounded by fiberglass insulation, which represents the worst case for thermal transfer and heat sinking. DS18B20 temperature probes monitor the temperature at various points throughout the wall section, including the insulation, outlet, junction box, and faceplate.

The experiment uses the thermal chamber in Figures 8 and 9, which is specifically designed to test thermal transfer through walls and windows. The setup consists of two insulated and thermally regulated half-chambers that are opened toward each other. The chambers use a clamping mechanism to hold the wall section (sandwiching the wall section between the chambers) and seal its edges. The chambers corresponding to the wall's conditioned interior and unconditioned exterior are held at 25°C and 40°C, respectively, for the duration of the experiment.

The DS18B20 temperature probes connect to an Atmega-based data acquisition system. A Raspberry Pi microcomputer logs the data at 10-second intervals. The resulting temperature data forms a set of asymptotic negative-exponential decay curves. For many of the test points, the experiment would require more than four hours for the temperature to reach

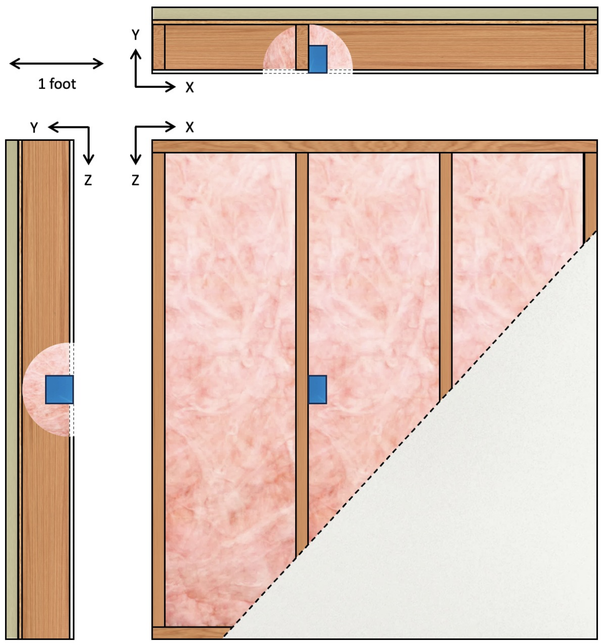

Fig. 7. Representative wall section with blue junction box. Layers from interior to exterior: 0.5” sheetrock, 6” fiberglass insulation, 0.5” plywood, 1.5” poly-iso foam board.

Fig. 8. The threshold wall section between the chamber’s cold side (left) and hot side (right). The two sides are secured and tightened with a clamp.

steady state. Thus much of the data is analyzed with a Python-based exponential regression fitting function, which can estimate the steady-state asymptote.

B. Experimental Results

The experimental data is organized as a set of steady-state temperatures. We extensively document the temperature distribution throughout the wall section. As an example, Figure 10 shows the steady-state temperatures of the USB-C prototype experiment, operating at 28 V 2.5 A output, which produces 3.05 W of loss that must be dissipated into the wall. Figure 11 shows the thermal distribution for the open face-plate mock up under the same conditions.

Fig. 9. Inside the thermal chamber’s hot side.

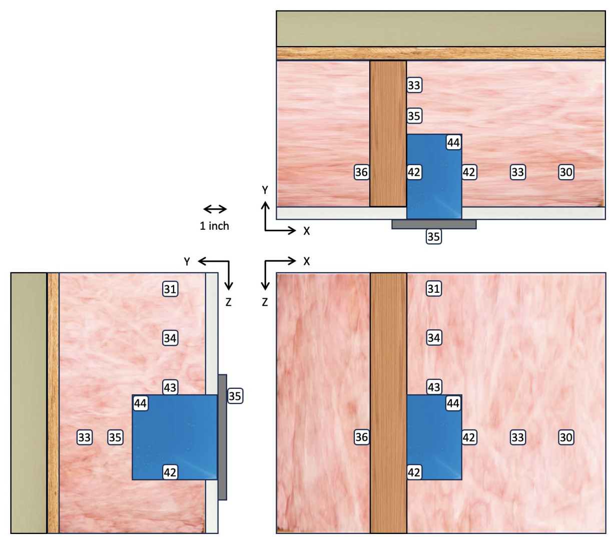

Fig. 10. Steady-state temperatures of the USB-C prototype experiment with 3.05 W loss.

The internal components’ temperatures are also measured for each experiment. For the USB-C outlet prototype, the transformer, InnoSwitch4 chip, the SRFET chip, and the ClampZ chip are all measured with thermocouples. For the mock-ups, the power resistor temperature is measured with a temperature probe. The steady-state temperature results (°C) of each are summarized in Table I.

In every experiment and set point, the internal wall temperature never exceeds levels that surpass wall component maximum temperature ratings. However, the internal components of the USB-C outlet can reach critical levels even with 4.57 W of loss (105 W output). At this setpoint, the outlet’s internal

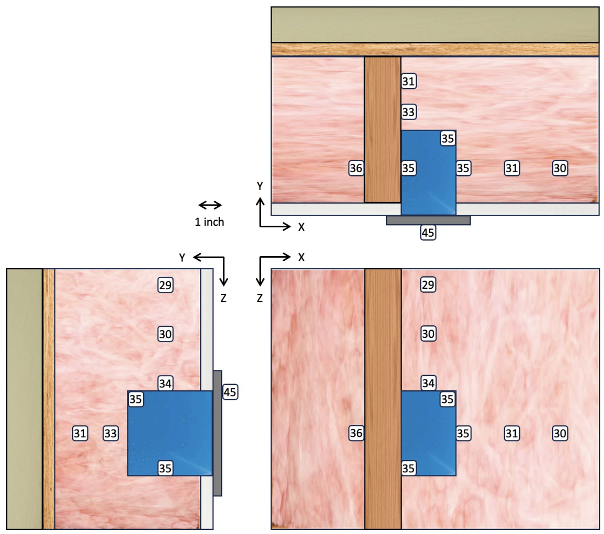

Fig. 11. Steady-state temperatures of the open-faceplate mockup experiment with 3.05 W loss.

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TABLE I
COMPONENT STEADY STATE TEMPERATURES (°C) SUBJECT TO ELECTRICAL LOSSES IN THE OUTLET

Experiment	Component	1.83 W Loss	3.05 W Loss	4.57 W Loss
USB-C	Transformer	49.4	77.2	
USB-C	InnoSwitch4	49.8	80.3	
USB-C	SRFET	49.5	78.9	
USB-C	ClampZ	48.5	74.5	
Closed Faceplate	Power Resistor	42.1	51.9	62.6
Open Faceplate	Power Resistor	39.9	48.0	56.6

temperature exceeds the thermal shutoff limit.

The mock-ups demonstrate an improvement in internal temperature management compared to the prototype USB-C outlet. The prototype uses a potting compound to thermally bridge the power components to the outlet's plastic housing. The closed faceplate mockup shows that at 3.05 W loss, directly heat sinking the electronics to a metal faceplate can reduce the internal temperature by 22.6°C to 28.4°C. Opening the faceplate with a 1 cm gap can further reduce the internal temperature by 3.9°C.

In practice, it is very difficult to directly heatsink so many components to the face plate, but the mockup still demonstrates the idealized scenario. However, a faceplate temperature of 58°C is too hot to touch. Opening the faceplate appears to reduce both the internal and faceplate temperatures by 4°C, which also reveals the limits of natural convection. The open faceplate setup would likely improve significantly with a small amount of forced convection behind the faceplate.

C. Thermal Discussion

The data suggests that high-power outlets in exterior wall sections can have significant thermal challenges. Even 3.05 W of loss can cause the internal components to reach 80°C. Such thermal constraints are no problem for mobile electronics. Laptops with a 70 Wh battery can fully charge at 140 W within half an hour, which is well below the time it takes for internal components to reach critical temperature. However with constant usage, the outlet can easily reach its thermal shutoff limit. Such results may suggest limits on the prospect of plug loads that require 240 W constant power for an extended duration.

Outlets with power electronics can be improved by directly heat-sinking the power components to a metal face plate. In addition, a vented outlet with forced convection may also be necessary to allow outlets to output continuously high power. Nonetheless, it is also possible that users may tolerate periodic thermal shutoff in high-power outlets, particularly for device charging as explained above.

In addition to the data, a FLIR imager can validate the heat transfer as shown in 12. These images show that the temperature is significantly greater in the upper half of the outlet. They imply the presence of convection currents that transfer heat from the outlet's housing to the upper edge of the junction box. Such may support the need for venting.

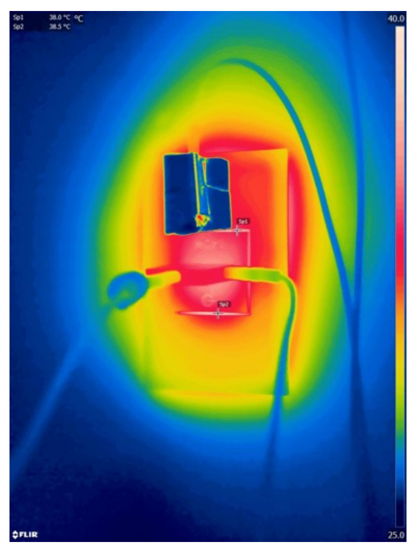

Fig. 12. Infrared image of the heat distribution in outlet.

V. CONCLUSION

USB-C now allows devices to draw up to 240 W, and many have suggested USB-C as a suitable candidate for plug loads, especially in DC buildings. This work documents a study that evaluates the technical and market feasibility of such a high-power USB-C outlet. The customer discovery interviews shows general enthusiasm across a broad set of experts. The efficiency analysis also shows encouraging results; the 140 W DC outlet prototype is nearly 11% more efficient than 140 W AC/DC wall adapters. However, the thermal experiments yielded more concerning results: the 140 W prototype can only operate at up to half power continuously without triggering a thermal shutoff. Nonetheless, subsequent mock-up experiments show several ways to improve outlet thermal characteristics.

While this paper addresses several initial feasibility questions, there is certainly room for future research. First, we recommend the use of a finite-element simulation engine to fully model the thermal effects of the outlet within the wall section. Such a model would certainly be useful in the future thermal design of USB-C outlets or any other power electronics embedded in a wall. Second, we recommend researchers investigate the opportunities for outlets to communicate with a home energy management system. Such a feature would be useful as energy reporting and demand response become increasingly important to energy management in buildings. Finally, there may be an opportunity for wall outlets to contain a small battery, granting some resilience limited to low-power loads.

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