Thermal Evaluation

of CCS and NACS Reference Devices and Adapters

CHARGEX consortium

AUGUST 2025

Argonne National Laboratory | INL Idaho National Laboratory | NREL

Disclaimer

Authors

Isaac Tolbert, Saroj Shinde, Marco Gaxiola, Douglas DeVoto, Joshua Major, Andrew Meintz, and Kristi Moriarty (NREL)

Contributors

Keith Beckstead (EVgo), Peter Nuechter (Amphenol), and Kenneth Tennyson (Electrify America)

Acknowledgments

The National Charging Experience Consortium (ChargeX Consortium) is a collaborative effort between Argonne National Laboratory, Idaho National Laboratory, National Renewable Energy Laboratory, electric vehicle charging industry experts, consumer advocates, and other stakeholders. This report was produced by the ChargeX Consortium's Hardware Task Force.

List of Acronyms

CCS	Combined Charging System
DC	direct current
DUT	device under test
EV	electric vehicle
EVSE	electric vehicle supply equipment
IEC	International Electrotechnical Commission
NACS	North American Charging System
NREL	National Renewable Energy Laboratory
OEM	original equipment manufacturer
RTD	resistance temperature detector
SAE	SAE International
UL	UL Solutions

Executive Summary

This work examines the development and performance of proposed SAE J1772 Combined Charging System (CCS) and SAE J3400 North American Charging System (NACS) reference electric vehicle inlet designs, as well as the performance of several electric vehicle charging adapters between NACS connectors and CCS inlets and between CCS connectors and NACS inlets.

First, we evaluated several different CCS and NACS charging connectors and inlets, supplied from multiple manufacturers, at rated operating current at 25°C ambient temperature until they reached steady-state temperature. The CCS and NACS charging connectors with the worst thermal performance in these evaluations was selected to be the mating connector with the proposed CCS or NACS reference inlet. Simultaneously, we simulated and fabricated busbar-based reference inlet designs for CCS and NACS inlets at 500, 600, 700, and 800 A. We selected the 500-A CCS reference inlet and 600-A NACS reference inlet for evaluation in a thermal chamber at 40°C ambient temperature with the previously selected "worst" CCS and NACS connectors. The experimental results provided a good match with the simulated results. Additionally, we demonstrated that the reference devices' built-in heater cartridges, integrated into the reference device design, were able to successfully simulate an overtemperature event and execute a thermal sensor evaluation defined by the International Electrotechnical Commission (IEC).

After evaluating the reference inlets, we evaluated two NACS-CCS and three CCS-NACS adapters in regard to their thermal performance and compliance to SAE J3400 and UL 2252 standards. We found that only two adapters properly signaled the J3400 thermal warning state, with two others partially compliant to the J3400 thermal warning state. No adapters fully complied with the J3400 thermal shutdown state, though two adapters were partially compliant, activating an improper state at the correct temperature limit, while a third activated the proper J3400 thermal shutdown state (though only after the temperature had exceeded the J3400-defined limit). One adapter never activated a thermal warning or shutdown signal at all. Additionally, no adapters were fully compliant with the UL 2252 temperature limits.

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1 Introduction

Electric vehicles (EVs) and electric vehicle supply equipment (EVSE) are being rapidly deployed across North America, using both the SAE J1772 Combined Charging System (CCS) and the SAE J3400 North American Charging System (NACS) charging standards. Additionally, NACS-to-CCS and CCS-to-NACS adapters have become more prevalent in the marketplace as automakers and EVSE suppliers have begun transitioning their standard inlet and connector offerings from CCS to NACS.

It is important for manufacturers to understand the thermal performance of their connectors, inlets, and adapters. Various standards from SAE International (SAE), the International Electrotechnical Commission (IEC), and UL Solutions (UL) (i.e., SAE 1772, SAE J3400, IEC 62196, UL 2251, and UL 2252) list temperature limits that connectors, inlets, and adapters must meet. One major problem is that there are very limited standardized reference devices against which to measure connector performance. None exist for SAE J3400 connectors, and while IEC 62196-1 provides a specification for CCS reference devices up to 500 A, the devices can be difficult to acquire or fabricate internally (and at the time of this work, there is no finalized IEC 62196-1 design for CCS reference devices higher than 500 A). As a result, connector manufacturers must acquire inlets (oftentimes from competitors, which can make acquisition difficult) to test their connectors against. This means that determining whether a connector meets the temperature criteria can be difficult, because a connector that passes a thermal evaluation in a lab setting with a certain inlet may not pass with a different inlet with, for example, looser pin/socket tolerances that cause additional heating. The choice of inlet can have an effect on the thermal performance of the connector, making comparisons difficult if the connectors are not evaluated with the same mating inlet.

Finally, as automakers and EVSE suppliers transition from SAE J1772 CCS to SAE J3400 NACS, a number of CCS-to-NACS and NACS-to-CCS adapters (which allow charging connectors of one standard to interface with charging inlets of another) are entering the market. These devices are being produced by both well-known automakers and original equipment manufacturers (OEMs) and lesser-known third-party suppliers across a wide range of price points and construction qualities. Though SAE J3400/1 and UL 2252 lay out standards for adapter construction, performance, and overtemperature response, there is no guarantee that any particular adapter will follow these standards and react to overtemperature events appropriately.

To address these issues, this project undertook thermal evaluations of CCS and NACS connectors, inlets, and adapters. We evaluated a wide range of connectors and inlets against each other in “round-robin” format to understand their performance. Additionally, the project developed CCS and NACS “reference devices”—standardized reference inlets that can be easily fabricated by any equipment supplier and used to validate the performance of charging connectors at a variety of current levels in the 500–800-A range. We did not consider current levels less than 500 A in this evaluation, as reference devices have already been defined for these lower current levels. We then used these reference devices to evaluate the thermal performance of multiple charging adapters at both steady-state current and overtemperature conditions.

2 Thermal Baseline Evaluations

2.1 Experimental Setup

The evaluation bench was set up to record instrumentation of thermal performance for CCS and NACS connector and inlet systems at up to 600 A during the evaluations. Figure 1 shows a rendering of the thermal interoperability evaluation bench with major features indicated, including plexiglass guards that were set up to prevent an operator from inadvertently contacting energized or hot device under test (DUT) components.

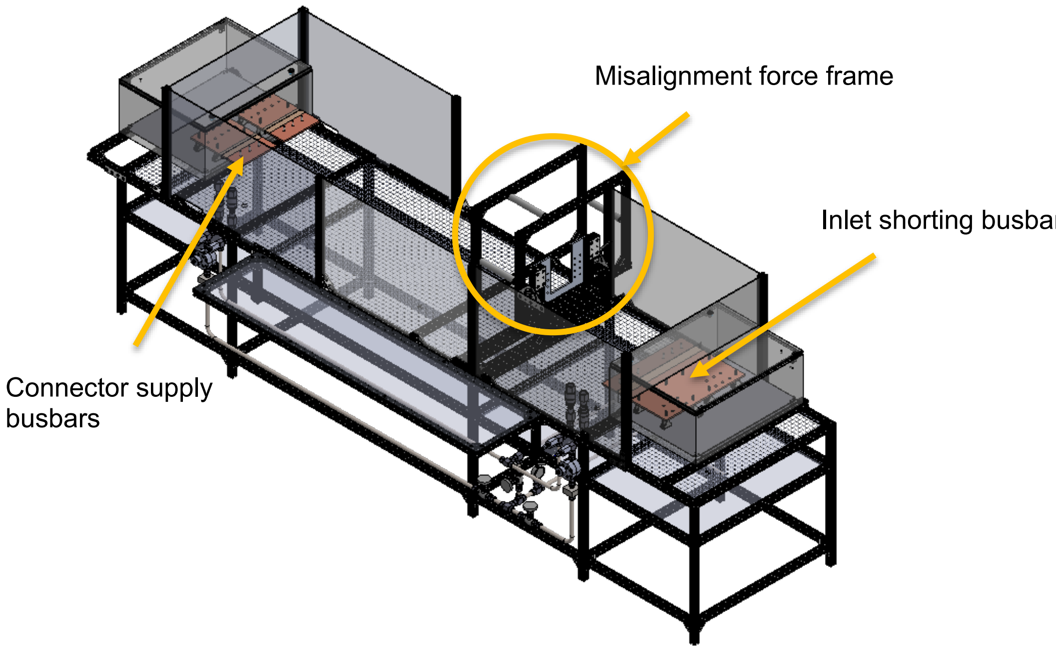


Figure 1. Thermal evaluation bench

We instrumented each connector and inlet with a suite of temperature sensors to monitor thermal performance. Additionally, we monitored the manufacturer-installed resistance temperature detector (RTD) sensors via a set of transducers and converted them into temperature values. These sensors were most often Pt1000-type RTDs, though we found some other sensor types in the DUTs. For these sensors, we recorded resistance values via the RTD transducers and converted these values to temperature values during post-processing using the manufacturer's RTD sensor datasheet (if available) or a generic resistance-to-temperature table for the appropriate temperature sensor type (if no datasheet was available). If the connector or inlet's internals were easily accessible (e.g., through screws or snap fittings), we placed additional thermocouples on the interior of the device to measure pin crimp temperatures (where the direct-current [DC] pin meets the conductor cable). To avoid risk of damaging the devices or altering thermal performance, we did not place internal thermocouples on devices that had been permanently sealed (e.g., via sonic welding or epoxy). We placed thermocouples on all devices to monitor exterior temperatures on cable surfaces, handles, and housings. Additionally, we monitored voltage and current through the DUTs. Table 1 summarizes equipment used to capture data during the thermal interoperability evaluations.

Table 1. Equipment Used for Thermal Evaluation Data Capture

Type	Description
Oscilloscope	Yokogawa DL850
Analog voltage input module (×4)	Yokogawa 720250
Analog voltage input module (×2)	Yokogawa 720268
Temperature/voltage input module (×2)	Yokogawa 720221
16-channel scanner box (×2)	Yokogawa 701953
Thermocouples	T-Type, special limits of error, no calibration
RTDs	Manufacturer-dependent
RTD measuring transducer (×6)	Phoenix Contact MACX MCR-T-UI-UP-2811394
Current transducer	Hioki CT9693
Force transducer	Interface SM-100

We acquired multiple connectors and inlets to understand the performance of production CCS and NACS connectors and inlets in the range of 500+ A. Additionally, we acquired multiple 200–400-A connectors to understand the performance of devices in lower-current categories to help understand how contact resistances change throughout the full range of the connector standard. Table 2 lists the connectors and inlets used in the baseline thermal evaluation.

Table 2. Thermal Baseline Evaluation Devices

Standard	Current Rating Class	Connector Quantity	Inlet Quantity
CCS	200 A	3	7
CCS	310 A	2	1
CCS	500 A	2	2
NACS	350 A	1	2
NACS	600 A	1	1

For actively cooled devices (the 500-A CCS connectors and 600-A NACS connector), we evaluated the devices with the chiller provided by the manufacturer, with the pump/fan speeds set according to manufacturer directions (if manually controlled) or set automatically (if the chiller featured an integrated controller).

2.2 Baseline Evaluation Procedure

We paired connectors and inlets of similar current ratings (as determined by the listed current rating in the case of components acquired directly from connector/inlet manufacturers, or by estimate in the case of automaker-acquired components without officially listed ratings) and evaluated them round-robin style. We placed the connector and inlet on the bench and mated them, with the inlet's locking mechanism activated. We curled any excess cable length on either the connector or inlet in such a way as to minimize overlaps and allow airflow. During each evaluation, we successively stepped up the current in 25-A increments, pausing after each increment to confirm the accuracy of instrumentation until reaching 150 A, at which point we measured the DUT resistance. We then gradually increased the current to the rated current. We held the current at this level until the DUT was determined to be at steady-state temperature, per the definition given in IEC 62196-1, Section 24.1: less than 2 K of temperature rise for three successive readings, spaced 10 minutes apart.

Once steady-state temperature was reached, we performed a misalignment evaluation as defined by IEC 62196-1, Section 36. We applied a 100-N load to the connector at the connector handle for approximately 3 minutes in a sequence of four directions ($-x$, $-y$, $+x$, $+y$), repeating this set three times. We monitored the DUTs for temperature variations greater than ±5 K. We marked DUT combinations that had no temperature variations greater than ±5 K as "compliant" and those with greater than ±5 K variance from steady state as "noncompliant." Figure 2 shows a view of the misalignment setup and force application directions, viewed facing into the charge port of the inlet from the connector end of the bench.

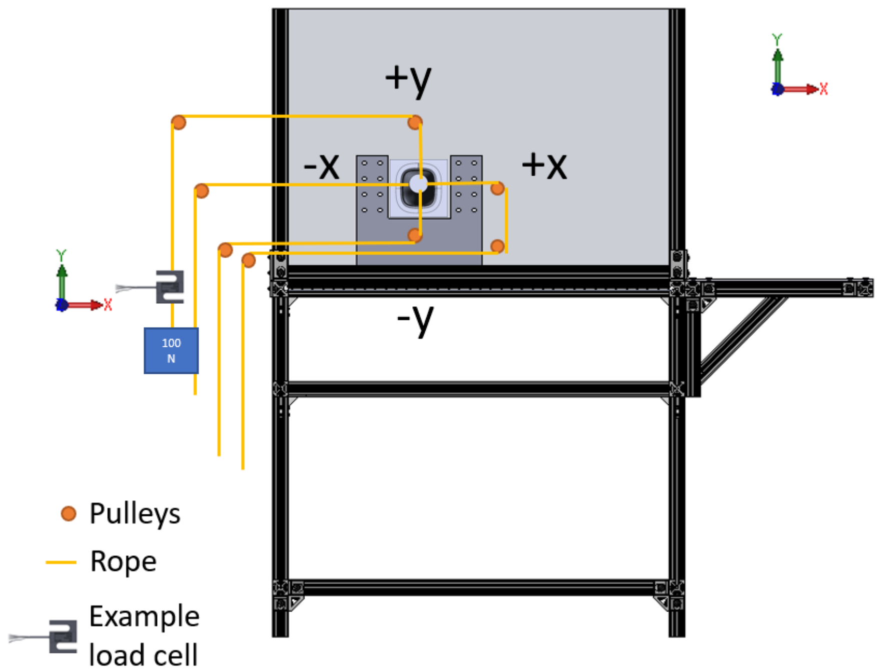


Figure 2. Layout of misalignment evaluation setup.

Shown with 100-N load, view facing toward the inlet from the connector end of the bench.

2.3 Results

This setup generated three categories of results from the baseline evaluations: DUT resistance at 150 A, steady-state temperature rise, and misalignment temperature rise.

During each evaluation, as current was ramped up to the maximum steady-state value for a particular DUT, we paused current at 150 A to obtain a resistance reading. Table 3, Table 4, Table 5, and Table 6 provide 150-A resistance values for each DUT. We measured resistance across the DC+ and DC− legs of the connector to obtain a "round-trip" resistance through the entire connector and inlet DUT assembly. Both connector and inlet DUTs varied in cable length, with most connector DUTs having a cable length between 5 and 6 meters, and most inlet DUTs having an attached cable length between 0.5 and 1 m. The varying lengths of connector and inlet cables would have an effect on the recorded resistance of each DUT.

Table 3. 200-A-Class CCS DUT Resistance at 150 A

DUT	Resistance (mΩ)
Connector A/Inlet D	5.26
Connector A/Inlet I	5.45
Connector A/Inlet J	5.80
Connector B/Inlet D	5.43
Connector B/Inlet E	5.38
Connector B/Inlet F	5.21
Connector B/Inlet G	5.38
Connector B/Inlet H	5.61
Connector B/Inlet J	5.92
Connector C/Inlet D	7.41
Connector C/Inlet H	7.63

Table 4. 310-A-Class CCS DUT Resistance at 150 A

DUT	Resistance (mΩ)
Connector K/Inlet M	3.17
Connector L/Inlet M	2.59

Table 5. 500-A-Class CCS DUT Resistance at 150 A

DUT	Resistance (mΩ)
Connector N/Inlet R	5.08
Connector N/Inlet S	5.19
Connector P/Inlet S	9.20

Table 6. NACS DUT Resistance at 150 A

Note: Due to the limited number of NACS devices available at the time of evaluation, the NACS evaluations featured more evaluations between connectors and inlets of differing current ratings.

DUT	Resistance (mΩ)
Connector T (350 A)/Inlet W(350 A)	3.9
Connector T (350 A)/Inlet V (350 A)	3.4
Connector Z (600 A)/Inlet V (350 A)	8.75
Connector Z (600 A)/Inlet W (350 A)	8.26
Connector Z (600 A)/Inlet X (350 A, aged)	8.99
Connector Z (600 A)/Inlet Y (600 A)	8.05

After collecting 150-A DUT resistances, we ramped up current to the devices' rated current for steady-state temperature analysis. In the steady-state analysis, we evaluated devices at their rated current until temperatures reached steady-state, and then evaluated the contact temperatures. To reduce the effect of any potential measurement noise, we averaged 1 minute of steady-state temperature data to determine the final steady-state value. We performed all these evaluations at an ambient temperature of approximately 25°C.

Due to the large number of samples, we did not perform a full round-robin evaluation matrix, with all connectors being evaluated against all inlets. Instead, evaluations focused on finding the "worst-performing" connector/inlet pair. We evaluated all connectors against a common inlet to find the worst connector, and then all inlets against a common connector to find the worst inlet, at which point we evaluated this worst connector and inlet against each other. We also performed spot-checks of other connector/inlet pairings to gather additional data and confirm that we chose the correct worst connector/inlet pairings, as time/resources allowed.

For many of the devices in these evaluations, the manufacturer did not provide an official steady-state current rating. We purchased many devices from automaker OEMs, who generally did not provide official steady-state current ratings. Additionally, some devices were pre-production prototypes provided by Tier 1 manufacturers, and an official rating had not yet been determined at the time of evaluation. If an official rating could not be determined, we determined the rating for the purposes of this evaluation by examining the vehicle of origin and known charging behavior (for automaker OEM inlets), or by estimating based on cable/conductor size. In cases where one device's current rating was lower than that of the device it was mated with, we used the lower of the two currents as the maximum steady-state current. This was primarily an issue on the NACS evaluations, where a lack of available devices at the time of this evaluation meant that few 600-A devices could be evaluated. As a result, we performed several evaluations between a 600-A NACS connector and lower-rated inlets.

Table 7, Table 8, Table 9, and Table 10 show the results of the steady-state evaluations. We evaluated the DUTs according to both IEC 62196-1 and SAE J3400 temperature criteria. IEC 62196-1 lists a temperature limit of 90°C at 40°C (effectively limiting the DUT temperature rise to 50 K over ambient), while SAE J3400 lists a temperature limit of 100°C, regardless of the ambient temperature. At the same 40°C ambient temperature, these temperature limits effectively translate to a 50-K temperature rise over ambient for the IEC 62196-1 limit and a 60-K temperature rise over ambient for the SAE J3400 limit. Due to experimental setup limitations, we performed these evaluations at 25°C ambient, recording the temperature rise over ambient and comparing them against the effective 50-K IEC 62196-1 and 60-K SAE J3400 limits.

Table 7. 200-A-Class CCS Steady-State Evaluation Outcomes (25°C)

DUT	Max. Contact Temperature (°C)	Max. Contact Temperature Rise (K)	IEC Outcome (50-K Rise Over Ambient)	SAE Outcome (60-K Rise Over Ambient)
Connector A/Inlet D	93.3	65.9	Noncompliant	Noncompliant
Connector A/Inlet I	88.1	63.8	Noncompliant	Noncompliant
Connector A/Inlet J	83.2	55.1	Noncompliant	Compliant
Connector B/Inlet D	72.6	48.4	Compliant	Compliant
Connector B/Inlet E	62.8	37.5	Compliant	Compliant
Connector B/Inlet F	55.4	31.1	Compliant	Compliant
Connector B/Inlet G	57.1	31.8	Compliant	Compliant
Connector B/Inlet H	62.6	37.7	Compliant	Compliant
Connector B/Inlet J	59.0	32.8	Compliant	Compliant
Connector C/Inlet D	82.6	57.7	Noncompliant	Compliant
Connector C/Inlet H	78.3	52.2	Noncompliant	Compliant

Table 8. 310-A-Class CCS Steady-State Evaluation Outcomes (25°C)

DUT	Max. Contact Temperature (°C)	Max. Contact Temperature Rise (K)	IEC Outcome (50-K Rise Over Ambient)	SAE Outcome (60-K Rise Over Ambient)
Connector K/Inlet M	94.6	67.6	Noncompliant	Noncompliant
Connector L/Inlet M	90.8	66.1	Noncompliant	Noncompliant

It should be noted in Table 9 and Table 10, which involve actively-cooled devices, that due to the effects of active cooling, the IEC and SAE outcomes may not be directly translatable between the 25°C ambient case (as evaluated here) and the 40°C ambient case (as described in the IEC/SAE standards). The "compliant/noncompliant" indications are given to improve clarity when comparing between devices, but may not directly represent the devices' compliance/noncompliance at a true 40°C ambient temperature evaluation.

Table 9. 500-A-Class CCS Steady-State Evaluation Outcomes (25°C)

DUT	Max. Contact Temperature (°C)	Max. Contact Temperature Rise (K)	IEC Outcome (50-K Rise Over Ambient)	SAE Outcome (60-K Rise Over Ambient)
Connector N/Inlet R	64.7	39.8	Compliant	Compliant
Connector N/Inlet S	78.4	55.9	Noncompliant	Compliant
Connector P/Inlet S	67.0	42.5	Compliant	Compliant

Table 10. NACS Steady-State Evaluation Outcomes (25°C).

Note: Due to the limited number of NACS devices available at the time of evaluation, the NACS evaluations featured more evaluations between connectors and inlets of differing current ratings.

DUT	Steady-State Current (A)	Max. Contact Temp. (°C)	Max. Contact Temp. Rise (K)	IEC Outcome (50-K Rise Over Ambient)	SAE Outcome (60-K Rise Over Ambient)
Connector T (350 A)/Inlet W (350 A)	300	86.8	62.4	Noncompliant	Noncompliant
Connector T (350 A)/Inlet V (300 A)	300	101.1	78.4	Noncompliant	Noncompliant
Connector Z (600 A)/Inlet V (300 A)	300	61.7	36.5	Compliant	Compliant
Connector Z (600 A)/Inlet W (350 A)	350	53.2	28.6	Compliant	Compliant
Connector Z (600 A)/Inlet X (350 A, aged)	350	71.4	46.4	Compliant	Compliant
Connector Z (600 A)/Inlet Y (600 A)	600	72.5	46.3	Compliant	Compliant

After determining the steady-state temperatures, we subjected the DUTs to a misalignment evaluation with a 100-N weight applied to the connector handle for 3 minutes in a sequence of four directions. We determined DUTs to be compliant with the misalignment evaluation if the temperature rise during misalignment did not exceed 5 K of difference from the recorded steady-state value. The maximum resistance rise and maximum contact temperature rise of each DUT combination are listed in Table 11, Table 12, Table 13. Table 14.

Table 11. 200-A-Class CCS Misalignment Evaluation Outcomes (25°C)

DUT	Outcome	Max. Resistance Rise (mΩ)	Max. Contact Temperature Rise (K)
Connector B/Inlet D	Compliant	0.159	1.1
Connector C/Inlet D	Compliant	0.175	1.5
Connector B/Inlet J	Compliant	0.212	1.7
Connector A/Inlet J	Compliant	0.186	2.5
Connector A/Inlet D	Compliant	0.167	2.1
Connector B/Inlet E	Compliant	0.209	1.4
Connector B/Inlet H	Compliant	0.151	1.3
Connector B/Inlet G	Compliant	0.153	2.8
Connector B/Inlet F	Compliant	0.169	1.7
Connector C/Inlet H	Compliant	0.251	3.1
Connector A/Inlet I	Compliant	0.176	0.9

Table 12. 310-A-Class CCS Misalignment Evaluation Outcomes (25°C)

DUT	Outcome	Max. Resistance Rise (mΩ)	Max. Contact Temp. Rise (°C)
Connector K/Inlet M	Compliant	0.103	2.0
Connector L/Inlet M	Compliant	0.097	1.4

Table 13. 500-A-Class CCS Misalignment Evaluation Outcomes (25°C)

DUT	Outcome	Max. Resistance Rise (mΩ)	Max. Contact Temp. Rise (°C)
Connector N/Inlet R	Compliant	0.109	2.7
Connector N/Inlet S	Compliant	0.1	1.7
Connector P/Inlet S	Compliant	0.089	1.9

Table 14. NACS Misalignment Evaluation Outcomes (25°C).

Note: Due to the limited number of NACS devices available at the time of evaluation, the NACS evaluations featured more evaluations between connectors and inlets of differing current ratings.

DUT	Outcome	Max. Resistance Rise (mΩ)	Max. Contact Temperature Rise (°C)
Connector T (350 A)/Inlet W(350 A)	Compliant	0.143	3.1
Connector T (350 A)/Inlet V (350 A)	Compliant	0.133	2.2
Connector Z (600 A)/Inlet V (350 A)	Compliant	0.132	1.1
Connector Z (600 A)/Inlet W (350 A)	Compliant	0.161	1.3
Connector Z (600 A)/Inlet X (350 A, aged)	Compliant	0.123	1.4
Connector Z (600 A)/Inlet Y (600 A)	Compliant	0.106	3.4

After performing the baseline evaluations, we determined to use **Connector N** (500-A CCS) and **Connector Z** (600-A NACS) for the reference device and adapter evaluations. Connector N had the highest steady-state temperature and experienced the highest contact temperature rise during misalignment of the two evaluated CCS connectors. For the NACS connectors, Connector Z was the only NACS connector rated for a current of 500 A or greater that the team was able to acquire at the time of evaluation.

3 Reference Device

The compatibility between the adapter and vehicle inlet is critical for proper electrical, thermal, and mechanical functionality during a charging session. The creation of J3400 NACS and J1772 CCS reference devices (vehicle inlets) allows for evaluation of proposed adapters under a controlled laboratory environment with the ability to complete a large design of experiments faster than with a donor vehicle. The reference devices also provide more control in managing heat losses at different current levels.

3.1 Design

The J3400 and CCS reference device designs followed design principles originally used to create reference devices for the Megawatt Charging System (MCS) inlet under IEC 63372. U-shaped busbars were sized appropriately to passively cool the reference inlet through natural air convection. Busbars were designed for current levels of 500, 600, 700, and 800 A. The height of the busbars was varied to control the overall surface area and match the thermal loads at each current level. Mechanical features were incorporated into the inlet frame for convenience in bolting to the existing inlet test frame at the National Renewable Energy Laboratory (NREL). Thermocouples were placed in three key locations: within the DC pins, behind the pins, and on the busbar. Figure 3 shows the exact thermocouple locations for the J3400 reference device.

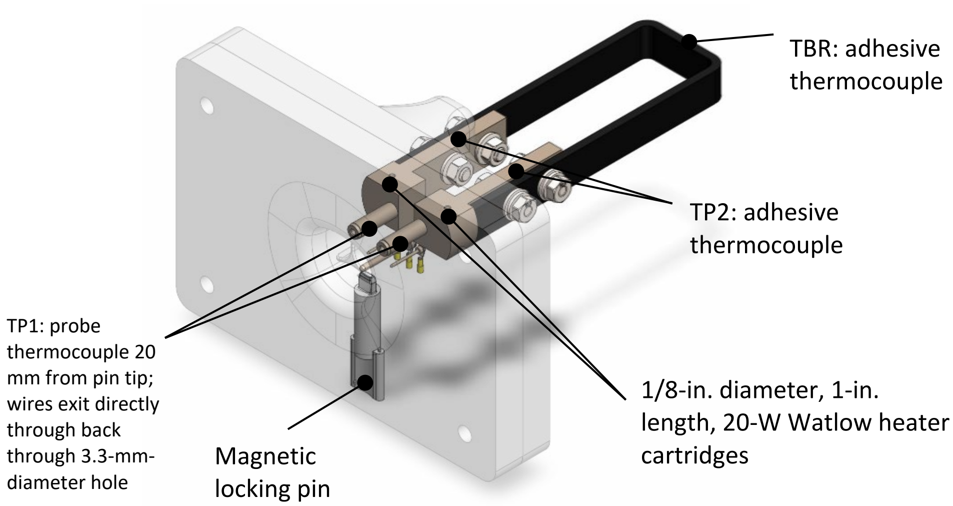


Figure 3. Thermocouple locations for the J3400 reference device

Figure 4 shows the full design of the J3400 and CCS reference devices.

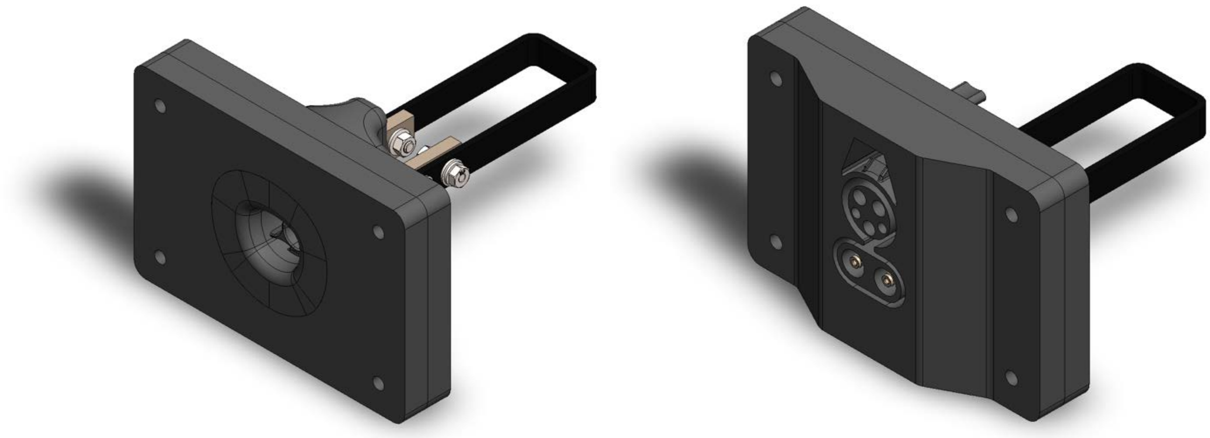


Figure 4. J3400 (left) and CCS (right) reference inlets

3.2 Simulation

For proper sizing of the reference inlet busbars, heat losses needed to be accurately modeled in a conjugate heat transfer analysis. The approach used by the reference device asserts that connector heat losses are the responsibility of the EVSE, and inlet losses are managed by the vehicle. Therefore, we added a cut plane to the model where heat flux was minimized based on adjusting the busbar height, as shown in Figure 5.

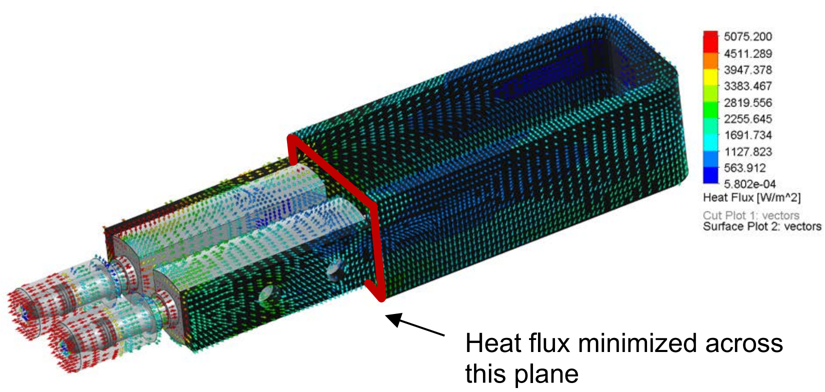


Figure 5. Reference device optimization

Internal joule heating in copper components and heat generation from contact resistance between copper components in the electrical path were balanced with natural convection and radiation over the surface area of the busbar. We set air temperature to 40°C and held the DC pins to a maximum temperature of 100°C. Figure 6 shows an example model iteration of the 800-A condition.

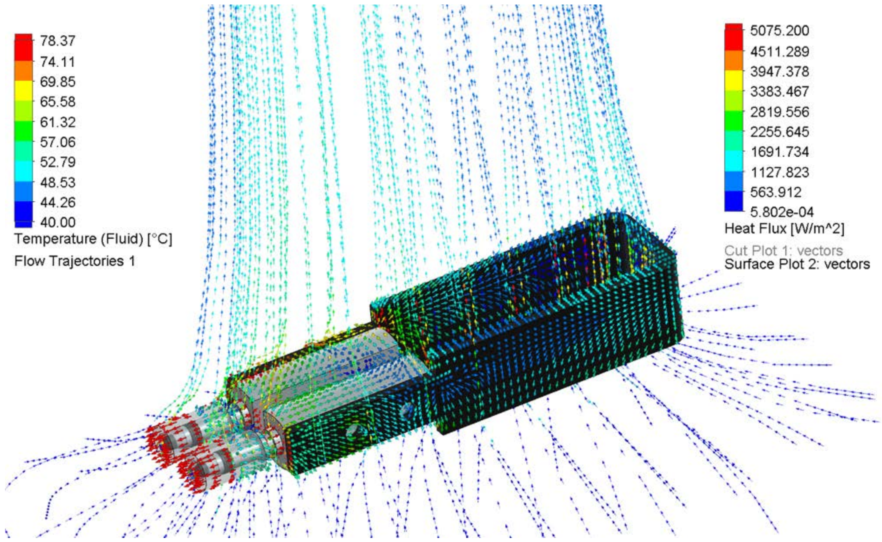


Figure 6. Conjugate heat transfer analysis of reference device at 800 A

While we ran models with both J3400 and CCS geometries, the optimized busbar heights were close enough to not require separate sets of busbars for each inlet standard.

We modeled the contact pins as five concentric rings as shown in Figure 7. These rings have a contact area of 78 mm^2 and a modeled resistance of 3 μΩ for each pin. The resulting contact joule heating and resistance heat are based on these geometry, material, and contact boundary conditions.

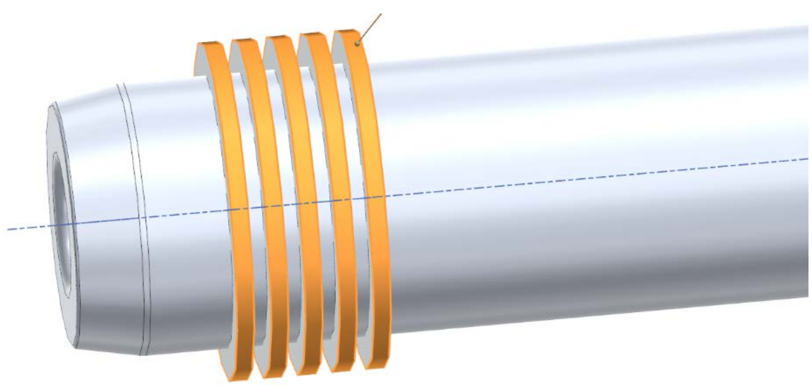


Figure 7. Inlet pin geometry

3.3 Fabrication

We obtained the components used for reference inlet fabrication from several sources. The housing, pin support plate, and locking pin were printed in PPS-CF material using a fused deposition modeling printer. The copper (C101 oxygen-free electronic copper) pins and busbars were machined to desired dimensions, and all pins were plated with a nickel/silver finish. The plating requirements are as follows:

- First plating layer: Nickel per ASTM B689-97, 2–12 µm thick. No post heat treatment. Must use sulfamate nickel. Matte surface finish.

- Second plating layer: Electrodeposited silver per ASTM B700-08, Type I, 2–12 µm thick, Grade B, Class N. Must use silver cyanide process. Bright surface finish.
- Plating thickness limit of barrel/sleeve: No less than 2-µm nickel, 2-µm silver.
- Plating thickness limit DC pin: No more than 12-µm nickel, 12-µm silver.
- Plating thickness test requirement: Adhesion though scribe grid test per ASTM B571.

We painted busbars with Krylon High Heat Matte black spray paint to achieve an expected emissivity of about 0.95. We applied two coatings and masked off areas in direct contact with high-power pins to avoid poor electrical contact. The remaining hardware—including nuts, washers, ring terminals, and thermocouples—completes the bill of materials, provided in Table 15 with one reference source included for convenience.

Table 15. Reference Inlet Bill of Materials

Item	Description	J3400 Quantity	CCS Quantity	Material	Source	Part Number	Reference
1	Housing	1	1	PPS-CF or equivalent	3D-printed	N/A	N/A
2	Pins support plate	1	1	PPS-CF or equivalent	3D-printed	N/A	N/A
3	Locking pin	1	1	PPS-CF or equivalent	3D-printed	N/A	N/A
4	High-power pin	2	2	Cu C101, Ni/Ag plating	Machined	N/A	N/A
5	500-A busbar	1	1	Cu 101, matte black paint	Machined	N/A	N/A
6	600-A busbar	1	1	Cu 101, matte black paint	Machined	N/A	N/A
7	700-A busbar	1	1	Cu 101, matte black paint	Machined	N/A	N/A
8	800-A busbar	1	1	Cu 101, matte black paint	Machined	N/A	N/A
9	Ground pin	1	1	Cu C101, Ni/Ag plating	Machined	N/A	N/A
10	Low-power pin	2	2	Cu C101, Ni/Ag plating	Machined	N/A	N/A
11	M8 × 1.25-mm coarse thread, 30-mm long hex head screw	4	4	Class 10.9 stainless steel	McMaster-Carr	91310A536	www.mcmaster.com/91310A536

Item	Description	J3400 Quantity	CCS Quantity	Material	Source	Part Number	Reference
12	M8 washer	4	4	18-8 stainless steel	McMaster-Carr	93475A270	www.mcmaster.com/93475A270
13	M8 spring lock washer	8	8	18-8 stainless steel	McMaster-Carr	91477A181	www.mcmaster.com/91477A181
14	M8 × 1.25-mm coarse thread hex nut	4	4	18-8 stainless steel	McMaster-Carr	91828A410	www.mcmaster.com/91828A410
15	M3.5 washer	2	2	18-8 stainless steel	McMaster-Carr	93475A220	www.mcmaster.com/93475A220
16	M1.6 washer	6	6	18-8 stainless steel	McMaster-Carr	93475A190	www.mcmaster.com/93475A190
17	No. 6 screw size ring terminal	1	1	Tin-plated Cu, nylon	McMaster-Carr	7113K265	www.mcmaster.com/7113K265
18	No. 2 screw size ring terminal	2	2	Tin-plated Cu, nylon	McMaster-Carr	7113K263	www.mcmaster.com/7113K263
19	1/16-in.-thick, 1/16-in.-OD neodymium magnet	6	4	Nickel-plated neodymium	McMaster-Carr	5862K137	www.mcmaster.com/5862K137
20	Watlow 1/8-in.-diameter, 1-in.-length, 24 V, 5 W Firerod cartridge heater	2	2	Inconel 600, MgO	Therm-X	C1A-9600	www.therm-x.com/watlow-1-8-diameter-cartridge-heaters.html
21	Adhesive Type K thermocouple	3	3	Chromel+/ alumel –, polyimide	McMaster-Carr	3648K34	www.mcmaster.com/3648K34/
22	1/8-in.-diameter probe Type K thermocouple	2	2	Chromel+/ alumel –, SS	McMaster-Carr	3857K212	www.mcmaster.com/3857K212/

Both high- and low-power pins are held in place by bolting the front housing to the rear pin support plate. The busbars can be interchanged with the high-power pins with four bolts. Figure 8 shows an assembled J3400 reference inlet with housing components semitransparent to aid in visibility of other components.

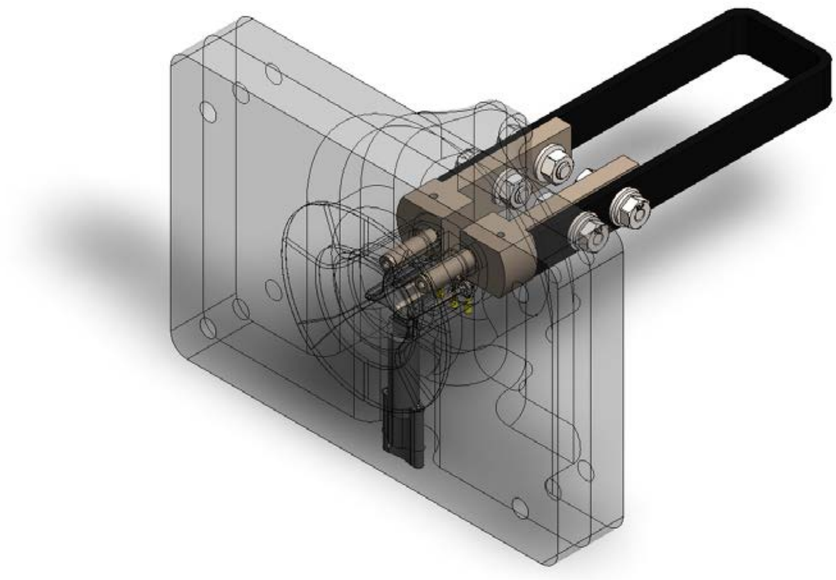


Figure 8. J3400 reference inlet with semitransparent housing

Appendix B and Appendix C provide full schematics of the SAE J3400 NACS reference inlet and SAE J1772 CCS reference inlet, respectively. These schematics, along with 3D computer-aided design of the reference inlet, can also be found on the SAE J3400 working group StandardsWorks site.

3.4 Experimentation

3.4.1 Reference Device Experimental Setup

For reference device evaluations, we modified the thermal evaluation bench and moved it into a thermal chamber to enable evaluations at an elevated ambient temperature of 40°C. Modifications included shortening the bench and removing the inlet shorting busbar box, instrumentation shelf, and misalignment fixture. We kept the plexiglass safety guarding in place to help minimize the airflow around the DUT. Data collection equipment, connector chiller control equipment, and the Magna DC supply were kept outside the chamber, and we routed required cabling into the chamber via a series of pass-through ports. We kept connector cooling units inside the chamber with the connector to eliminate the need for additional lengths of coolant piping. Figure 9 shows the layout of the thermal chamber and evaluation bench, while Figure 10 and Figure 11 show pictures of the interior of the chamber and evaluation bench, respectively.

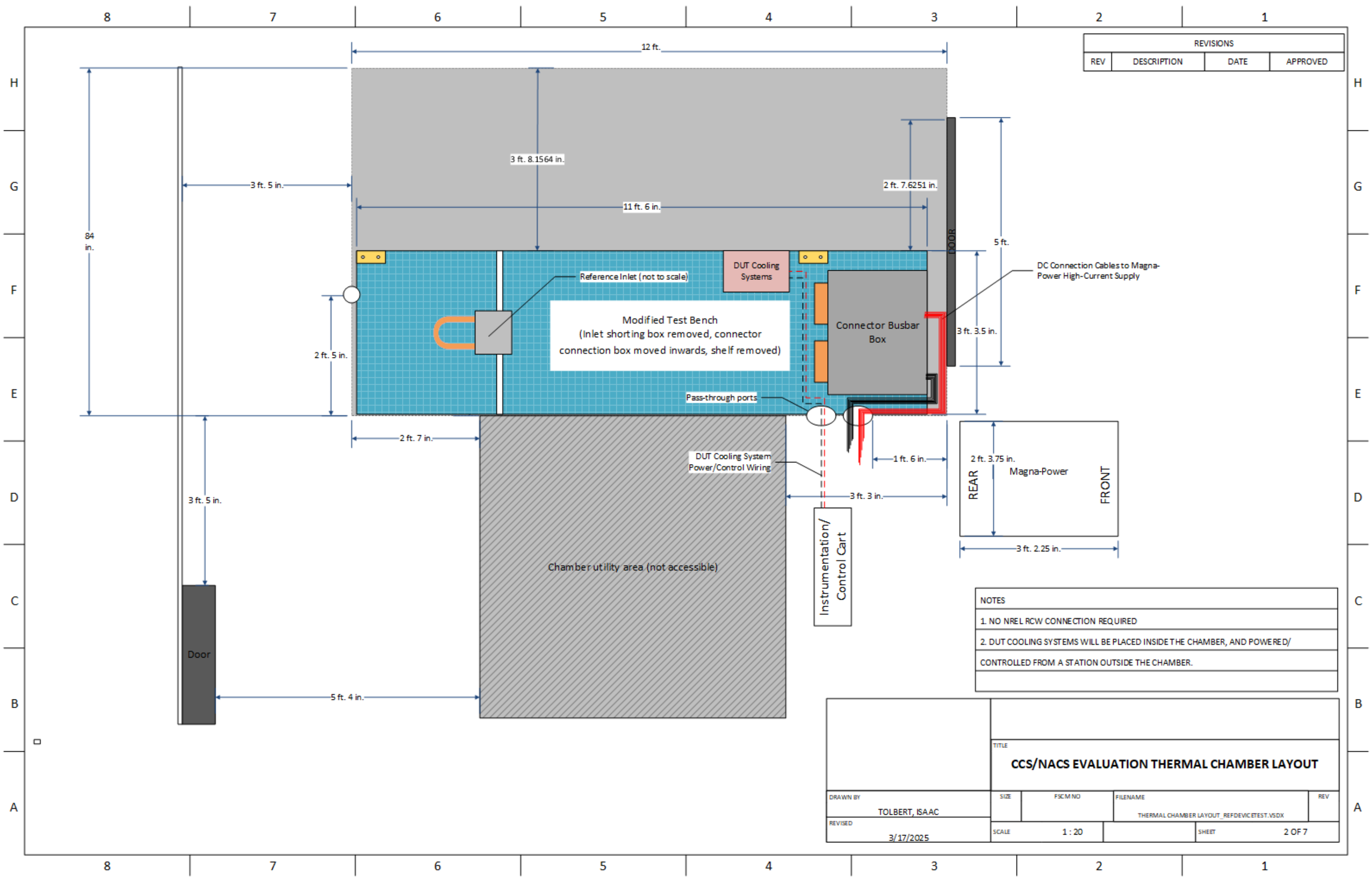


Figure 9. Schematic of thermal chamber and evaluation bench setup

Figure 10. View of evaluation bench from the thermal chamber door

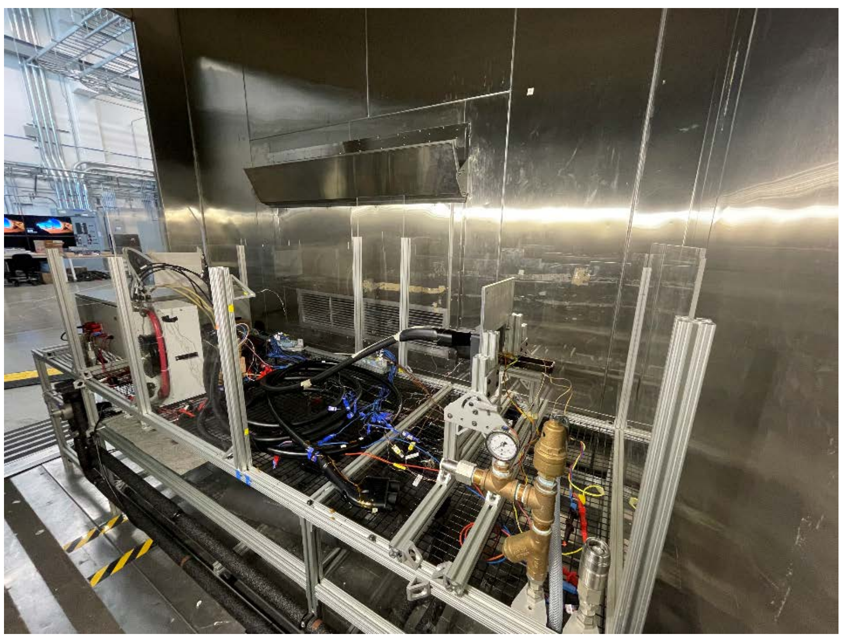


Figure 11. Evaluation bench within the thermal chamber

We instrumented the reference device with several thermocouples to monitor its thermal characteristics, listed in Table 16 and shown in Figure 12. The pin heaters were connected to an adjustable 24-V DC power supply, which was used to provide the appropriate amount of power to the heaters when activated.

Table 16. Reference Device Temperature Sensor Locations

Sensor Name	Location
TP1 (+/−)	Inside inlet DC+/DC− pins (20 mm behind pin front face)
TP2 (+/−)	Inlet DC+/DC− pin "collars"
TBR	Rear of inlet busbar
TBS	Side of inlet busbar

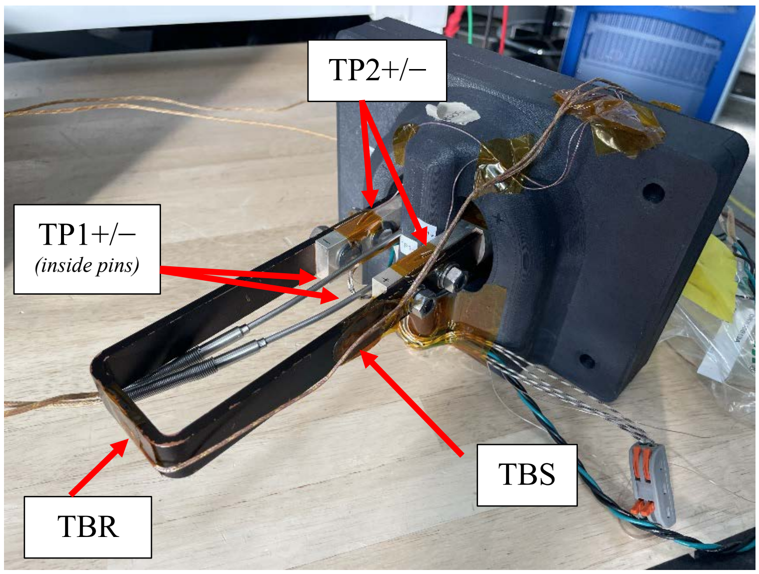


Figure 12. Reference inlet thermocouple locations.

Shown on 500-A NACS reference inlet. Pin heaters are embedded within the DC+/− pins, obscured by the inlet housing.

3.4.2 Reference Device Experimental Procedure

For reference device evaluations, we mounted the reference device on the thermal evaluation bench within the thermal chamber and mated it with the corresponding CCS or NACS connector. We then brought the chamber up to 40°C ambient temperature. Once the devices reached the 40°C ambient temperature, we turned on the Magna DC supply and ramped up the current flow to 150 A, at which point we took a resistance measurement by calculating voltage drop across the connector/inlet DUT at 150 A. We then increased the current until the temperatures reached the rated current of the reference device, and temperatures were allowed to stabilize until steady state was achieved.

Once steady-state temperature was achieved, we then used the reference device heaters to perform the "Test for Thermal Sensing Device of Cable Assembly," as described in IEC TS 62196-3-1:2020, Section 24.103. The pin heaters embedded in the reference device DC+ and DC− pins were activated, and their power output continually adjusted throughout the test to achieve a 2.5-K/min ± 0.5-K/min temperature rise rate on the reference inlet DC+/− pins. The operator manually adjusted the heater power each minute to maintain this temperature ramp rate.

We also evaluated the reference devices at several different current levels lower than their rated current, to assist in evaluations of NACS-CCS and CCS-Tesla Legacy adapters (which would be mated to a reference inlet).

3.4.3 Reference Device Experimental Results

3.4.3.1 500-A CCS Reference Device: Steady-State Temperatures

We examined the performance of the CCS reference device with a 500-A busbar and compared it to simulated results, as shown in Table 17. The 500-A CCS reference device was mated with Connector N, a 500-A-rated CCS connector with active cooling, which we determined to be the worst-performing CCS connector during the baseline evaluation.

Table 17. 500-A CCS Reference Device Experimental vs. Simulated Temperatures.

At 500-A steady-state, 40°C ambient temperature. Experimental results are with reference inlet mated with Connector N. Temperatures given as absolute temperature (°C)/temperature rise over ambient (K).

Location	Experimental Temperature (With Airflow) (°C/K)	Experimental Temperature (No Airflow) (°C/K)	Simulated Temperature (°C/K)
Ambient	45.5°C	43.4°C	40°C
TP1+	87.3°C/41.8 K	88.4°C/45 K	86.1°C/46.1 K
TP1−	88.8°C/43.3 K	89.9°C/46.5 K	86.1°C/46.1 K
TP2+	78.3°C/32.8 K	85.8°C/42.4 K	86.6°C/46.6 K
TP2−	77.7°C/32.2 K	87.1°C/43.7 K	86.5°C/46.5 K
TBS	86.4°C/40.9 K	91.6°C/48.2 K	--
TBR	85.9°C/40.4 K	91.5°C/48.1 K	90.4°C/50.4 K

As demonstrated in Table 17, the reference device's experimental temperatures are noticeably lower during the "With Airflow" evaluation compared to the "No Airflow" evaluation. This is due to the circulation of air within the chamber increasing the transfer of heat away from the reference device. During the evaluation, we placed barriers around the reference device to block as much airflow as possible, while still allowing the reference device's natural convection to draw heat away as designed. However, we observed during evaluation that these barriers were not sufficient to fully eliminate the cooling effect of the chamber's airflow, so we performed most evaluations with the chamber's airflow turned off. Comparing the "No Airflow" evaluation experimental temperatures with the simulated temperatures demonstrates that the experimental results offer a close match with the expected simulated temperatures.

We also captured steady-state temperature values at lower currents, while mated with the same 500-A CCS connector, as shown in Table 18. These values can help provide some comparison with the steady-state temperatures seen in the NACS-CCS adapter tests (which featured steady-state currents less than 500 A).

Table 18. 500-A CCS Reference Device Steady-State Temperatures at Varying Current.

40°C ambient temperature. Reference inlet mated with Connector N (500-A CCS).

Location	Temperature (°C) (350 A)	Temperature (°C) (400 A)	Temperature (°C) (450 A)	Temperature (°C) (500 A)
TP1+	65.4	71.2	79.6	88.4
TP1-	66.8	73.1	81.7	89.9
TP2+	64.5	70.2	77.8	85.5
TP2-	64.7	70.2	77.9	87.1
TBS	66.8	73.3	82.2	90.9
TBR	67	73.1	81.6	91
Connector DC+	56	59.3	64.4	70.15
Connector DC−	54.5	57.28	61.9	67.8
Ambient	41.7	41	41.7	43.8

3.4.3.2 600-A NACS Reference Device: Experimental vs. Simulated

We examined the performance of the NACS reference device with a 600-A busbar and compared it to simulated results, as shown in Table 19. The 600-A NACS reference device was mated with a 600-A-rated NACS connector with active cooling.

Table 19. 600-A NACS Reference Device Experimental vs. Simulated Temperatures.

At 600-A steady state, 40°C ambient temperature. Experimental results are with reference inlet mated with Connector Z. Temperatures given as absolute temperature (°C)/temperature rise over ambient (K).

Location	Experimental Temperature (With Airflow) (°C/K)	Experimental Temperature (No Airflow) (°C/K)	Simulated Temperature (°C/K)
Ambient	42.4°C	41.8°C	40°C
TP1+	94.5°C/52.1 K	97.6°C/55.8 K	91.2°C/51.2 K
TP1−	95.1°C/52.7 K	98.6°C/56.8 K	91.2°C/51.2 K
TP2+	80.5°C/38.1 K	90.3°C/48.5 K	91.3°C/51.3 K
TP2−	82.1°C/39.7 K	92.6°C/50.8 K	91.3°C/51.3 K
TBS	88.8°C/46.4 K	95.2°C/53.4 K	--
TBR	88.4°C/46 K	96.6°C/54.8 K	95.1°C/55.1 K

Table 19 shows that the reference device’s experimental temperatures are noticeably lower during the “With Airflow” evaluation than the “No Airflow” evaluation. This is due to the circulation of air within the chamber increasing the transfer of heat away from the reference device. During the evaluation, barriers were placed around the reference device to block as much airflow as possible, while still allowing the reference device’s natural convection to draw heat away as designed. However, we observed during evaluation that these barriers were not sufficient to fully eliminate the cooling effect of the chamber’s airflow, so we performed most evaluations with the chamber’s airflow turned off. Comparing the “No Airflow” evaluation experimental temperatures with the simulated temperatures, we see that the experimental results offer a close match with the expected simulated temperatures.

3.4.3.3 500-A NACS Reference Device

We also evaluated the NACS reference device at different steady-state current levels with the 500-A busbar attached, paired with the 600-A NACS connector. This was to facilitate comparisons with the adapter evaluations (which would be performed with a 500-A NACS reference inlet and the 600-A NACS reference connector, due to a lack of available 500-A NACS connectors at the time of the evaluation).

As this was a nonideal evaluation of the reference inlet as a stand-alone item, we did not perform the IEC thermal sensing device evaluation and the comparison to simulated results. Table 20 presents the steady-state results to help provide a comparison point for adapter evaluation.

Table 20. 500-A NACS Reference Device Steady-State Temperatures at Varying Current.

40°C ambient temperature. Reference inlet mated with Connector Z (600-A NACS connector).

Location	Temperature (°C) (250 A)	Temperature (°C) (300 A)	Temperature (°C) (350 A)	Temperature (°C) (400 A)	Temperature (°C) (450 A)	Temperature (°C) (500 A)
TP1+	53.4	58.2	67.5	73.4	81.4	91
TP1−	53.7	58.6	68.4	74.2	82.4	92.1
TP2+	52.7	57.4	65.7	72.2	79.4	88.4
TP2−	52.2	56.9	65.9	72	79.5	88.1
TBS	53.5	58.7	68.2	74.2	82.5	92.2
TBR	53.2	58.4	68.1	73.2	81.7	90.8
Connector DC+	50.8	54.5	62	65.6	71.9	79.5
Connector DC−	51	55	62.8	66.8	73.2	80.8
Ambient	41.3	41.9	45.7	45.4	46.5	46.9

3.4.3.4 25°C vs. 40°C Ambient, Comparison to Production Inlets

We also compared the performance of the busbar-based reference design to the performance of cable-based vehicle inlets purchased from OEMs. We compare the 500-A CCS reference device to the worst-performing 500-A CCS cable-based inlet (Inlet S) in Table 21. We performed all these evaluations with the same CCS connector (Connector N, 500-A CCS) to allow for easier comparison.

Table 21. 500-A CCS Reference Device vs. Cable Inlet.

Comparison between 500-A CCS reference inlet at 40°C and 25°C ambient, and production inlet at 25°C ambient. All evaluations performed with Connector N mated to corresponding inlet. Inlet S DC pin temperatures are from the inlet's OEM-installed RTD temperature sensors.

Temperature	500-A CCS Reference Inlet	500-A CCS Reference Inlet	500-A CCS Cable Inlet (Inlet S) [1 × 120 mm^2]
Ambient temperature	43.4°C	23.6°C	22.6°C
Inlet DC+ pin temp. (absolute/rise)	88.4°C/45 K	70.7°C/47.1 K	74.6°C/52 K
Inlet DC− pin temp. (absolute/rise)	89.9°C/46.5 K	70.6°C/47.0 K	78.4°C/55.8 K
Connector RTD+ temp. (absolute/rise)	69.7°C/26.3 K	53°C/29.4 K	51.1°C/28.5 K
Connector RTD− temp. (absolute/rise)	67.3°C/23.9 K	49.1°C/25.5 K	48.5°C/25.9 K
Connector coolant supply temp. (absolute/rise)	58.5°C/15.1 K	39.4°C/15.8 K	37.5°C/14.9 K
Connector coolant return temp. (absolute/rise)	67.1°C/23.7 K	48.9°C/25.3 K	46.7°C/24.1 K

Table 22 compares the performance of the 600-A NACS reference inlet with a 600-A cable-based inlet. The cable-based inlet was originally provided by the manufacturer without any cables, and cable sizing was left to the research team. The team selected two 107-mm^2 cables as the conductors for each DC+ and DC− leg. The evaluations were all performed with the same 600-A NACS connector (Connector Z, 600-A NACS) to allow for easier comparison.

Table 22. 600-A NACS Reference Inlet vs. Cable Inlet.

Comparison between 600-A NACS reference inlet at 40°C and 25°C ambient, and 600-A cable inlet at 25°C ambient. All evaluations performed with Connector Z mated to corresponding inlet. It should be noted that this Connector Z (600-A NACS) is approximately 50% longer than the Connector N (500-A CCS) used in Table 21, contributing to additional DUT heat generation.

Temperature	600-A NACS Reference Inlet	600-A NACS Reference Inlet	600-A NACS Cable Inlet Y [2 × 107 mm^2]
Ambient temperature	42.8°C	25.5°C	26.2°C
Inlet DC+ pin temp. (absolute/rise)	94.5°C/51.7 K	79.7°C/54.2 K	66.7°C/40.5 K
Inlet DC− pin temp. (absolute/rise)	95.0°C/52.2 K	81.9°C/56.4 K	65.0°C/38.8 K
Connector RTD+ temp. (absolute/rise)	90.2°C/47.4 K	70.3°C/44.8 K	71.5°C/45.3 K
Connector RTD− temp. (absolute/rise)	91.5°C/48.7 K	72.1°C/46.6 K	72.4°C/46.2 K
Connector coolant supply temp. (absolute/rise)	85.6°C/42.8 K	62.9°C/37.4 K	65.0°C/38.8 K
Connector coolant return temp. (absolute/rise)	107.5°C/64.7 K	84.8°C/58.9 K	86.7°C/60.5 K

3.4.3.5 Thermal Sensing Sensitivity Evaluation Results

Each reference device was equipped with two 20-W heater cartridges to allow the DC pins to be heated at a constant rate. The "Test for Thermal Sensing Device of Cable Assembly," described in IEC TS62196-3-1:2020, Section 24.103, specifies that the evaluation should be performed in an ambient temperature of 40°C (± 5°C), without forced convection. Rated current is passed through the device until thermal stabilization is reached. Then, an overtemperature condition is simulated by heating the inlet pins at a constant temperature rise of 2.5 K/min ± 0.5 K/min.

The evaluation performed during this work was similar, but differed from the IEC-described evaluation in several ways. First, the IEC evaluation calls for temperature sensors (e.g., thermocouples) to be installed on the connector's DC pins by the evaluating team, in addition to the factory-installed thermal sensors. The NREL evaluation team did not install these thermocouples, as they did not want to risk damaging or altering the thermal performance of the connectors. The reference device's TP1+/− sensors, placed at the mating interface of the connector/inlet pins, serve as a surrogate replacement for the IEC-specified sensors. These sensors are placed within the DC pins of the reference device, measuring temperature at the mating point of the connector and inlet pins. Second, because the goal of performing this evaluation was not to evaluate the performance of the connectors per se, but rather to understand the ability of the reference devices to perform the evaluation, we evaluated and presented an abbreviated set of compliance criteria. We present the following compliance criteria from the IEC thermal sensitivity evaluation:

1. The temperature gradient of the connector's thermal sensing devices (ConnRTD+/−) deviates by less than 1.5 K/min compared to the temperature gradient measured by the corresponding temperature sensor (TP1+/−).
2. |(gradient of ConnRTD+ / gradient of TP1+) – (gradient of ConnRTD− / gradient of TP1−)| < 0.2

Table 23 presents the results of the thermal sensitivity evaluation.

Table 23. Thermal Sensitivity Evaluation Results

DUT	Inlet DC+ Pin Gradient (K/min)	Connector DC+ RTD Gradient (K/min)	DC+ Gradient Difference	Inlet DC− Pin Gradient (K/min)	Connector DC− Gradient (K/min)	DC− Gradient Difference	Criteria 1	Criteria 2
Connector N/500-A CCS reference	2.4	0.3	2.1	2.3	0.4	1.9	Noncompliant	Compliant
Connector Z/600-A NACS reference	2.6	0.4	2.2	2.6	0.4	2.2	Noncompliant	Compliant

The reference device was able to enact the appropriate temperature rise on the inlet DC pins, with both reference devices enacting a temperature rise of 2.3–2.6 K/min on the inlet DC pins. Due to the manual control of the heater cartridges, this fell slightly outside the specified 2 K ± 0.5 K range, but this does demonstrate that the heater cartridges are capable of effecting the necessary ramp rate. This ramp rate could be further refined either through use of a digital controller or by finer manual control, which we did not do in this work due to time constraints. The mated connector in each evaluation was not compliant with Criteria 1, with the connector sensor-to-inlet pin gradient difference ranging from 1.9 to 2.2 K/min (outside the acceptable 1.5-K/min deviation). However, both were compliant with Criteria 2.

4 Adapter Evaluation

With many automakers and EVSE suppliers beginning to offer NACS charging connectors and inlets, a market for adapters (devices that allow charging connectors of one standard to interface with charging inlets of another) has begun to emerge. These adapters carry some limitations. Adapters can be susceptible to overheating; due to their size, most cannot accommodate 500 A of current indefinitely (as a liquid-cooled charge cable may), so adapters need to sense when their internal temperature is approaching safety limits and communicate this to the EVSE and EV. If the adapter does not communicate an overtemperature event to the EV and EVSE, the EV and EVSE have no way to adequately sense internal adapter temperatures. To address this issue, SAE J3400 includes "thermal foldback" communication states on the proximity circuit. In the adapter's "thermal warning" foldback state, the EVSE is instructed to reduce the temperature to 50% of the maximum charge current; if temperatures continue to rise, a second "Thermal Shutdown" state is triggered, stopping current flow immediately. Table 24 lists the various proximity voltage states as described in SAE J3400. We performed the evaluations described in this section to examine how various adapters implemented thermal warning/shutdown states, as well as the thermal performance of adapters more generally.

Table 24. SAE J3400 Proximity Detection Circuit States.

As described in SAE J3400 recommended practice draft (July 2024)

Status	Units	Nominal Value	SAE J1772 Coupler	SAE J3400 Coupler	Cross-Coupler Interop. Detection Range
Disconnected	VDC	4.46	4.13–4.78	4.20–4.71	--
Reserved	VDC	4.09	--	--	--
SAE J1772 unlatched	VDC	2.76	2.38–3.16	2.55–2.98	2.46–3.09
Connector inserted	VDC	1.51	1.23–1.82	1.37–1.65	1.30–1.74
DC thermal warning (proposed)	VDC	1.16	--	1.04–1.28	0.99–1.35
DC thermal shutdown (proposed)	VDC	0.63	--	0.56–0.71	0.54–0.73

We evaluated several different adapters with a goal of evaluating both official automaker OEM-built devices and unofficial third-party devices. In this report, "NACS→CCS adapter" refers to an adapter intended to allow a NACS charging cable to interface with a CCS vehicle inlet, and "CCS→Tesla Legacy adapter" refers to an adapter intended to allow a CCS charging cable to interface with a pre-J3400 Tesla charging inlet. We did not evaluate any post-J3400 CCS-NACS adapters. At time of evaluation, the team was unable to acquire any CCS-NACS adapters that were designated for greater than 500 V; all appeared to be designed for the voltage ratings of legacy Tesla vehicles, rather than J3400 vehicles. It should be noted that NACS is physically compatible with legacy Tesla connectors/inlets, but legacy Tesla devices do not share the same voltage ratings or overtemperature warning protocols as J3400 devices. Table 25 summarizes the evaluated adapters.

Table 25. Adapter Summary

Type	First Party	Third Party
CCS-Tesla Legacy	1	2
NACS-CCS	1	1

The goal of these evaluations was to demonstrate and validate the thermal warning/thermal shutdown functionality of adapters, as well as understand the general thermal performance of a selection of adapters.

4.1 Adapter Evaluation Setup

The adapter evaluation setup was nearly identical to the reference device evaluation setup in the thermal chamber. The primary difference was the addition of a proximity generation and monitoring circuit to enable monitoring of the adapters' thermal warning and shutdown circuits. On the reference device ("vehicle" side), the proximity generation circuit was built according to the SAE J1772 and J3400 standards. The proximity circuit's vehicle/inlet side is identical in each standard (excepting the tighter resistance tolerances in SAE J3400 compared to J1772), with the only differences occurring on the connector/supply equipment side. Monitoring leads were then attached to the appropriate connector-side and inlet-side proximity detection points. Figure 13 shows a diagram of the SAE J3400 proximity generation circuit as constructed on the NREL NACS reference device, with measurement points. The inlet-side proximity generation and monitoring circuit was identical on the NREL CCS reference device. Table 26 lists the proximity circuit resistance and tolerance values used during these evaluations.

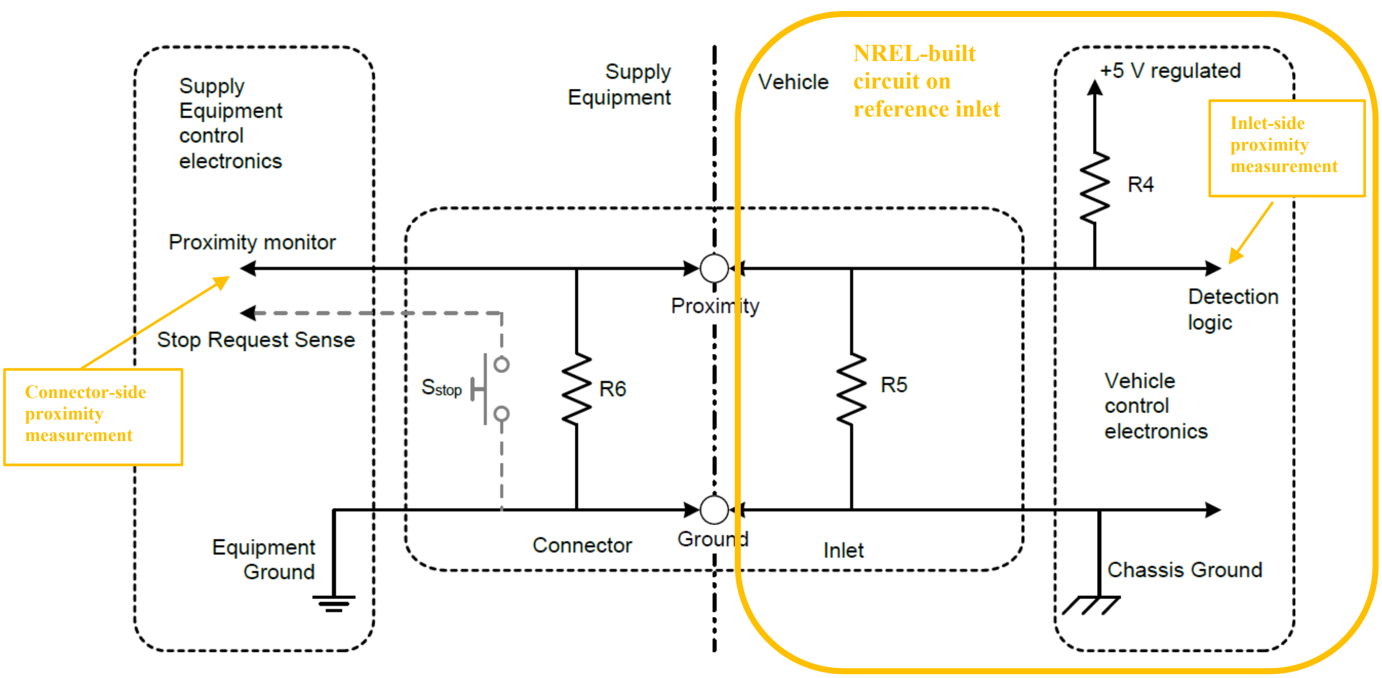


Figure 13. SAE J3400 proximity detection circuit.

As described in SAE J3400 (December 2023)

Table 26. Reference Device Proximity Circuit Values

Component	Value	Tolerance
R4	330 Ω	1%
R5	2,700 Ω	1%
Power supply	5 V	2%

For the evaluation, we instrumented each adapter with four thermocouples to monitor thermal performance. Two of these thermocouples were external, one placed on top of the adapter and one on the bottom, to monitor the temperature of likely touch/grasp zones. The other two thermocouples were placed inside the adapter to monitor the internal electrical busbar temperature. For these internal thermocouples, we comprehensively examined the adapters to determine the optimal location to drill into the adapter housing to place the thermocouples. Due to the unique design of each adapter, identical placement on each adapter was not possible. However, we attempted to make the placement as optimal and identical across samples as possible, taking into account the adapters' internal busbar and pin geometry, wire routing, and structural design. To place these thermocouples, we drilled small holes in each adapter's casing using a small rotary tool to expose the busbars. We then placed a thin piece of polyimide tape over the exposed busbar to provide electrical isolation from the thermocouple, and then placed the thermocouple onto the busbar and secured it with another piece of polyimide tape. We then routed the thermocouple and secured it to the adapter housing to prevent movement and/or disconnection, and covered the hole in the adapter housing with a layer of vinyl electrical tape. Examples of this instrumentation can be seen in Figure 14 and Figure 15 (with the internal thermocouples exposed).

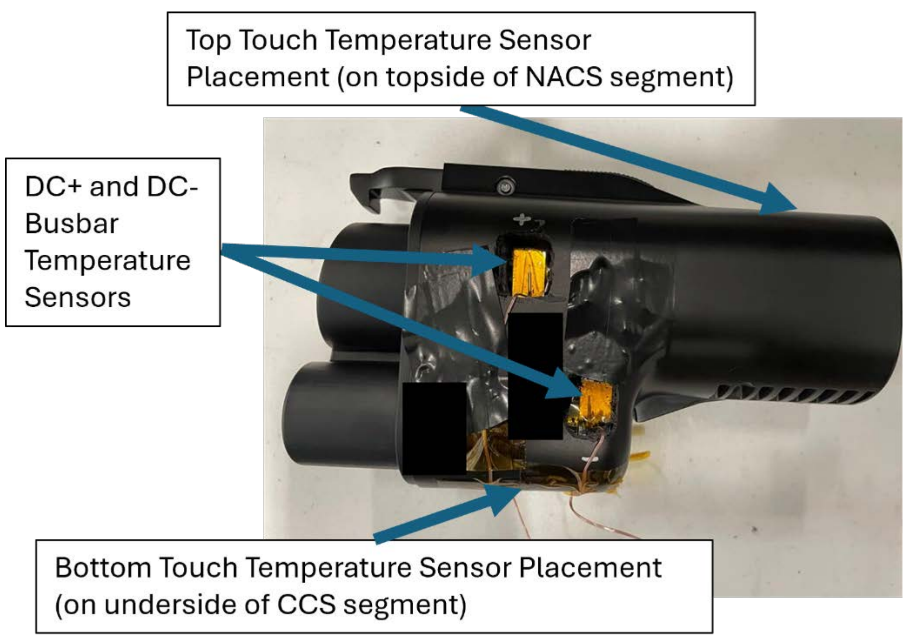


Figure 14. NACS-CCS adapter instrumentation example

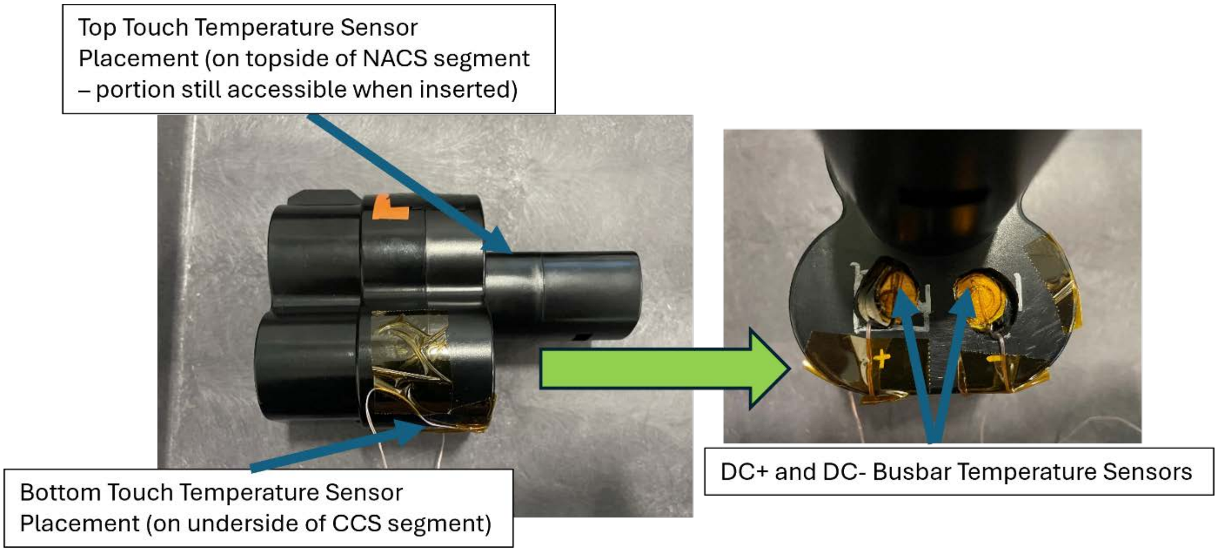


Figure 15. CCS-Tesla Legacy adapter instrumentation example

4.2 Adapter Evaluation Procedure

After instrumentation, we placed adapters onto the evaluation bench and mated them with either the 500-A CCS connector and 500-A NACS reference inlet (for CCS-Tesla Legacy adapters) or the 600-A NACS connector and 500-A CCS reference inlet (for NACS-CCS adapters). For NACS-CCS adapters, we chose the 600-A NACS connector due to a lack of available 500-A NACS connectors when the evaluation was performed. We chose the 500-A reference inlet as it had the lowest rating of the reference inlets available, and most closely matched the 500-A rating given on some of the adapters. We then soaked the mated devices at 40°C ambient temperature. Though some of the devices advertised ambient temperature ratings of 50°C, we chose the ambient evaluation temperature of 40°C to maintain consistency across all adapters and ensure easier comparison to previous reference device evaluations, which were also performed at 40°C ambient temperature.

We activated the charging connector's cooling system and ramped the current from 0 A to an appropriate current level, as chosen by the operator, with a goal of determining the maximum steady-state current that each adapter could maintain without activating the thermal warning or thermal shutdown states. We maintained this current level until reaching a steady-state temperature. We then increased the current level by 50 A, pausing to allow temperatures to reach steady state at each level, until both the thermal warning and thermal shutdown proximity states were activated or busbar temperatures exceeded 110°C.

Table 27 lists the type and labeled ratings of each adapter featured in the adapter evaluations. Current, voltage, and power ratings (if listed) for each device are given. These ratings are from datasheets (if available), adapter/packing labels, and/or online storefront listings.

Table 27. Adapter Labeled Ratings

Adapter	Type	Manufacturer Type	Labeled Rating
BB	NACS→CCS	Automaker OEM	No current rating | 1,000 V
CC	NACS→CCS	Third party	500 A | 1000 V
DD	CCS→Tesla Legacy	Third party	400 A | 500 V | 200 kW
EE	CCS→Tesla Legacy	Third party	No current rating | 500 V | 250 kW
FF	CCS→Tesla Legacy	Automaker OEM	No current rating | 500 V | 250 kW

4.3 Adapter Evaluation Results

Although many adapters either explicitly advertised current ratings of 500 A (or implied a current rating of approximately 500 A via a power rating of 250 kW), no evaluated adapters were able to maintain a steady-state current of 500 A at 40°C ambient.

4.3.1 Adapter Steady-State Evaluations

First, we evaluated adapters to determine the maximum steady-state current they could successfully transfer without activating their thermal warning circuitry, as described in Section 4.2. Table 28 describes the maximum steady-state current that each adapter could transfer before activating the thermal warning, along with the internal adapter busbar temperature observed at that current level.

When determining the maximum steady-state temperature of the adapters, the operator quickly ramped up the test current to an initial steady-state point (usually either 250, 300, or 350 A). We chose this initial test current based on the adapter's stated rating, thickness of the busbars, or prior experience, with a goal of choosing a reasonable starting point that would not trigger overtemperature detection immediately, while also not needlessly prolonging the test (as reaching steady-state temperature at a given current level could take in excess of 30 minutes). If thermal warnings were not activated at this initial current level, we increased current by 50 A and allowed temperatures to stabilize again. We repeated this process until one of the following conditions was reached:

- Thermal shutdown proximity state was activated (for adapters that implemented the SAE J3400 thermal foldback system).
- "Disconnected" or "SAE J1772 Unlatched" proximity state was activated (if adapter did not implement the SAE J3400 thermal foldback system).
- Internal adapter temperatures or connector/inlet pin temperatures exceeded safe temperatures as determined by the operator.

It should be noted that the thermal warning/shutdown temperature noted in these summary tables is the warning/shutdown temperature when the adapters have been soaking at 40°C and transferring high current for an extended time, allowing the temperature to gradually rise and giving the temperature sensors a more generous response window. Other evaluations, discussed later, examine the performance of the thermal warning circuit when adapters were immediately subjected to 500 A, necessitating a quick response from the thermal warning circuit to react to a sudden temperature rise.

Table 28 summarizes the maximum achieved steady-state current at 40°C ambient. Maximum steady-state current was determined by the highest current the adapters could achieve (in 50-A increments) without activating their thermal warning circuitry or exceeding safe temperatures.

Table 28. Adapter Maximum Steady-State Current

Type (Inlet-Connector)	Adapter	Listed Current (A)	Max. Steady-State Current (A)	Adapter Busbar Steady-State Temp. (°C)
NACS-CCS	BB	Not listed	350	74.6
NACS-CCS	CC	500	400	79.6
CCS-Tesla Legacy	DD	400	250 [a]	88
CCS-Tesla Legacy	EE	500 [b]	400	90
CCS-Tesla Legacy	FF	500 [b]	300	69.4

[a] Adapter DD never activated a thermal warning system. The maximum steady-state current was chosen based on the highest current observed before internal temperatures exceeded generally accepted safe operating levels.

[b] Adapter EE/FF 500-A listed current is based on given voltage/power ratings of 500 V/250 kW (no explicit current rating given).

Additionally, we compared the temperature of the reference inlet pins with an adapter in the system to the temperature of the pins without an adapter, as shown in Table 29. While this is not an entirely one-to-one comparison due to the use of two different connectors—as, necessarily, the mating connector of a CCS inlet (without an adapter) is a CCS connector, while the mating connector of a CCS inlet (with a NACS-CCS adapter) is a NACS connector—this can offer a high-level view of the temperature difference experienced by an inlet during a charge session with an adapter.

Table 29. Heat Added by Adapter.

Evaluations performed with Connector N (500-A CCS), Connector Z (600-A NACS), 500-A CCS reference inlet, and 500-A NACS reference inlet. Ambient temperature of 40°C.

Type	Adapter	Max. SS Current (A)	Reference Inlet DC Pin Temp. (at Max. SS Current) (DC+/DC−)		Difference Between the Reference Inlet DC Pin Temp. With and Without Adapter (∆K)
			With Adapter (°C)	Without Adapter (°C)	
NACS-CCS	BB	350	80.6/81.1	65.4/66.8	15.2/14.3
NACS-CCS	CC	400	89.8/89.7	71.2/73.1	18.6/16.6
CCS-Tesla Legacy	DD	250	76.6/77.8	53.4/53.7	23.2/24.1
CCS-Tesla Legacy	EE	400	90.9/90.6	73.4/74.2	17.5/16.4
CCS-Tesla Legacy	FF	300	66.7/66.7	58.2/58.6	8.5/8.1

4.3.2 SAE J3400 Thermal Warning and Recovery Evaluation

For NACS-CCS adapters, we performed an additional evaluation to examine the performance of the adapters in the proposed thermal foldback process described in SAE J3400/1 TIR (Aug. 22, 2024, draft), Section 8.1.3.2. The control sequence used for this evaluation simulates a scenario in which a charge session is undertaken at 500 A. The sequence begins with a charge session current of 500 A ($I_{MAX\_PRE\_WARN}$). When the "DC Thermal Warning" state was activated, we immediately reduced the current to [0.5 × $I_{MAX\_PRE\_WARN}$] (i.e., 250 A). We then held the current at 250 A until reaching steady-state temperature. If the device reentered the "Connector Inserted" proximity state ("Thermal Recovery"), we then increased the current to [0.8 × $I_{MAX\_PRE\_WARN}$] (i.e., 400 A) and held it there until either reaching temperature stabilization or the device reentered "DC Thermal Warning." This evaluation was intended to see the adapters' performance under the prescribed control sequence and understand when J3400 thermal warning would activate and enter thermal recovery. We performed all these evaluations at an ambient temperature of 40°C.

In the first evaluation, we applied 500 A of current to Adapter BB for approximately 20 minutes before the "DC Thermal Warning" state was activated (with adapter internal temperatures at approximately 92.7°C). We then immediately reduced current to 250 A and held it there for approximately 96 minutes for temperatures to achieve steady state. In that time, proximity state remained in "DC Thermal Warning," with adapter internal temperatures stabilizing to 60.2°C. Then, we decided to shut off current to allow the adapter to cool and understand the temperature at which the adapter would enter thermal recovery. The adapter then entered thermal recovery at an internal temperature of 49°C, and shortly afterward the current was reenergized to 400 A. However, we held this current level for only about 6 minutes before the adapter reentered "DC Thermal Warning," when internal temperatures were roughly 62.6°C. This shows significant hysteresis in the adapter's thermal warning circuit. For this adapter, once thermal warning activates, it seems unrealistic that it would enter thermal recovery during a charge session before very near the end of the session. Figure 16 provides a full plot of this evaluation with Adapter BB.

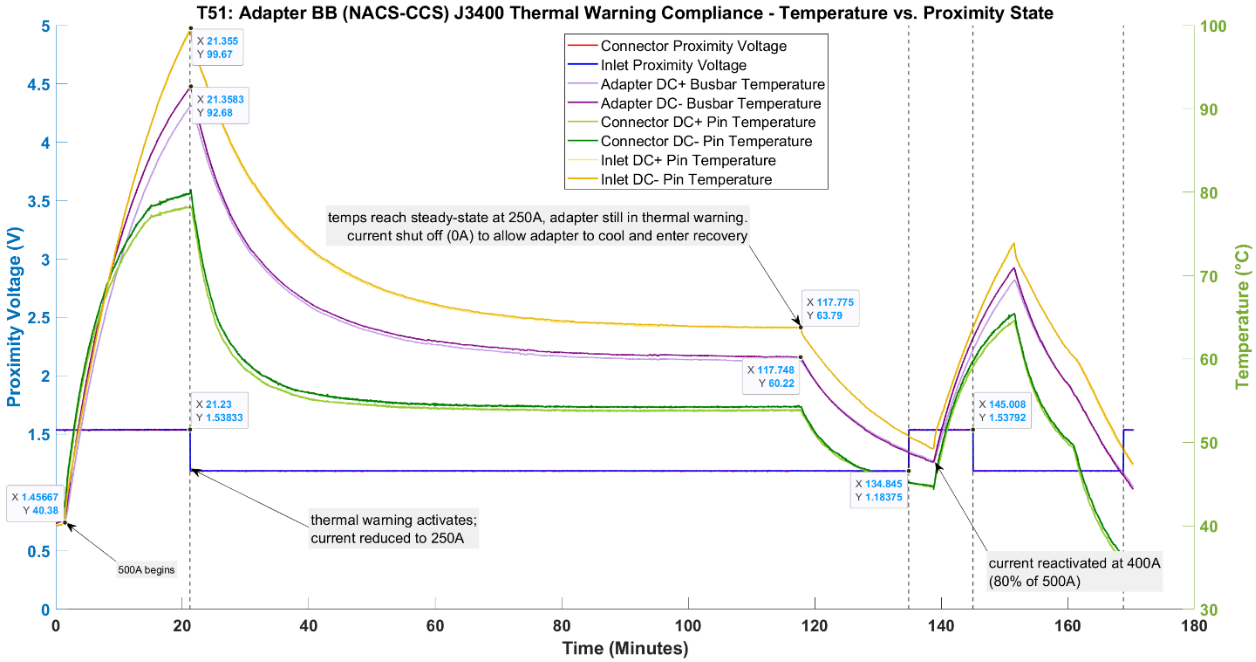


Figure 16. Adapter BB (NACS-CCS) J3400 thermal warning and recovery

Next, we subjected Adapter CC to the same evaluation, applying 500 A for just under 22 minutes before the adapter activated “DC Thermal Warning” at an internal temperature of 89.4°C. We then immediately reduced current to 250 A and held it there for roughly 35 minutes, at which point the adapter internal temperature had fallen to approximately 70°C and the adapter reentered the “Connector Inserted” state (thermal recovery). We then increased the current to 400 A, and approximately 51 minutes later, at an internal temperature of 83.2°C, the device reentered “DC Thermal Warning.” While this adapter does have some amount of hysteresis in its thermal warning circuit, it is a much smaller amount than found in Adapter BB. This means that, unlike Adapter BB, this adapter enters thermal recovery while still transferring 250 A of current, and Adapter CC is also able to transfer the 400-A recovery current longer than Adapter BB before reentering “DC Thermal Warning.” Figure 17 provides the full plot of this evaluation.

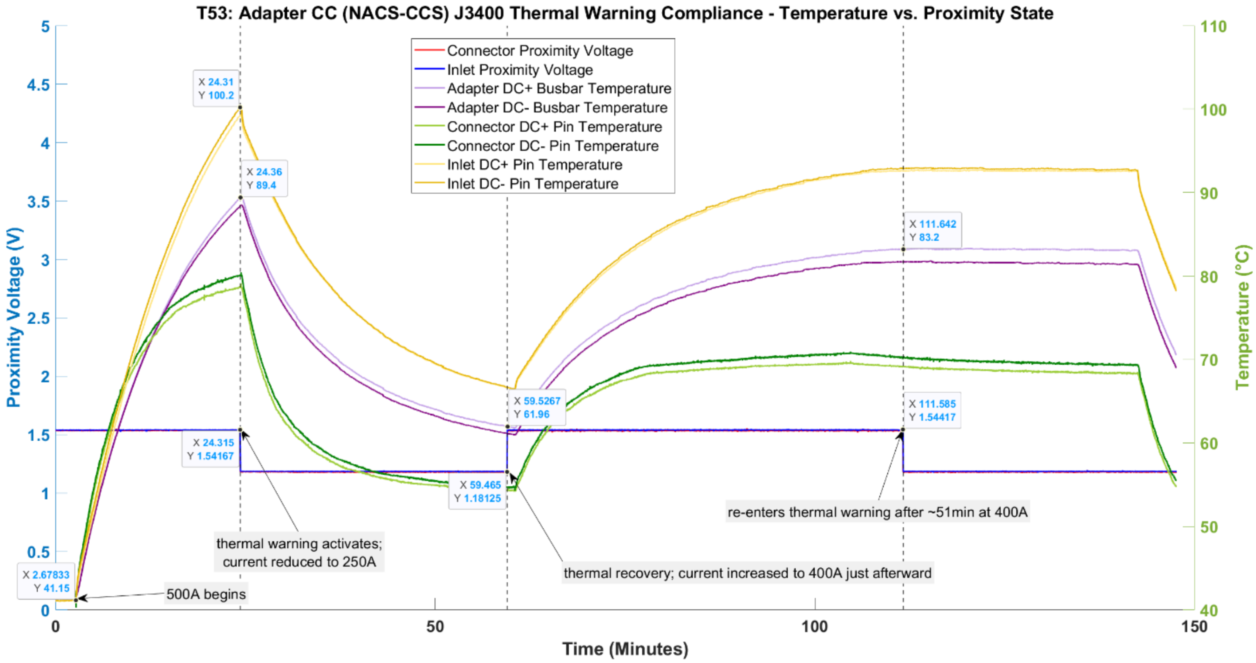


Figure 17. Adapter CC (NACS-CCS) J3400 thermal warning and recovery

4.3.3 500-A Evaluation

The prior steady-state evaluations examined the maximum possible steady-state current without activating thermal warning. We recorded the temperature at which warning was activated during those evaluations; however, during those evaluations the adapters had all been transferring current for an extended period, allowing the heat generated during current transfer to soak the adapter thoroughly. We also performed several evaluations to examine adapters' internal temperatures when heat increased suddenly (e.g., by a charge session that quickly ramps up to 500 A and holds there), without leaving time for heat to thoroughly soak the adapter busbars and temperature sensors. Direct correlation between CCS-Tesla Legacy adapters and NACS-CCS adapters is not possible, as current through CCS-Tesla Legacy adapters was ramped up from 25 A to 500 A over the course of approximately 6 minutes, while NACS-CCS adapters were started instantly at 500 A. (We altered the evaluation procedure after evaluating CCS-Tesla Legacy adapters, and there was not sufficient time available to redo prior evaluations.) However, the quick ramp-up of CCS-Tesla Legacy adapter current and low temperature rise experienced by the adapters during that time enables them to be somewhat comparable to the later NACS-CCS evaluations. We did not evaluate the CCS-Tesla Legacy Adapter DD at this 500-A current level due to time constraints, its lack of thermal warning functionality, and its poor performance at current levels of only 300–350 A.

Figure 18 shows Adapter EE's 500-A evaluation. After approximately 27 minutes of 500-A current, adapter internal temperatures reached 98.9°C, and the adapter's thermal warning circuit began to activate. The EV-sensed proximity voltage exited the "Connector Inserted" state approximately 1.3 minutes later (when adapter internal temperatures reached 99.8°C and pin temperatures reached 96°C). However, due to the adapter's gradual proximity change, the EVSE-sensed proximity voltage did not reduce to 1.3 V (the bottom of the "Connector Inserted" state) until the internal temperatures reached 106°C (with pin temperatures at 103.3°C), after approximately 46 minutes of 500-A current.

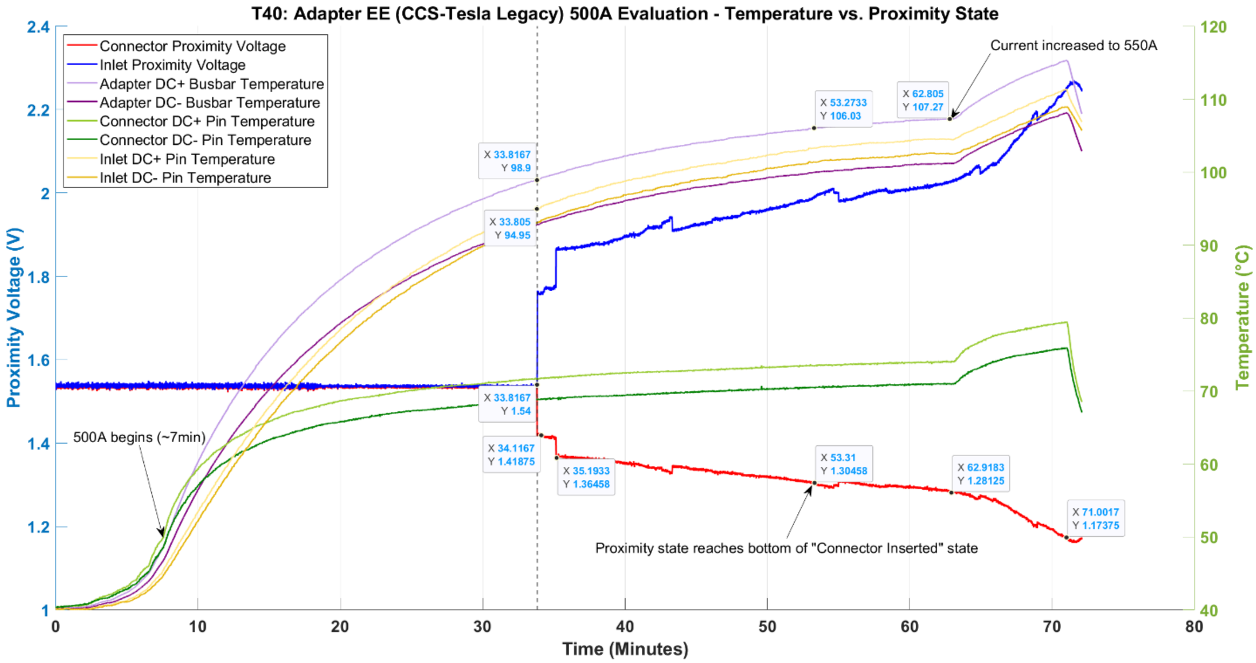


Figure 18. Adapter EE 500-A evaluation: temperature vs. proximity state

Adapter FF, as shown in Figure 19, maintained 500 A for approximately 13 minutes before it began to activate its thermal warning circuit at an internal temperature of 92.8°C. However, as mentioned previously, the proximity voltage change shown here would likely be too small for an EVSE to detect. Five minutes later (after approximately 18 minutes of 500-A current), internal temperature reached 100°C, and the adapter activated the “Disconnected” state.

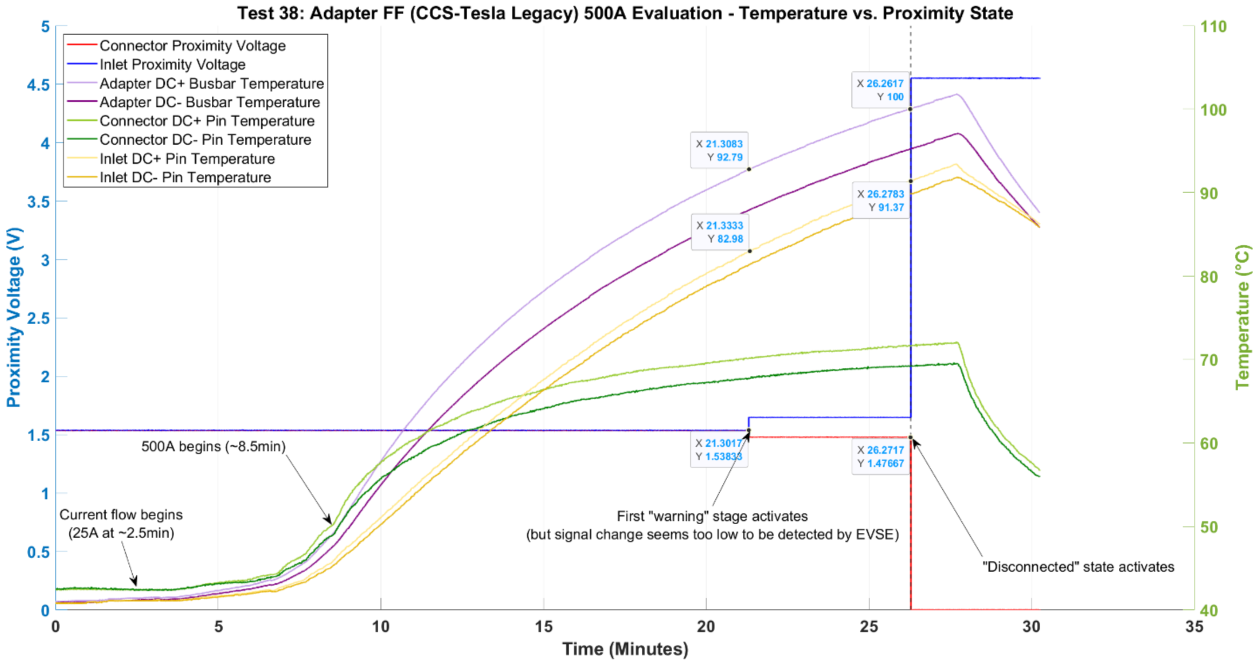


Figure 19. Adapter FF (CCS-Tesla Legacy) 500-A evaluation: temperature vs. proximity state

We examined NACS-CCS adapter thermal performance as part of the previously discussed J3400 thermal warning compliance evaluations (Section 4.3.2). Figure 16 shows Adapter BB's 500-A performance, with the adapter maintaining 500 A of current transfer for approximately 20 minutes before activating thermal warning at an internal temperature of 92.7°C. Similarly, Figure 17 shows Adapter CC maintaining 500 A of current transfer for roughly 21.5 minutes before activating thermal warning at an internal temperature of 89.4°C.

From this evaluation, we see that when quickly ramping current up to 500 A, both of the J3400 NACS-CCS adapters activated the thermal warning proximity state before reaching an internal temperature of 100°C. Of the CCS-Tesla Legacy adapters, we see that one adapter successfully triggered the "Disconnected" state as the internal temperature reached 100°C, but the other did not exit the "Connector Inserted" state until the internal temperature had exceeded 106°C (and even then, it did not trigger the "Disconnected" state). It should also be noted that another CCS-Tesla Legacy adapter did not trigger a thermal warning at all in prior evaluations, despite internal temperatures exceeding 119°C, and so we did not evaluate it in this portion.

Overall, we saw that both NACS-CCS adapters maintained 500 A for roughly 20 minutes at 40°C ambient temperature before activating thermal warning, and both activated this thermal warning before internal temperatures reached 100°C. Performance for the CCS-Tesla Legacy adapters was more mixed—one adapter maintained 500 A for around 18 minutes before activating the "Disconnected" state at an internal temperature of 100°C, while another maintained 500 A for around 27 minutes before starting to activate its thermal warning (but this warning signal was very gradual and did not move out of the normal "Connector Inserted" range until 20 minutes later, when internal temperatures had reached 106°C). Another adapter did not have any thermal warning activation at all in prior evaluations.

4.3.4 Adapter Discussion

We performed the adapter evaluation considering performance relative to requirements in SAE J3400, SAE J3400/1, and UL 2252. All adapters evaluated in this work were manufactured prior to the release of these standards. However, these standards were written to improve the interoperability and safety of adapters on the market, and thus this work helps provide a snapshot of performance as the industry designs and manufactures adapters, while also identifying areas of improvement within the standards. The following discussion compares these standards to the SAE J3400 Recommended Practice (September 2024), SAE J3400/1 Technical Information Reference, and UL 2252 (Edition 1, March 2025).

4.3.4.1 SAE J3400 Conformance

We evaluated the adapters based on their compliance with the J3400 thermal warning/shutdown standard. SAE J3400 states that if an adapter detects an overtemperature event, the adapter should trigger a "Thermal Warning" proximity state to signal the EV and EVSE to reduce current, in order to curb the temperature increase while still allowing the charge session to proceed. If temperatures continue to rise, the adapter should trigger the "Thermal Shutdown" proximity state in order to terminate the charge session. The adapter should activate these signals in time to avoid the pin temperature exceeding 100°C. Table 30 summarizes the adapters' SAE J3400 thermal warning/shutdown performance.

Table 30. Adapter SAE J3400 Thermal Warning/Shutdown Compliance.

Compliance is rated by the following criteria: **Yes:** Adapter is compliant with thermal warning/shutdown in J3400/1. **Partial:** Adapter partially complies with J3400/1 thermal warning/shutdown (e.g., signals an overtemperature state at proper temperature, but activates an incorrect proximity state). **No:** Adapter does not activate thermal warning/shutdown, or only activates after temperature limits have been exceeded.

Type	Adapter	Listed Current	Observed Max. Steady-State Current	Thermal Warning Compliance	Thermal Shutdown Compliance
NACS-CCS	BB	Not listed	350 A	Yes; compliant thermal warning at pin temp. = 86.7°C (400 A)	No; activates thermal shutdown after pin temp. >100°C (activated at 105.2°C)
NACS-CCS	CC	500 A	400 A	Yes; compliant thermal warning at pin temp. = 94.6°C (450 A)	No; never activated thermal shutdown (pin temp. >130°C, internal temp. >110°C)
CCS-Tesla Legacy	DD	400 A	250 A	No; never activates thermal warning	No; never activates thermal shutdown (internal temp. >119°C at 300 A)
CCS-Tesla Legacy	EE	500 A [a]	400 A	Partial; only exits "Connector Inserted" state; does not activate thermal warning or "J1772 Unlatched" state	Partial; only exits "Connector Inserted" state; does not activate thermal warning or "J1772 Unlatched" state
CCS-Tesla Legacy	FF	500 A [a]	300 A	Partial; very small proximity voltage step change at "warning" level—still within "Connector Inserted" state	Partial; thermal shutdown activates "Disconnected" state (not allowed due to negating vehicle immobilization)

[a] Adapter EE/FF 500-A "listed current" is based on given voltage/power ratings of 500 V/250 kW (no explicit current rating given).

It should be noted that no adapters were fully compliant with the SAE J3400 thermal warning/shutdown protocol, though most evaluated adapters did activate some sort of thermal warning system (though that thermal warning system may have activated at an incorrect temperature level or set an improper proximity state). Adapter DD never activated any sort of thermal warning or shutdown signal at all. An identical version of Adapter DD had been cut open for internal analysis as part of prior failure mode and effects analysis.[1] Visual inspection of this adapter confirmed that the temperature sensors had been installed on the control pilot (CP) line, not the proximity pilot (PP) line as was the case in all other evaluated adapters. A subsequent evaluation performed on Adapter DD, with the control pilot line monitored, also showed no noticeable thermal sensor activation, even when internal temperatures exceeded 100°C.

4.3.4.2 UL 2252 Conformance

We also evaluated adapters for their adherence to the UL 2252 temperature limits. UL 2252, Table 35.1, lists a maximum acceptable contact temperature of 90°C, along with other temperature limits for wiring terminals, internal wiring, and the temperature at the cable entry to the connector body. For the purposes of this evaluation, we primarily examined the adapters with regard to their contact temperature. The temperature sensors within the reference devices' DC pins (TP1+/TP1−, placed at the point of mating between the reference inlet and the adapter), served as the point of measurement of the adapters' contact temperatures.

In addition to contact temperature, we also evaluated the adapters in regard to their compliance with UL 2252's maximum surface temperatures. UL 2252, Table 35.3, lists a maximum acceptable surface temperature of 60°C for "handles, knobs, or surfaces that are grasped for lifting, carrying, or holding," with a note that for adapters carried by hand, the entire adapter body is considered to be a surface grasped for lifting, carrying, or holding. These limits cannot be exceeded when the device is carrying its maximum rated current. Table 31 summarizes the adapters' UL 2252 temperature limit compliance.

[1] Andrew Meintz, Marco Gaxiola, Vivek Singh, Isaac Tolbert, Saroj Shinde, and Kristi Moriarty. 2024. *Recommended Actions to Improve Adapter Safety*. ChargeX Consortium. DOE/GO-102024-6398. driveelectric.gov/files/adapter-safety.pdf.

Table 31. Adapter UL 2252 Temperature Limit Compliance

Type	Adapter	Listed Current	Observed Max. Steady-State Current	UL 2252 Pin Temp. Limit Compliance (90°C limit)	Touch Temp. at Observed Max. Steady-State Current	UL 2252 Touch Temp. Limit Compliance (60°C limit)
NACS-CCS	BB	Not listed	350 A	No; no listed current given; pin temp. = 81.2°C at 350 A; 92.6°C at 400 A	58.5°C	Yes
NACS-CCS	CC	500 A	400 A	No; pin temp. = 116.4°C at 500 A	51.6°C	Yes
CCS-Tesla legacy	DD	400 A	250 A	No; pin temp. = ~93°C at 300 A	74.1°C	No
CCS-Tesla legacy	EE	500 A [a]	400 A	No; pin temp. = ~91°C at 400 A	78.5°C	No
CCS-Tesla legacy	FF	500 A [a]	300 A	No; pin temp. >95°C at 400 A	58.9°C	Yes

[a] Adapter EE/FF 500-A "listed current" is based on given voltage/power ratings of 500 V/250 kW (no explicit current rating given).

As shown in Figure 14 and Figure 15, we recorded the surface temperature of the adapter from both the top and bottom surfaces. Table 32 presents the surface temperatures for steady-state current. According to UL 2252, the maximum surface temperature for nonmetallic parts is 60°C. However, as indicated in Table 32, some top touch surface temperatures exceeded 60°C.

Table 32. Adapter Touch Temperature at Steady-State Current

Type	Adapter	Max. Steady-State Current	Adapter Surface Temperature at Max. Steady-State Current (°C)		Current at Thermal Warning Activation	Adapter Surace Temperature at Thermal Warning Activation (°C)	
			Top Touch Temp.	Bottom Touch Temp.		Top Touch Temp.	Bottom Touch Temp.
NACS-CCS	BB	350 A	48.4	58.5	400 A	49.5	60.9
NACS-CCS	CC	400 A	50.9	51.6	450 A	50.8	51.8
CCS-Tesla legacy	DD	250 A	74.1	50.9	No thermal warning	--	--
CCS-Tesla legacy	EE	400 A	78.5	50.6	450 A	79.1	50.8
CCS-Tesla legacy	FF	300 A	58.9	48.4	350 A	78.1	53.8

5 Conclusion

This work demonstrates the performance of a range of CCS and NACS EV charging connectors and inlets, evaluates a new reference device design for CCS and NACS charging connectors in the 500–800-A range, and assesses the thermal performance and thermal warning characteristics of several EV charging adapters.

Overall, it was seen that experimental performance of the 500A and 600A reference devices matched the simulated results, and schematics for fabrication of these devices is provided in Appendix B (for NACS reference devices) and Appendix C (for CCS reference devices). Additionally, this project demonstrated that the reference devices were able to perform the thermal sensitivity evaluation described in IEC TS 62196-3-1.

Of the five DC EV charging adapters evaluated in this work, none were found to be fully compliant with the SAE J3400/1 thermal warning/shutdown signaling scheme or the temperature limits described in UL 2252. While this may be understandable, as the adapters evaluated in this work were all released before the publication of J3400/1 and UL 2252, this demonstrates the necessity of the defined overtemperature warning schemes and temperature limits laid out in these standards. As shown in Table 30, the adapters varied widely in their ability to appropriately signal thermal warning or shutdown. While some adapters activated the correct thermal warning communications state at the correct limit, no adapters activated the thermal shutdown state completely correctly, and several adapters activated neither the thermal warning nor shutdown states completely correctly as indicated in J3400 (with one adapter never activating any kind of thermal warning/shutdown signal at all). Additionally, no adapters were compliant with the UL 2252 temperature limits at their manufacturer-listed current, and would therefore require accurate thermal control signaling. While most of the adapters could maintain their manufacturer-listed current for several minutes, none could hold the listed current at steady state while remaining under temperature limits, and several exceeded safe touch temperature limits, as shown in Table 31, and Table 32.

Appendix A. Adapter Thermal Evaluation Plots

A.1 Adapter FF (CCS-Tesla Legacy) Temperature vs. Proximity State

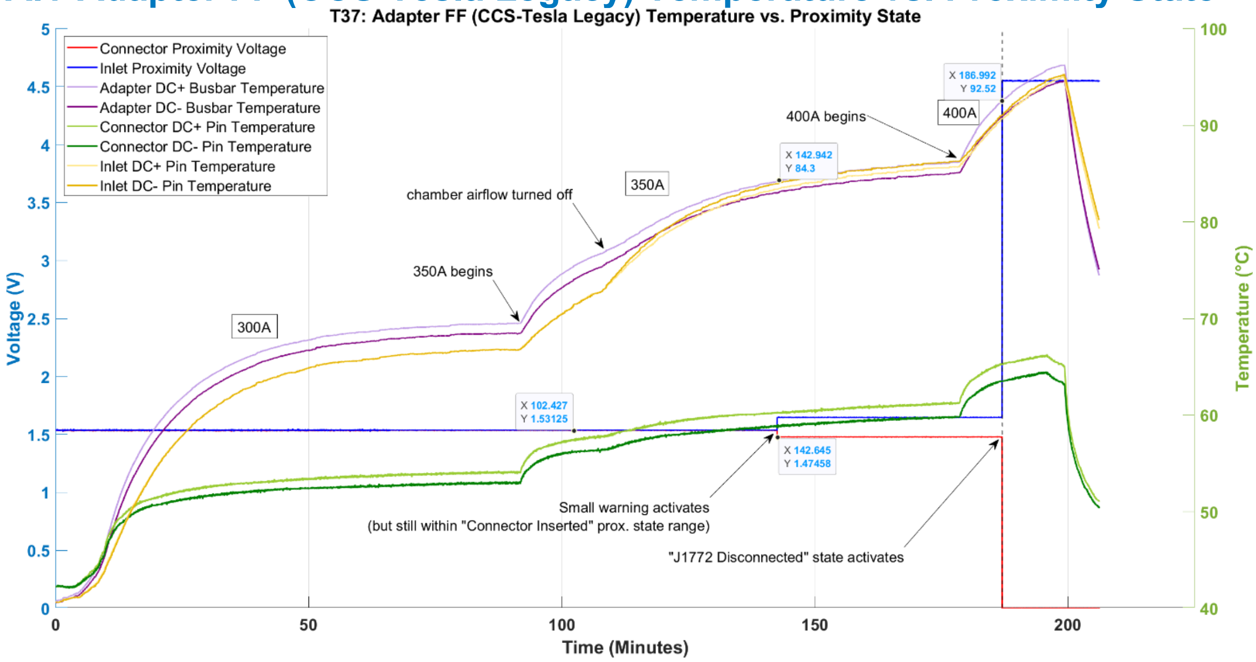


Figure A-1. Adapter FF (CCS-Tesla Legacy) temperature vs. proximity state

During evaluation, we found that CCS-Tesla Legacy Adapter FF began to activate a thermal warning system when internal adapter busbar temperatures were around 84°C, at 350 A. However, this initial warning signal changed the connector proximity sense signal by only around 0.06 V (from 1.53 to 1.47 V), which is still within the 1.3–1.74-V “Connector Inserted” proximity state range. After increasing the current to 400 A, busbar temperatures rose to 92.5°C, at which point the adapter triggered the “Disconnected” proximity state.

A.2 Adapter EE (CCS-Tesla Legacy) Temperature vs. Proximity State

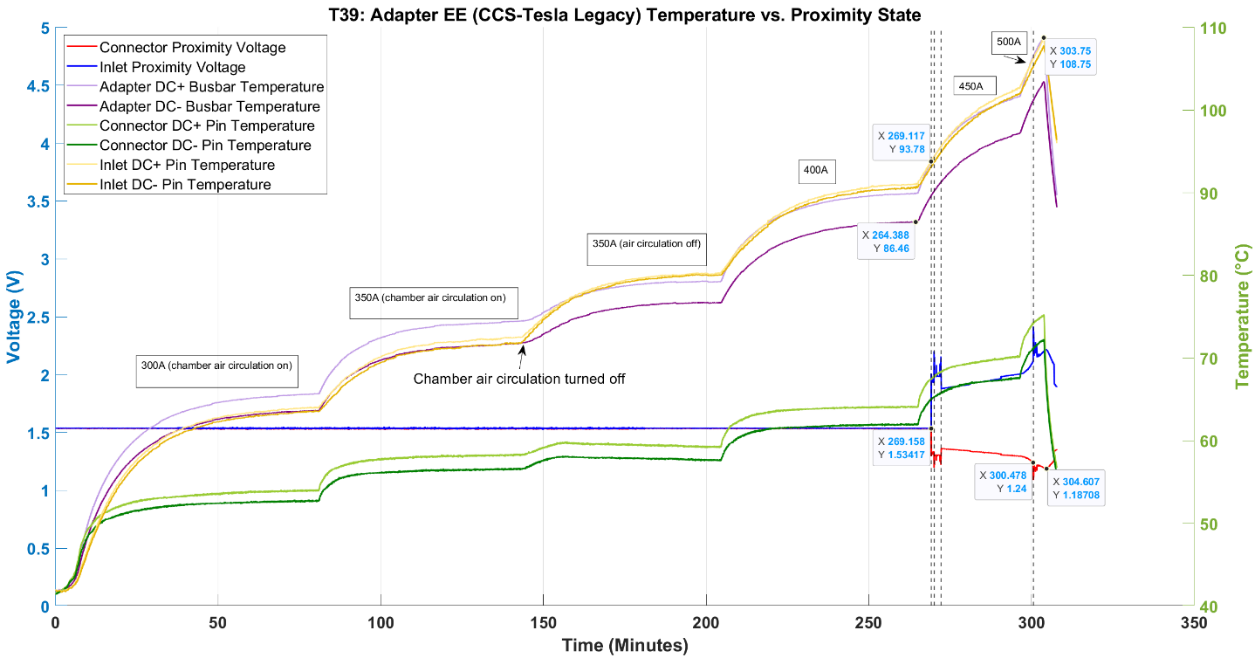


Figure A-2. Adapter EE (CCS-Tesla Legacy) temperature vs. proximity state

Adapter EE activated a thermal sensing circuit at an internal temperature of 93.8°C, increasing the inlet-sensed proximity voltage 1.88 V (out of the "Connector Inserted" range), dropping the connector-sensed proximity voltage to 1.36 V, and then gradually reducing the connector-sensed proximity voltage as temperatures continued to increase. The connector-sensed proximity voltage dropped to 1.3 V (the low range of the "Connector Inserted" state) when internal temperatures reached approximately 101°C, and reached a minimum of 1.19 V at the end of the test, when temperatures had reached approximately 109°C, as seen in Figure A-2. Though this adapter did signal an overtemperature event, it is not clear how this signal would be interpreted by a J1772 EV or EVSE. The EVSE-sensed proximity signal only reached the bottom end of the "Connector Inserted" state when temperatures had already exceeded 100°C, and even when temperatures continued climbing, the connector-sensed proximity voltage just continued to drop, without entering the "Disconnected" state. The EV-sensed proximity signal exited the "Connector Inserted" state immediately upon activation at 93.8°C, but it did not go to any specific proximity state.

A.3 Adapter DD (CCS-Tesla Legacy) Temperature vs. Proximity State

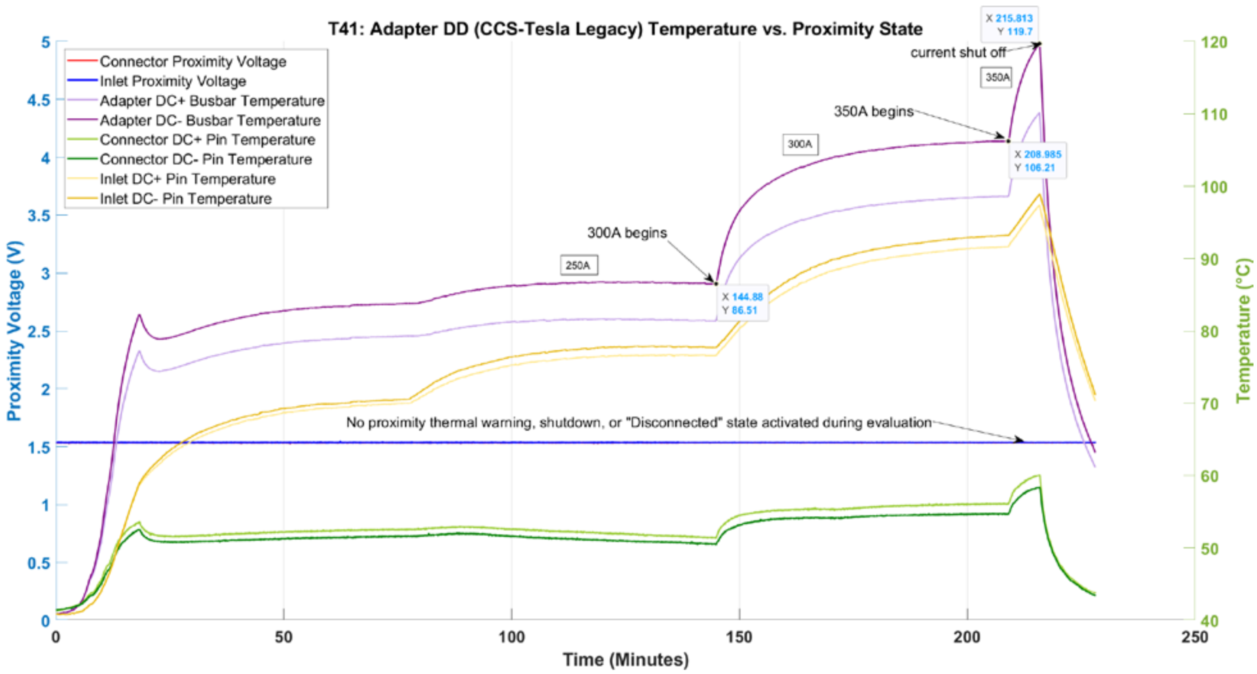


Figure A-3. Adapter DD (CCS-Tesla Legacy) temperature vs. proximity state

We observed that on CCS-Tesla Legacy Adapter DD, there was no proximity state change at all during the evaluation, even when internal temperatures exceeded 110°C (with a peak temperature of 119.7°C recorded). As shown in Figure A-3, throughout the evaluation, the adapter held a constant 1.53-V proximity signal, with no changes detected. This was of particular concern to the evaluation team, as these temperatures occurred at a much lower current compared to the other CCS-Tesla Legacy adapters under test. The other adapters held temperatures of roughly 79°C–86°C at 350 A, compared to Adapter DD managing to hold an internal steady-state temperature of 106.2°C at only 300 A, and exceeding 119°C only 7 minutes after increasing the current from 300 to 350 A. Even at 250 A, the maximum steady-state temperature inside the adapter was 86.5°C, very near the point at which the other adapters began activating their thermal warning systems. This shows a very low steady-state current capability of this adapter.

An identical version of Adapter DD had been cut open for internal analysis as part of prior failure mode and effects analysis.[2] Visual inspection of this adapter confirmed that the temperature sensors had been installed on the control pilot line, not the proximity pilot line as was the case in all other evaluated adapters. A subsequent evaluation performed on Adapter DD, with the control pilot line monitored, also showed no noticeable thermal sensor activation, even when internal temperatures exceeded 100°C.

[2] Meintz et al. 2024. *Recommended Actions to Improve Adapter Safety*.

A.4 Adapter BB (NACS-CCS) Temperature vs. Proximity State

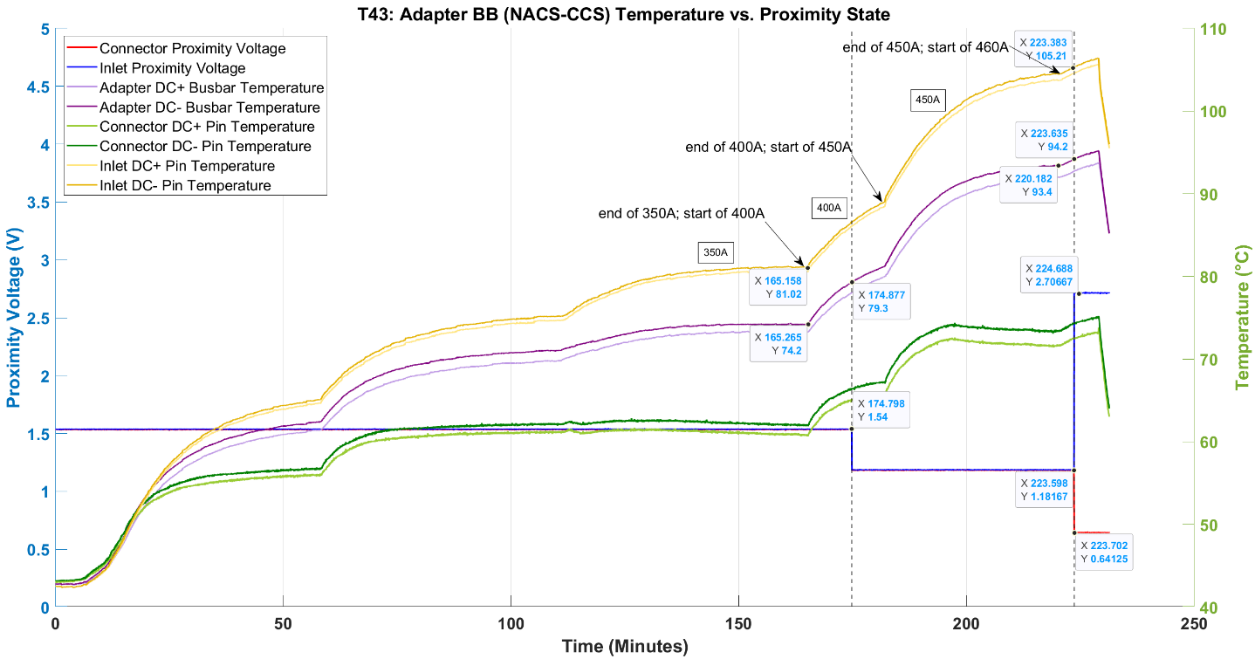


Figure A-4. Adapter BB (NACS-CCS) temperature vs. proximity state

Adapter BB was able to maintain a maximum current of 350 A at 40°C without activating thermal warning. After increasing the current to 400 A, we observed that the SAE J3400 DC thermal warning state was activated when the internal temperature reached 79.3°C, and the DC thermal shutdown state activated when the internal temperature reached 94.2°C at 460 A.

A.5 Adapter CC (NACS-CCS) Temperature vs. Proximity State

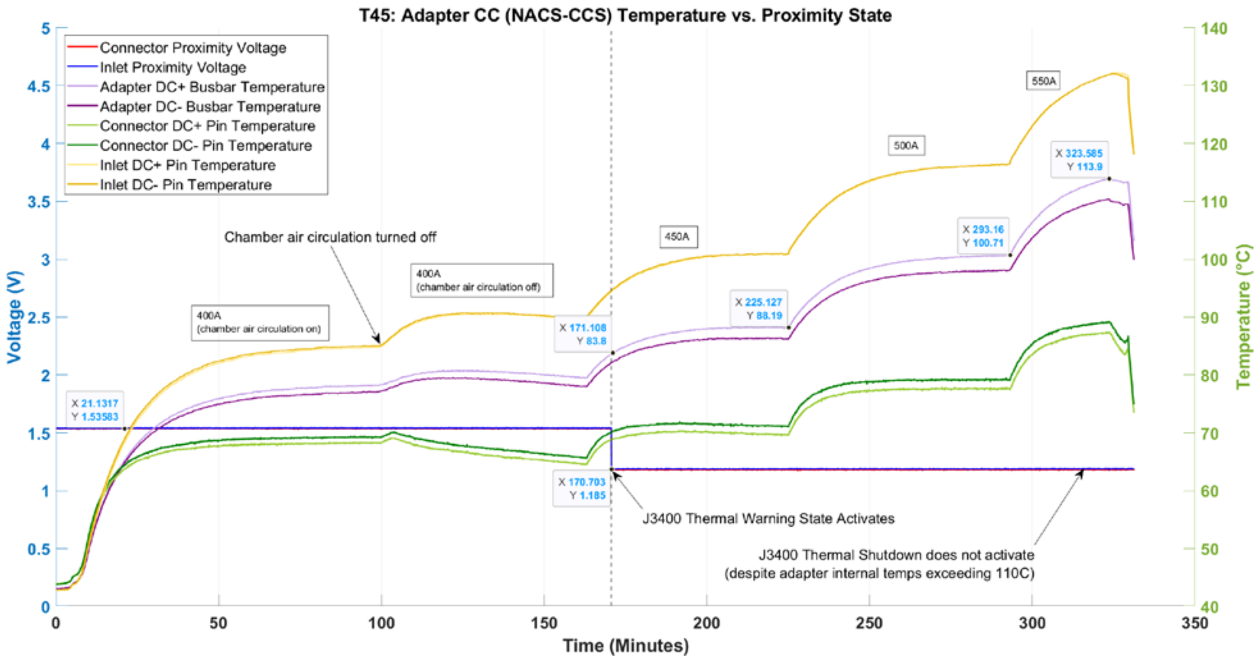
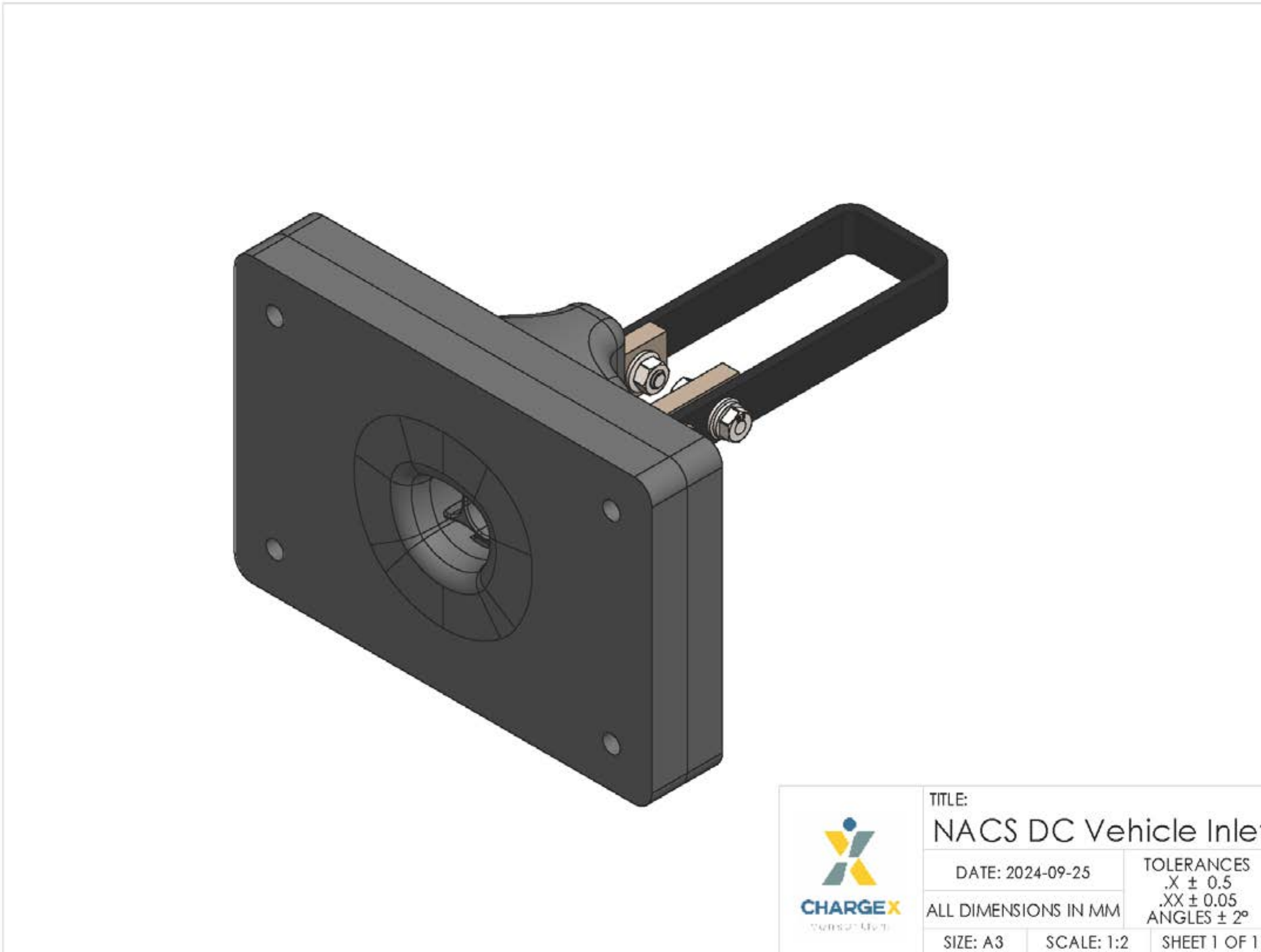
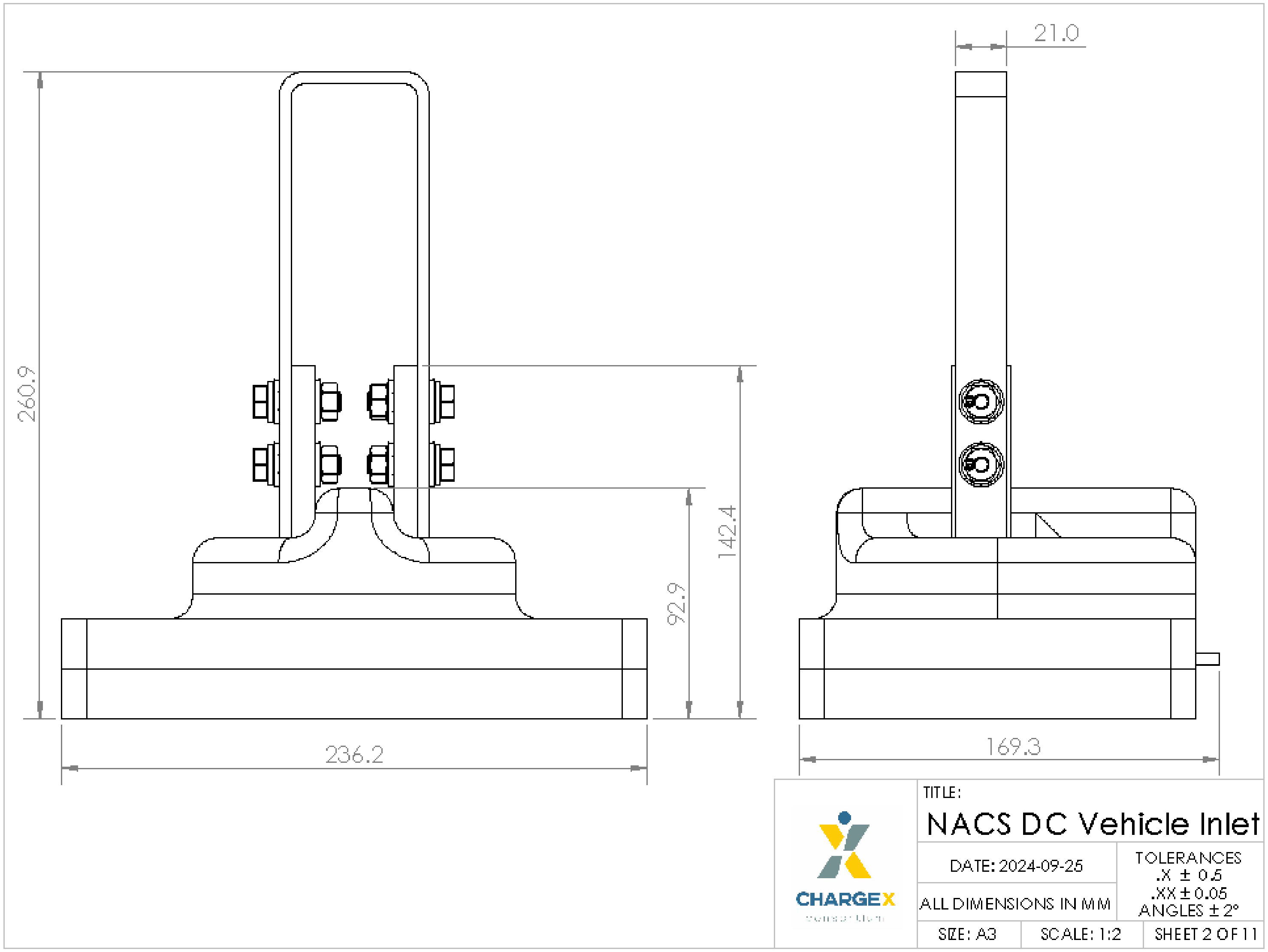


Figure A-5. Adapter CC (NACS-CCS) temperature vs. proximity state

Adapter CC activated the DC thermal warning state at a temperature of 83.8°C, but notably never activated a DC thermal shutdown proximity state. Figure A-5 demonstrates that thermal warning was triggered shortly after increasing current from 400 to 450 A, but thermal shutdown never activated, even when internal temperatures reached 100.7°C at 500 A and peaked at 113.9°C shortly after increasing current to 550 A (at which point the evaluation was terminated by the operator due to overtemperature condition).

Appendix B. NACS Reference Inlet Drawings

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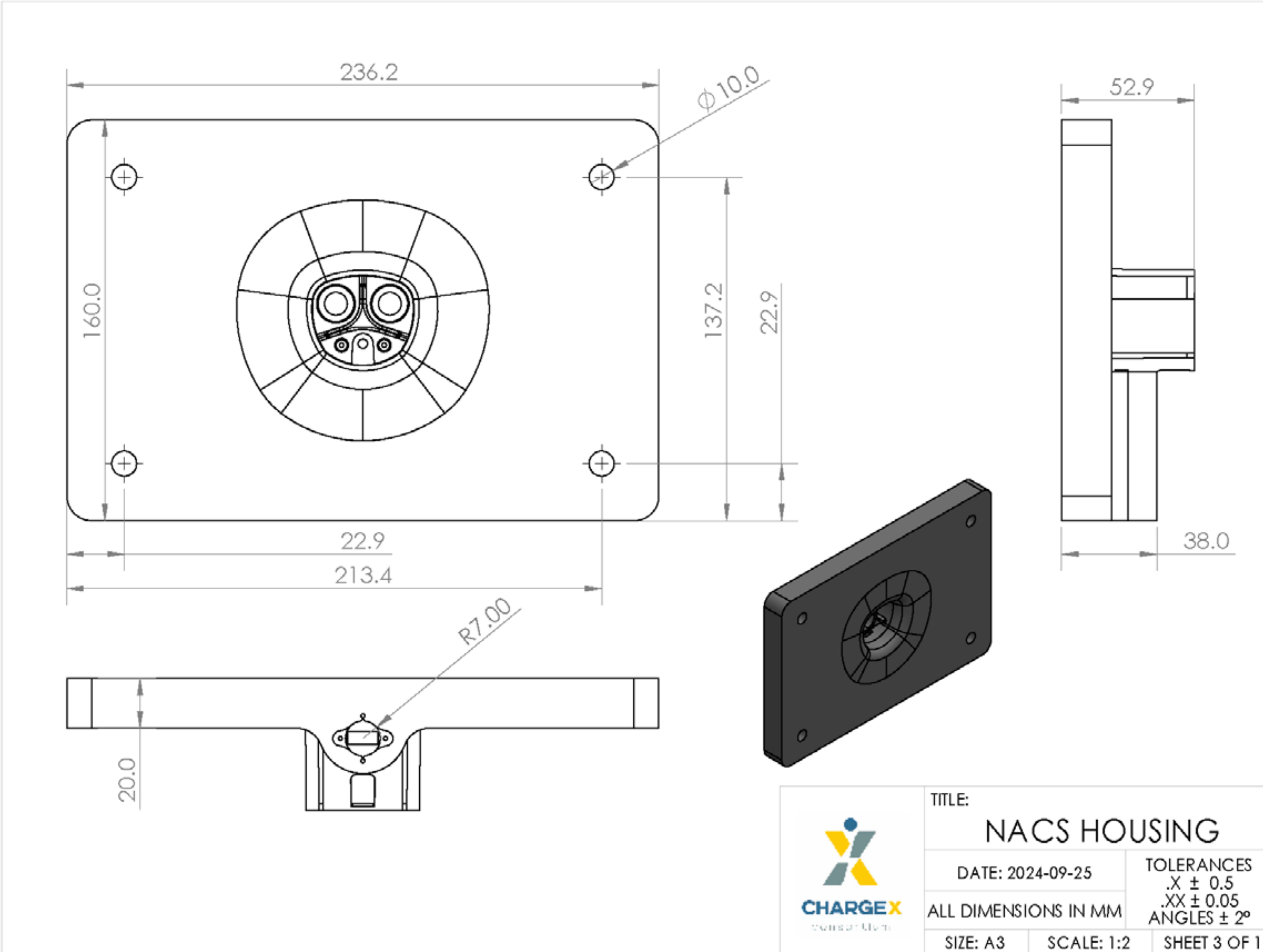
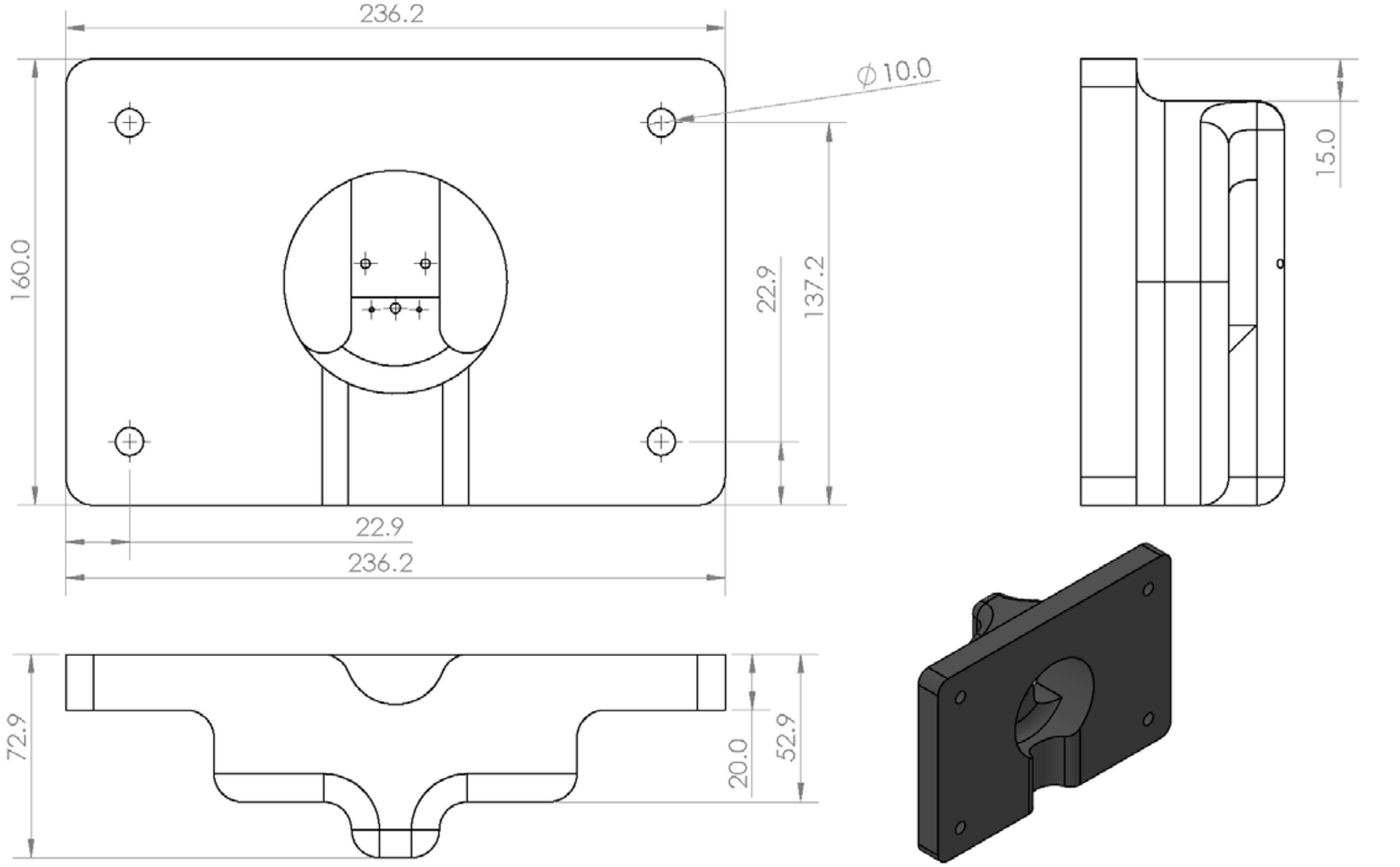
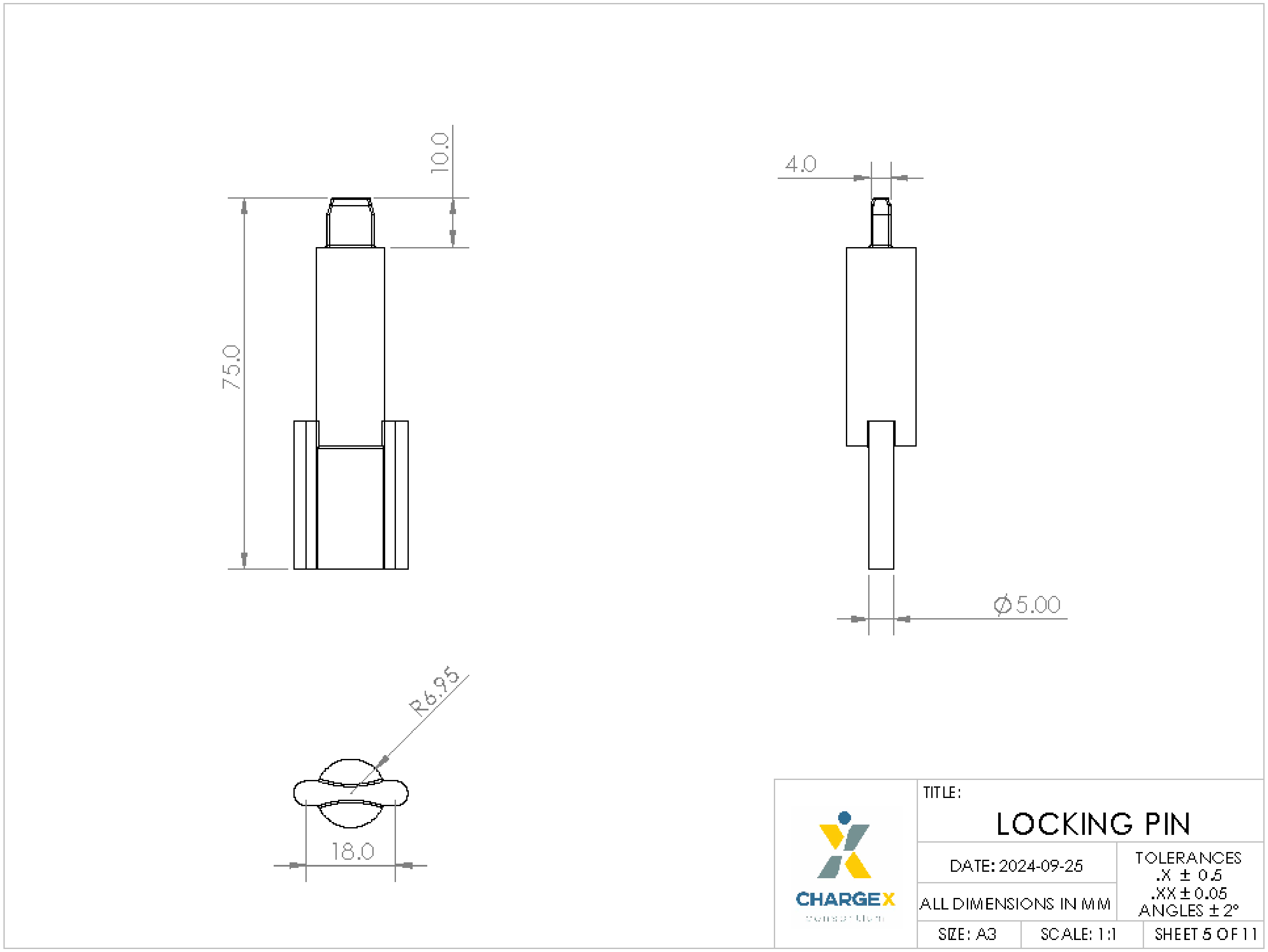
260.9
142.4
92.9
236.2
169.3
TITLE:
NACS DC Vehicle Inlet
DATE: 2024-09-25
ALL DIMENSIONS IN MM
TOLERANCES
.X ± 0.5
.XX ± 0.05
ANGLES ± 2°
SIZE: A3
SCALE: 1:2
SHEET 2 OF 11

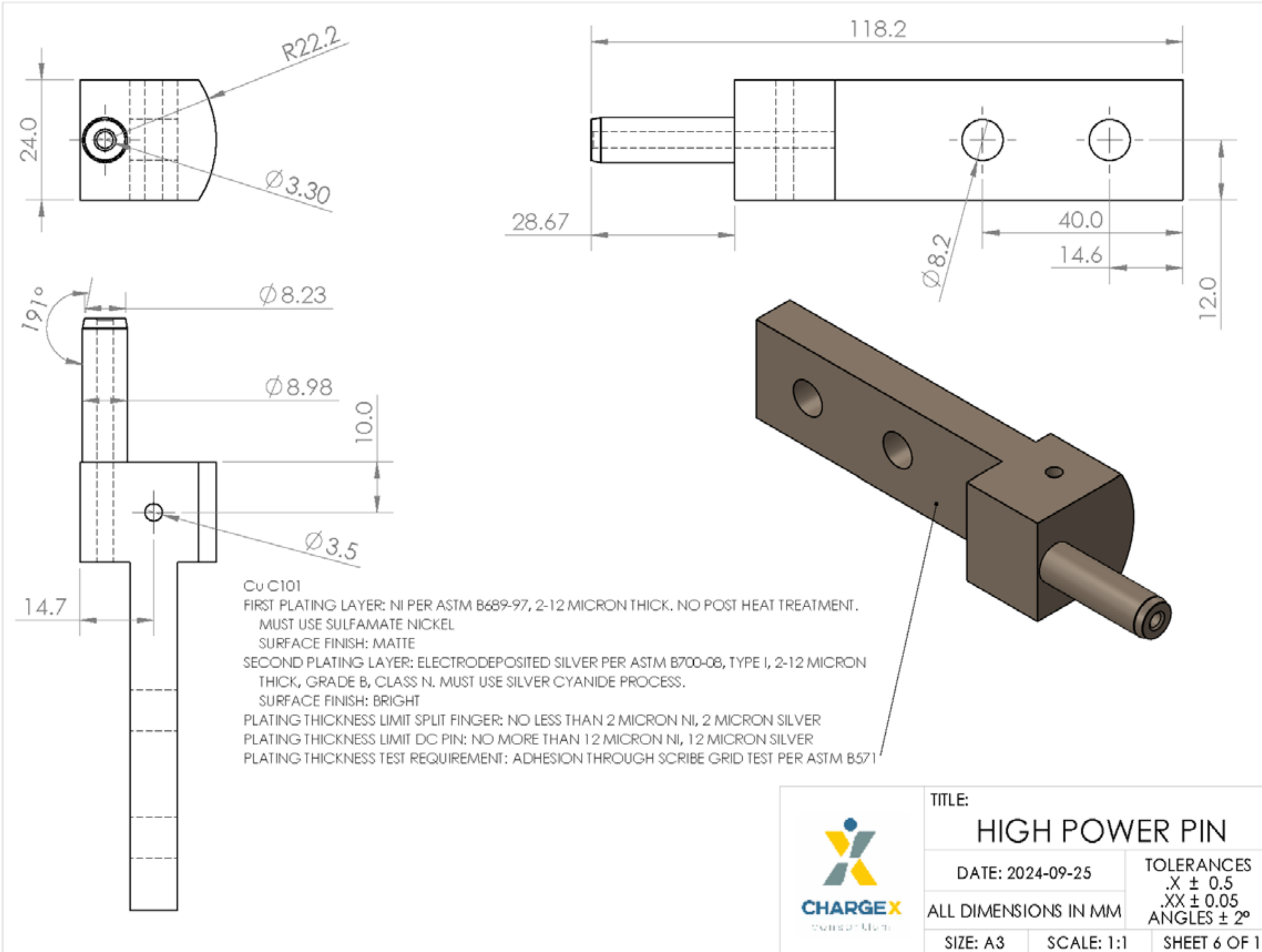

236.2
ϕ10.0
52.9
160.0
137.2
22.9
22.9
213.4
38.0
R7.00
20.0
TITLE:
NACS HOUSING
DATE: 2024-09-25
ALL DIMENSIONS IN MM
TOLERANCES
.X ± 0.5
.XX ± 0.05
ANGLES ± 2º
SIZE: A3
SCALE: 1:2
SHEET 3 OF 11

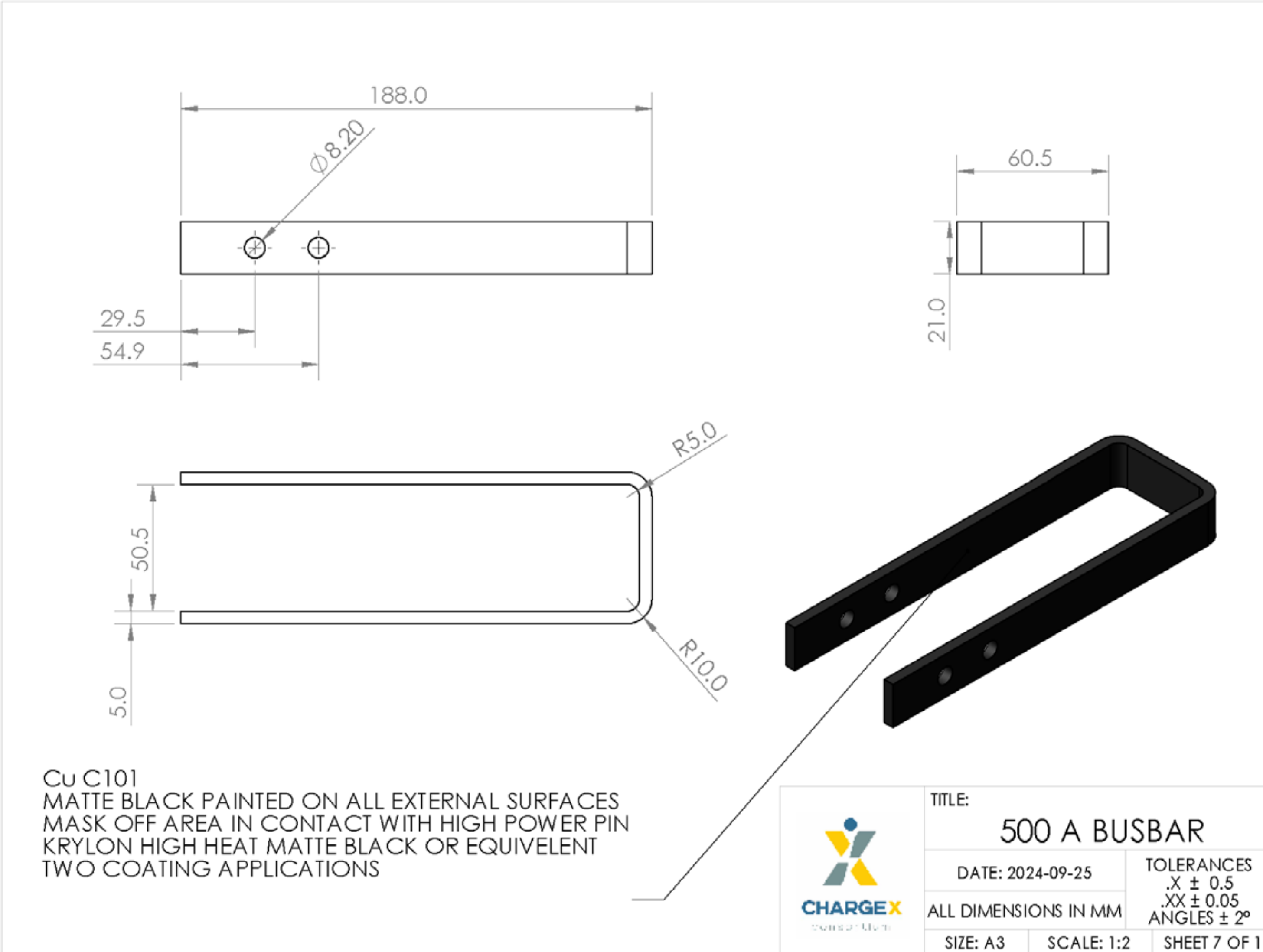


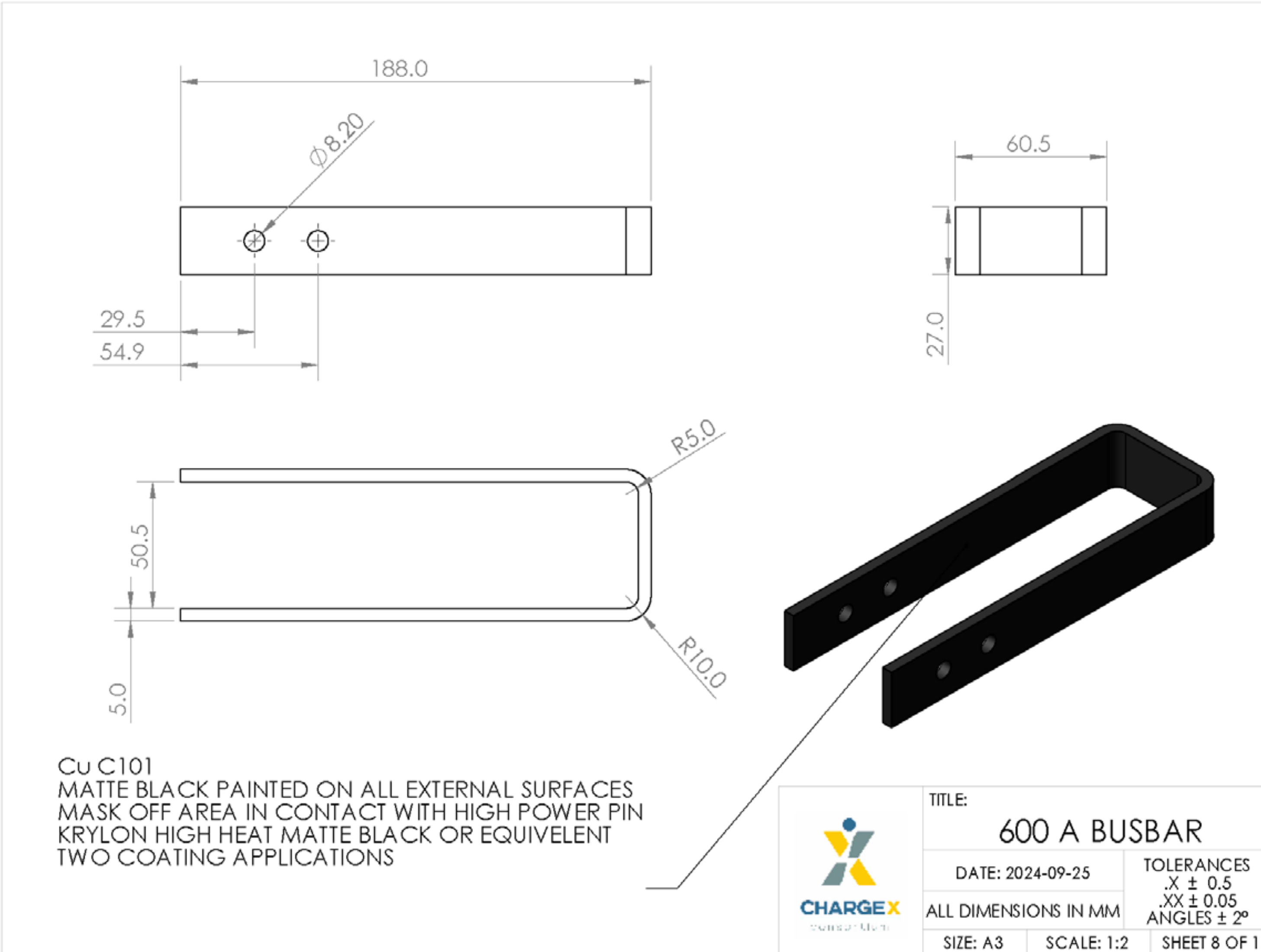
TITLE: PINS SUPPORT PLATE		
DATE: 2024-09-25	TOLERANCES .X ± 0.5 .XX ± 0.05 ANGLES ± 2º	
ALL DIMENSIONS IN MM		
SIZE: A3	SCALE: 1:2	SHEET 4 OF 11

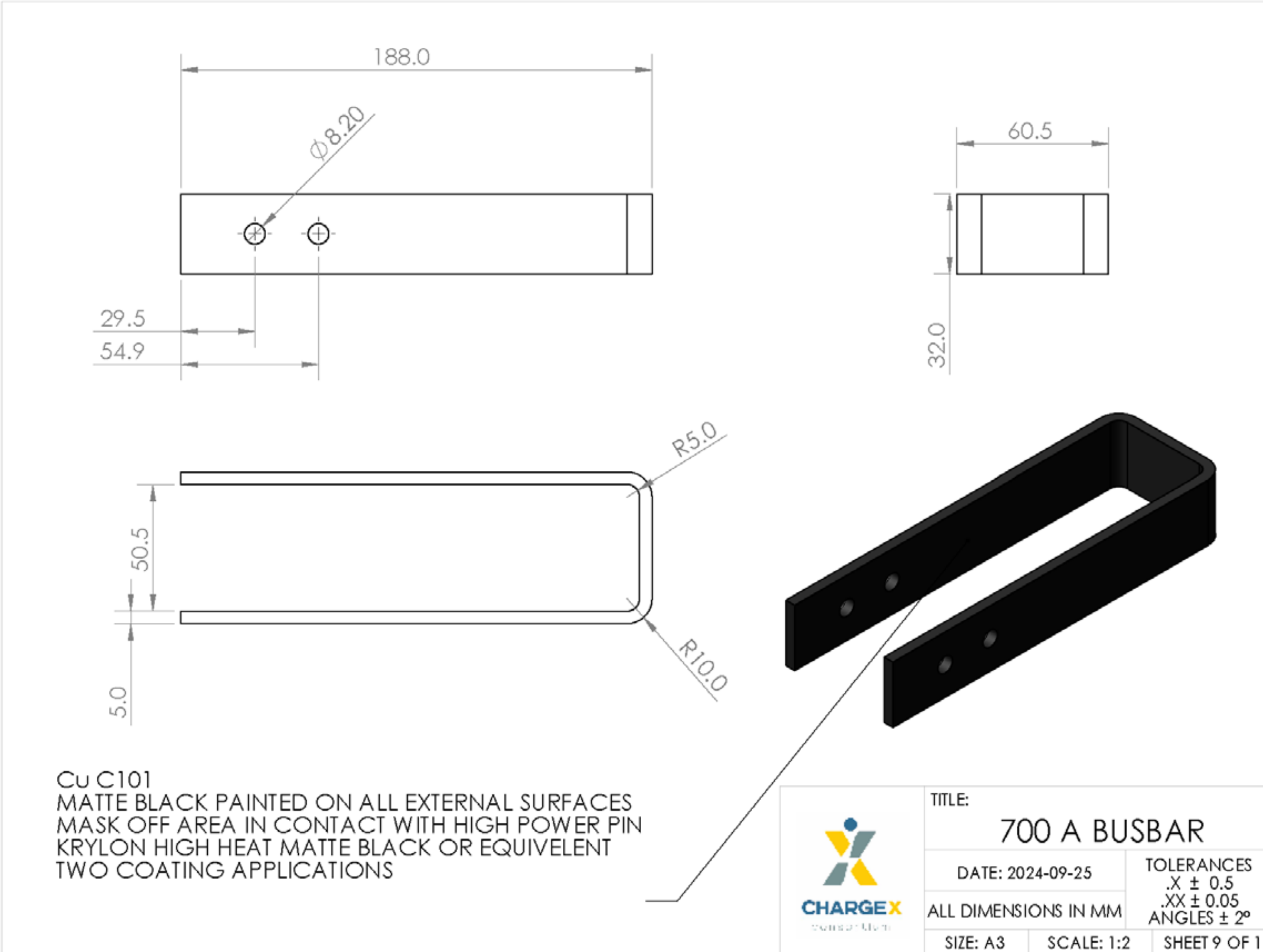


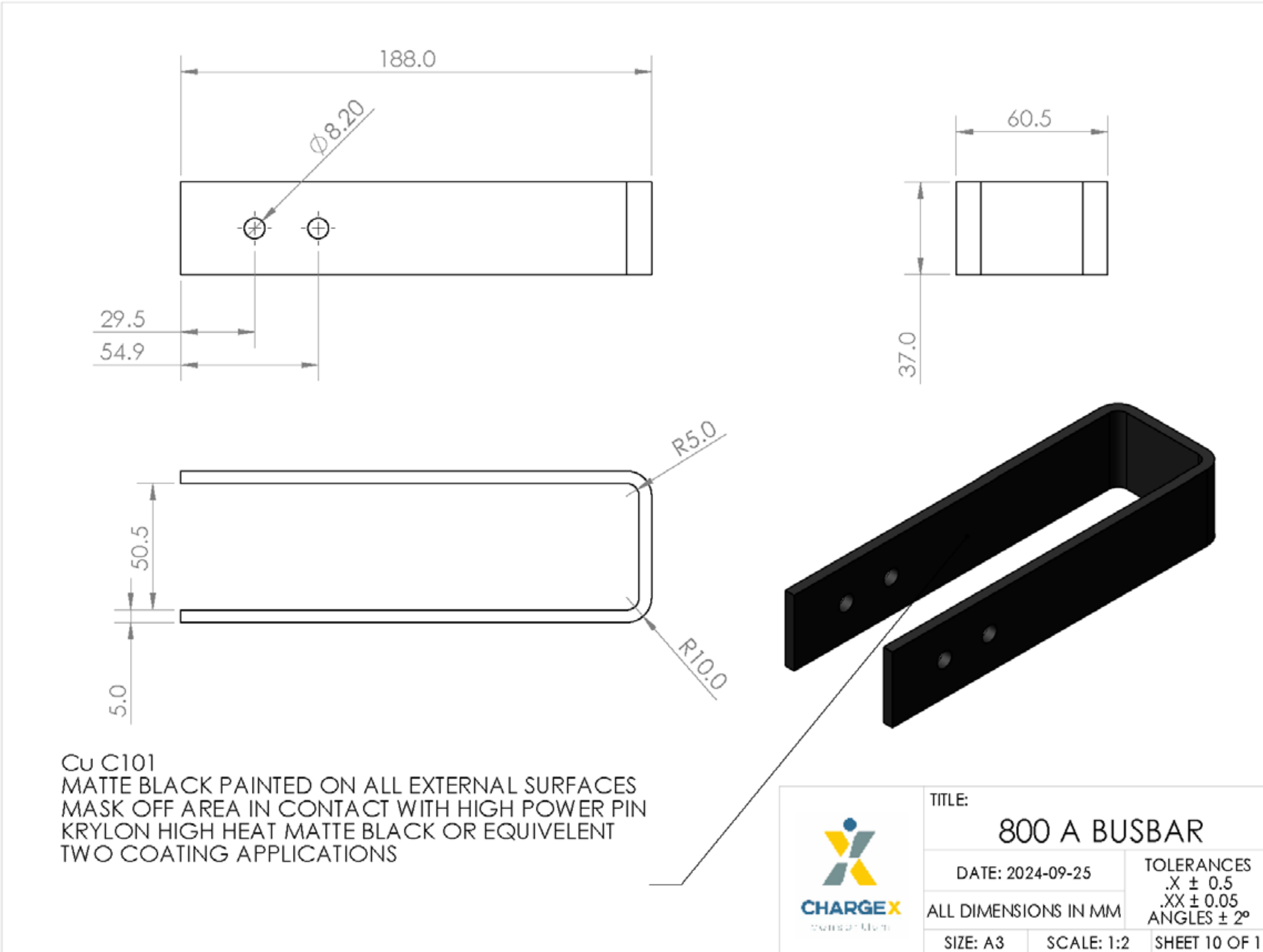
10.0
75.0
4.0
Ø5.00
R6.95
18.0
TITLE:
LOCKING PIN
DATE: 2024-09-25
ALL DIMENSIONS IN MM
TOLERANCES
.X ± 0.5
.XX ± 0.05
ANGLES ± 2°
SIZE: A3
SCALE: 1:1
SHEET 5 OF 11
CHARGEX


R22.2
24.0
∅3.30
118.2
28.67
∅8.2
40.0
14.6
12.0
191°
∅8.23
∅8.98
10.0
∅3.5
14.7
Cu C101
FIRST PLATING LAYER: NI PER ASTM B689-97, 2-12 MICRON THICK. NO POST HEAT TREATMENT.
MUST USE SULFAMATE NICKEL
SURFACE FINISH: MATTE
SECOND PLATING LAYER: ELECTRODEPOSITED SILVER PER ASTM B700-08, TYPE I, 2-12 MICRON
THICK, GRADE B, CLASS N. MUST USE SILVER CYANIDE PROCESS.
SURFACE FINISH: BRIGHT
PLATING THICKNESS LIMIT SPLIT FINGER: NO LESS THAN 2 MICRON NI, 2 MICRON SILVER
PLATING THICKNESS LIMIT DC PIN: NO MORE THAN 12 MICRON NI, 12 MICRON SILVER
PLATING THICKNESS TEST REQUIREMENT: ADHESION THROUGH SCRIBE GRID TEST PER ASTM B571
CHARGEX
TITLE:
HIGH POWER PIN
DATE: 2024-09-25
ALL DIMENSIONS IN MM
TOLERANCES
.X ± 0.5
.XX ± 0.05
ANGLES ± 2°
SIZE: A3
SCALE: 1:1
SHEET 6 OF 11


188.0
⌀8.20
60.5
29.5
54.9
21.0
R5.0
50.5
5.0
R10.0
Cu C101
MATTE BLACK PAINTED ON ALL EXTERNAL SURFACES
MASK OFF AREA IN CONTACT WITH HIGH POWER PIN
KRYLON HIGH HEAT MATTE BLACK OR EQUIVELENT
TWO COATING APPLICATIONS
CHARGEX
TITLE:
500 A BUSBAR
DATE: 2024-09-25
ALL DIMENSIONS IN MM
TOLERANCES
.X ± 0.5
.XX ± 0.05
ANGLES ± 2°
SIZE: A3
SCALE: 1:2
SHEET 7 OF 11


188.0
⌀8.20
60.5
29.5
54.9
27.0
R5.0
50.5
5.0
R10.0
Cu C101
MATTE BLACK PAINTED ON ALL EXTERNAL SURFACES
MASK OFF AREA IN CONTACT WITH HIGH POWER PIN
KRYLON HIGH HEAT MATTE BLACK OR EQUIVELENT
TWO COATING APPLICATIONS
CHARGEX
TITLE:
600 A BUSBAR
DATE: 2024-09-25
ALL DIMENSIONS IN MM
TOLERANCES
.X ± 0.5
.XX ± 0.05
ANGLES ± 2º
SIZE: A3
SCALE: 1:2
SHEET 8 OF 11


188.0
⌀8.20
29.5
54.9
60.5
32.0
R5.0
50.5
5.0
R10.0
Cu C101
MATTE BLACK PAINTED ON ALL EXTERNAL SURFACES
MASK OFF AREA IN CONTACT WITH HIGH POWER PIN
KRYLON HIGH HEAT MATTE BLACK OR EQUIVELENT
TWO COATING APPLICATIONS
TITLE:
700 A BUSBAR
DATE: 2024-09-25
ALL DIMENSIONS IN MM
TOLERANCES
.X ± 0.5
.XX ± 0.05
ANGLES ± 2º
SIZE: A3
SCALE: 1:2
SHEET 9 OF 11


188.0
⌀8.20
29.5
54.9
60.5
37.0
R5.0
50.5
5.0
R10.0
Cu C101
MATTE BLACK PAINTED ON ALL EXTERNAL SURFACES
MASK OFF AREA IN CONTACT WITH HIGH POWER PIN
KRYLON HIGH HEAT MATTE BLACK OR EQUIVELENT
TWO COATING APPLICATIONS
TITLE:
800 A BUSBAR
DATE: 2024-09-25
ALL DIMENSIONS IN MM
TOLERANCES
.X ± 0.5
.XX ± 0.05
ANGLES ± 2º
SIZE: A3
SCALE: 1:2
SHEET 10 OF 11

Item	Description	Quantity	Material	Source	Part Number	Reference
1	Housing	1	PPS CF or Equivalent	3D Printed	NA	NA
2	Pins Support Plate	1	PPS CF or Equivalent	3D Printed	NA	NA
3	Locking Pin	1	PPS CF or Equivalent	3D Printed	NA	NA
4	High Power Pin	2	Cu 101, Ni/Ag Plating	Machined	NA	NA
5	500 A Busbar	1	Cu 101, Matte Black Paint	Machined	NA	NA
6	600 A Busbar	1	Cu 101, Matte Black Paint	Machined	NA	NA
7	700 A Busbar	1	Cu 101, Matte Black Paint	Machined	NA	NA
8	800 A Busbar	1	Cu 101, Matte Black Paint	Machined	NA	NA
9	Ground Pin	1	Cu 101, Ni/Ag Plating	Machined	NA	NA
10	Low Power Pin	2	Cu 101, Ni/Ag Plating	Machined	NA	NA
11	M8 x 1.25 mm Coarse Thread, 30 mm Long Hex Head Screw	4	Class 10.9 Stainless Steel	McMaster-Carr	91310A536	https://www.mcmaster.com/91310A536/
12	M8 Washer	4	18-8 Stainless Steel	McMaster-Carr	93475A270	https://www.mcmaster.com/93475A270/
13	M8 Spring Lock Washer	8	18-8 Stainless Steel	McMaster-Carr	91477A181	https://www.mcmaster.com/91477A181/
14	M8 x 1.25 mm Coarse Thread Hex Nut	4	18-8 Stainless Steel	McMaster-Carr	91828A410	https://www.mcmaster.com/91828A410/
15	M3.5 Washer	2	18-8 Stainless Steel	McMaster-Carr	93475A220	https://www.mcmaster.com/93475A220/
16	M1.6 Washer	6	18-8 Stainless Steel	McMaster-Carr	93475A190	https://www.mcmaster.com/93475A190/
17	No. 6 Screw Size Ring Terminal	1	Tin-Plated Cu, Nylon	McMaster-Carr	7113K265	https://www.mcmaster.com/7113K265/
18	No. 2 Screw Size Ring Terminal	2	Tin-Plated Cu, Nylon	McMaster-Carr	7113K263	https://www.mcmaster.com/7113K263/
19	1/16" Thick, 1/16" OD Neodymium Magnet	6	Nickel-Plated Neodymium	McMaster-Carr	5862K137	https://www.mcmaster.com/5862K137/
20	Watlow 1/8" D, 1" L, 24 V, 5 W Firerod Cartridge Heater	2	Inconel 600, MgO	Therm-X	C1A-9600	https://www.therm-x.com/watlow-1-8-diameter-cartridge-heaters.html
21	Adhesive Type K Thermocouple	3	Chromel +/ Alumel −, Polyimide	McMaster-Carr	3648K34	https://www.mcmaster.com/3648K34/
22	1/8" D Probe Type K Thermocouple	2	Chromel +/ Alumel −, SS	McMaster-Carr	3857K212	https://www.mcmaster.com/3857K212/

TITLE:

Bill of Materials

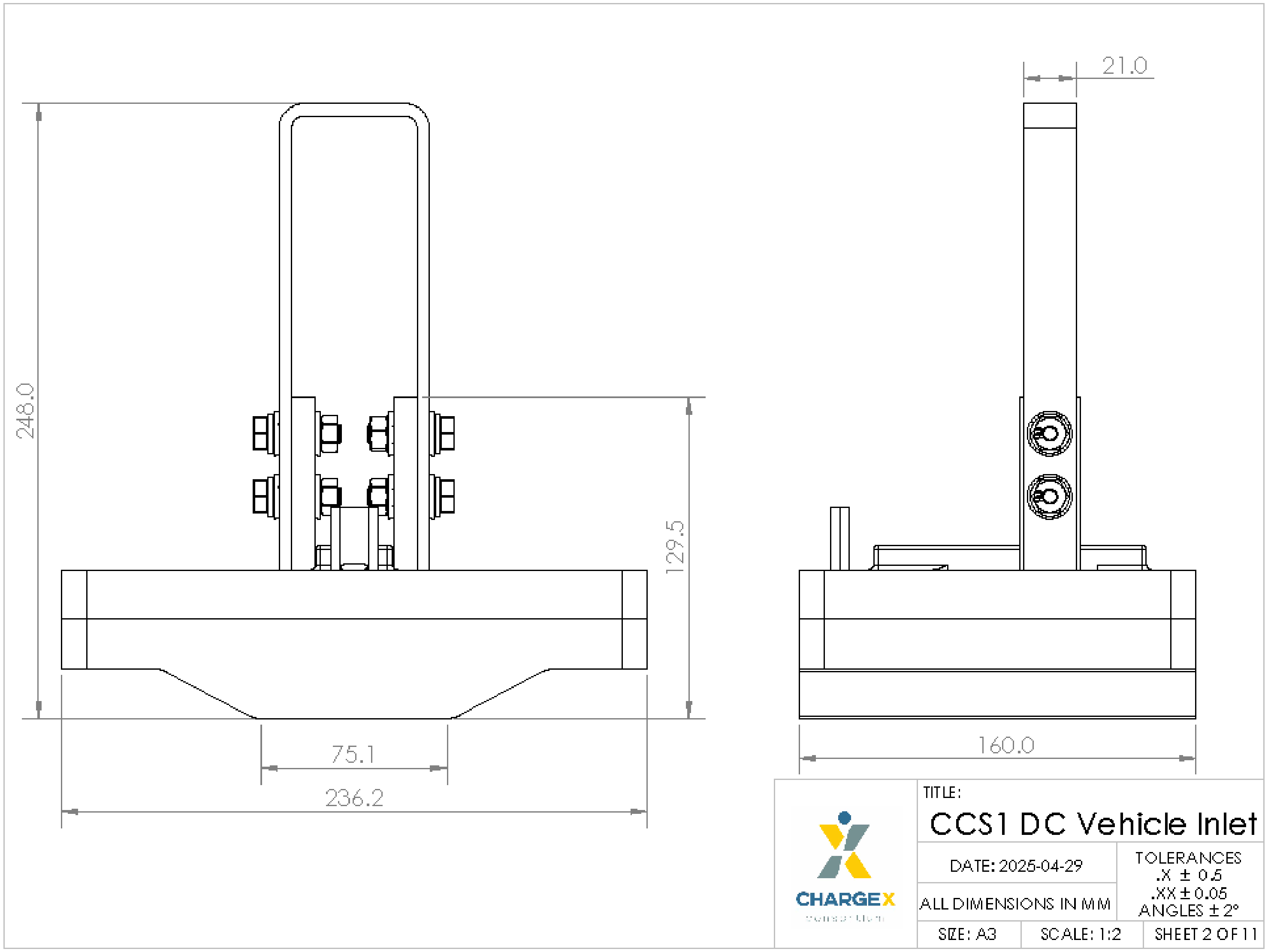
DATE: 2024-09-25

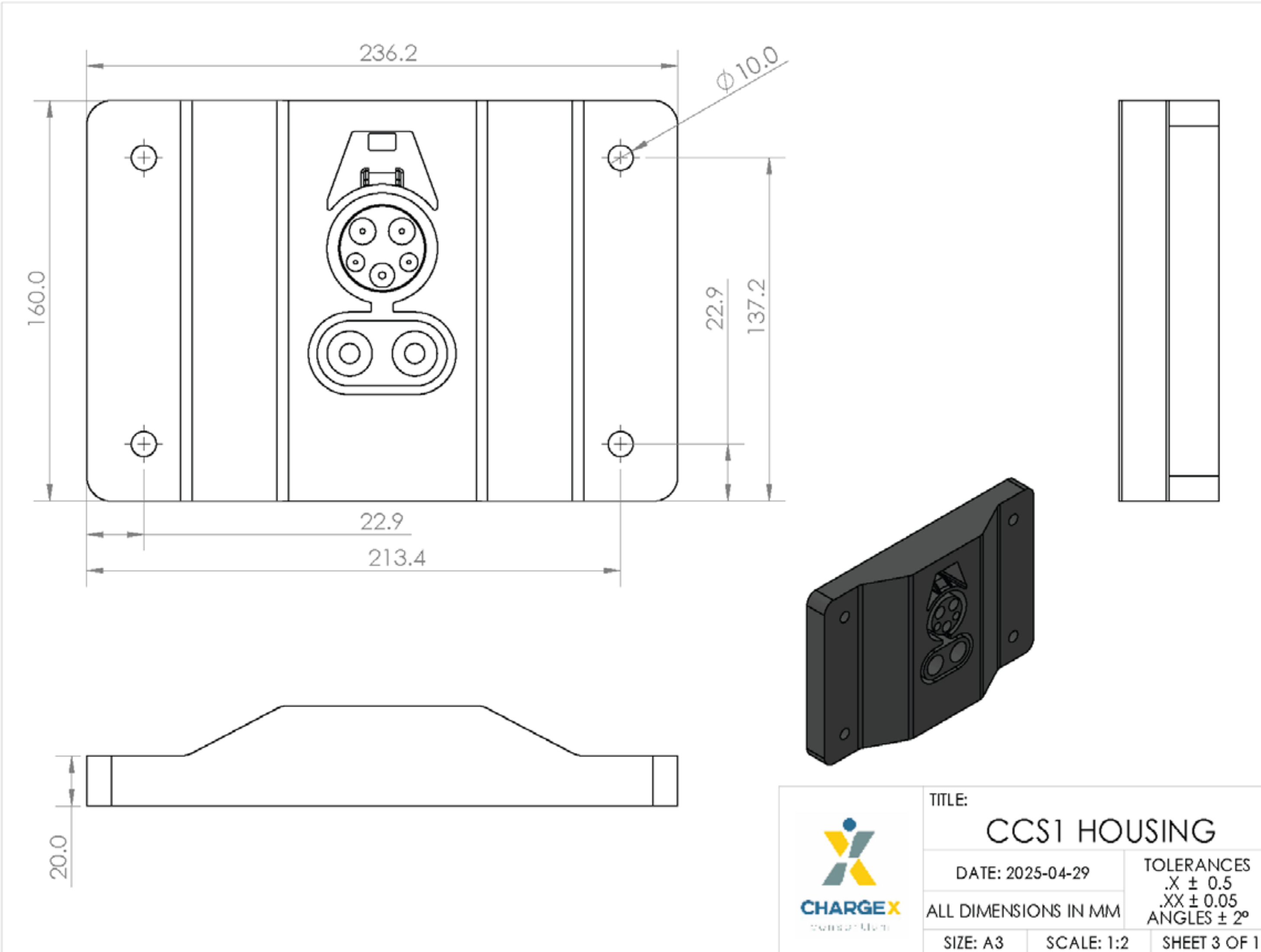
ALL DIMENSIONS IN MM

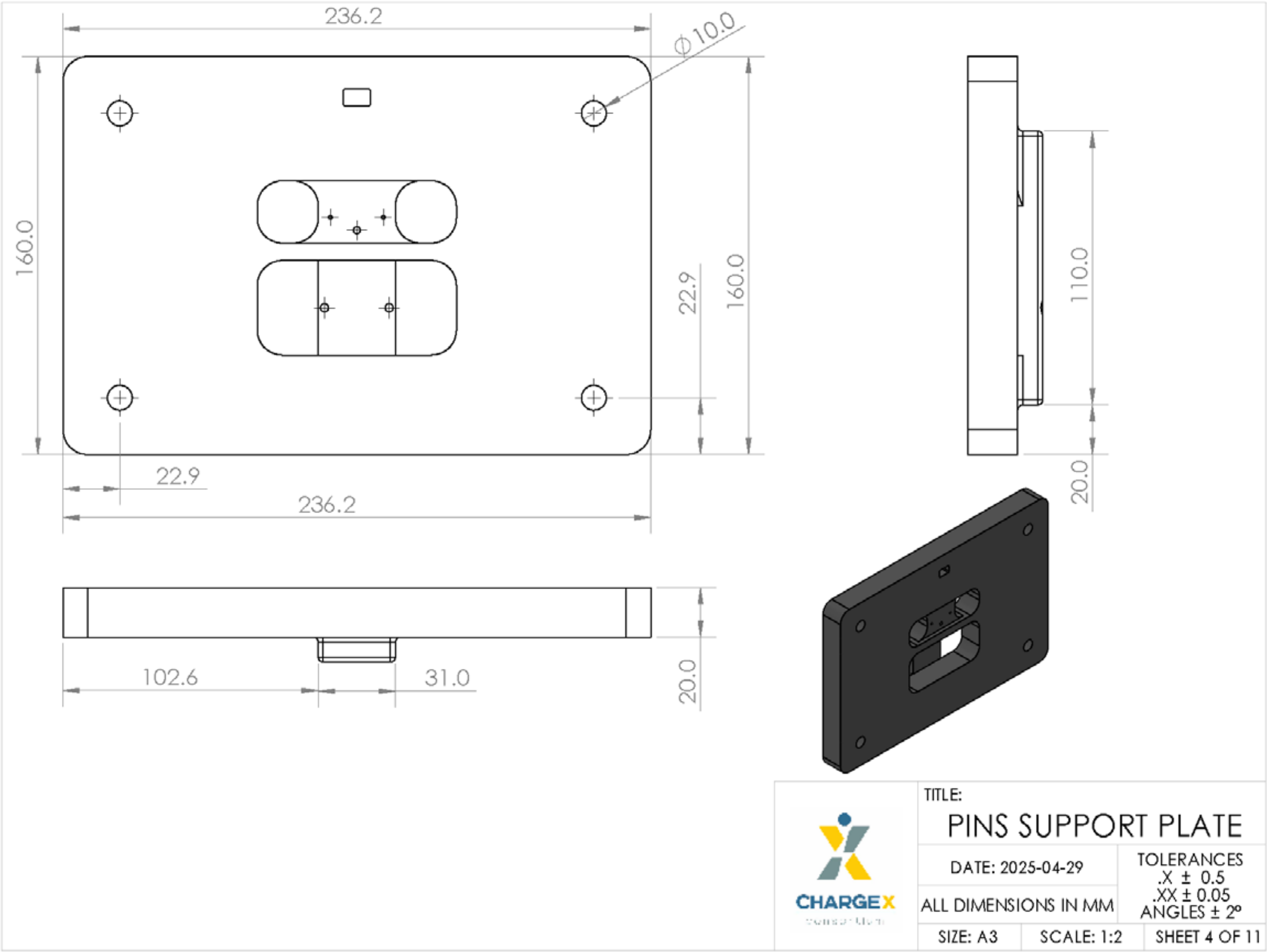
TOLERANCES
.X ± 0.5
.XX ± 0.05
ANGLES ± 2°

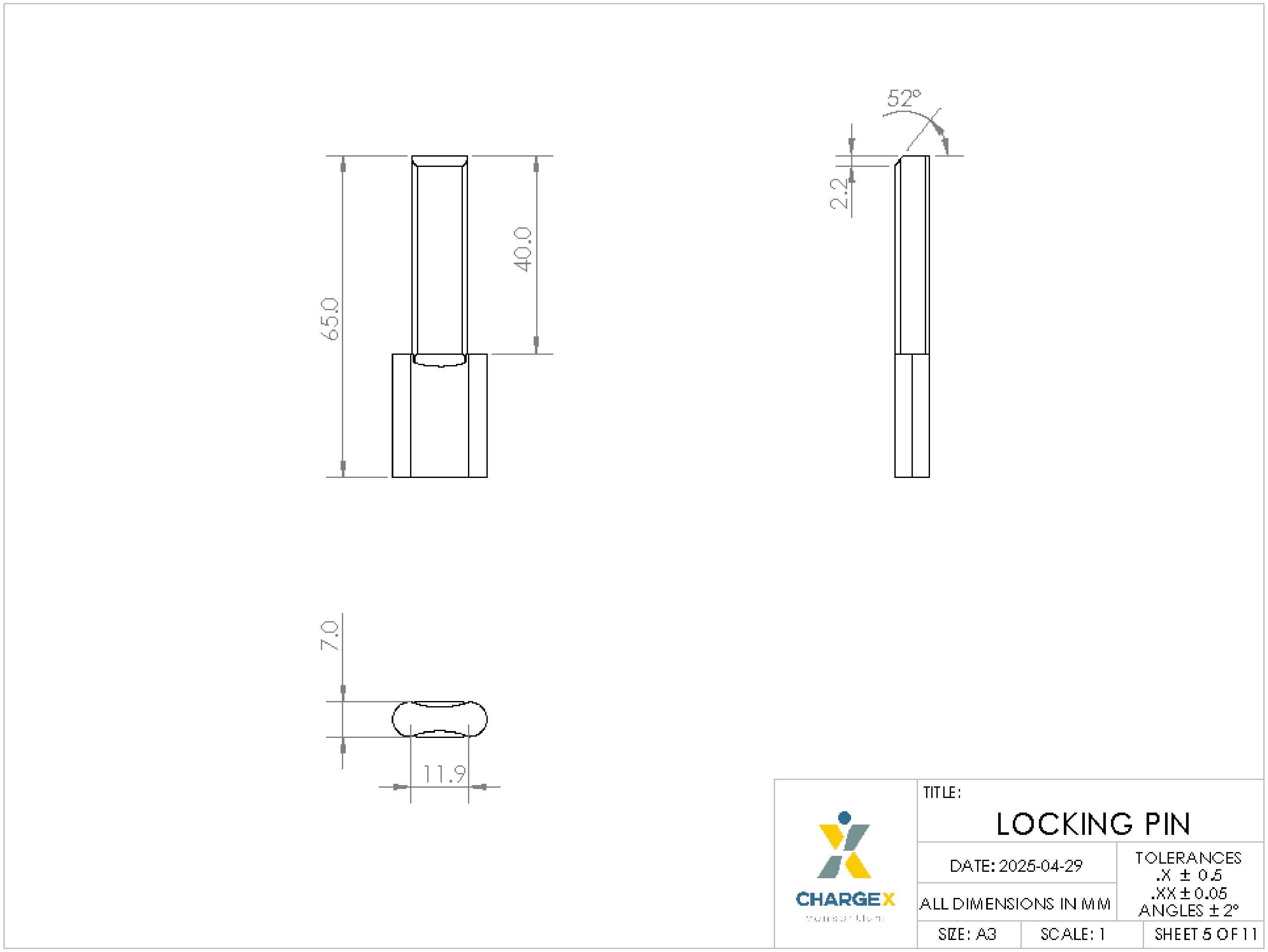
SIZE: A3 SCALE: NA SHEET 11 OF 11

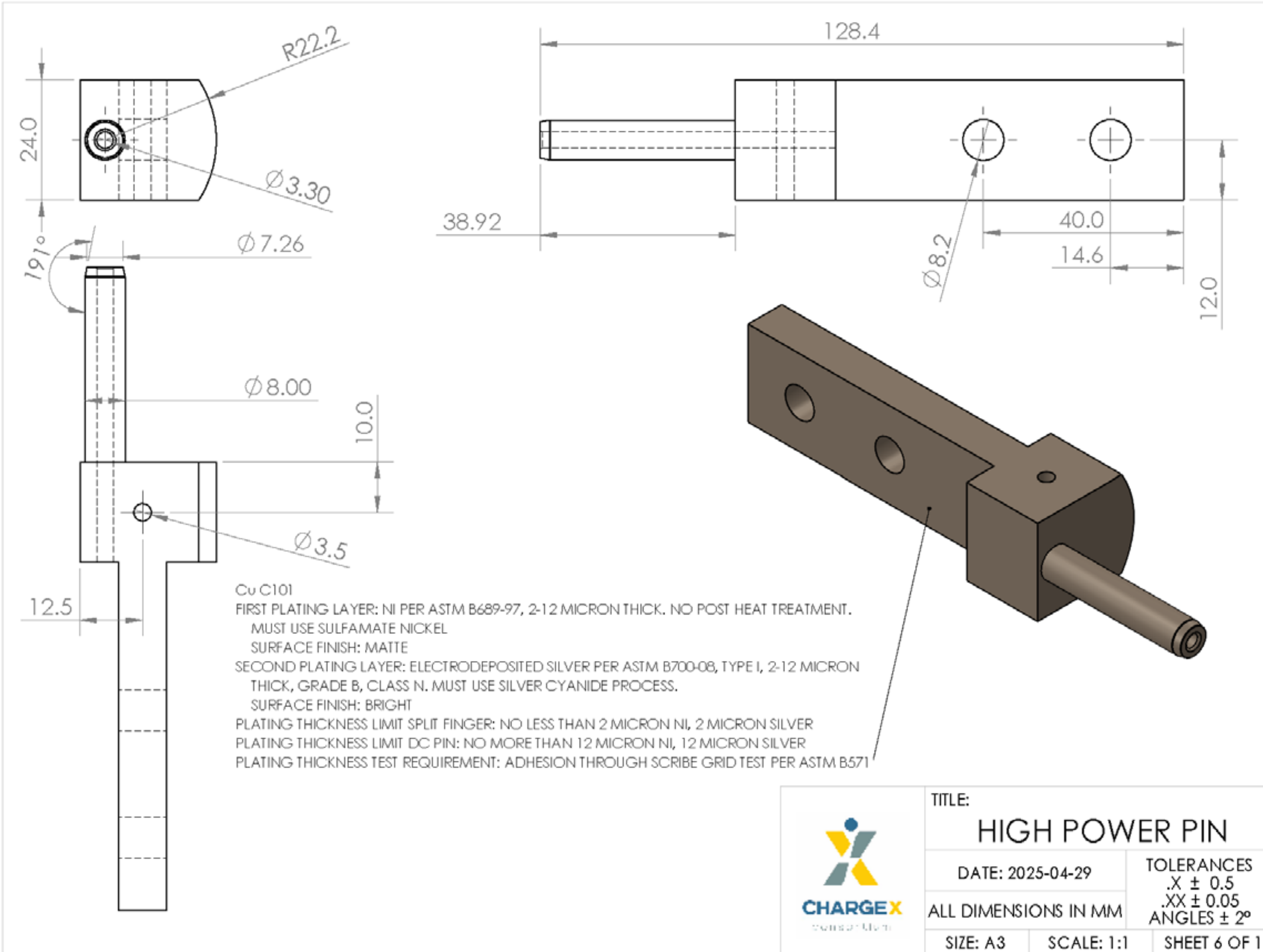
Appendix C. CCS Reference Inlet Drawings

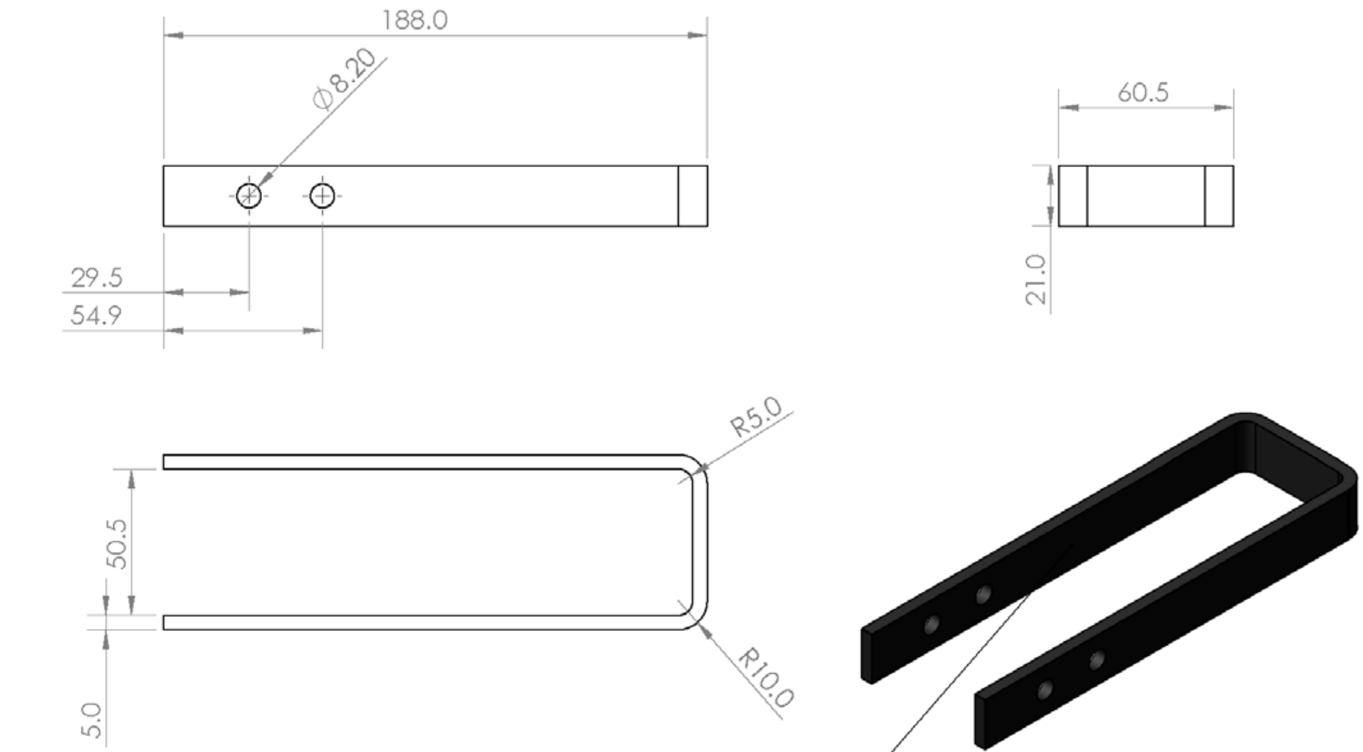

21.0
248.0
129.5
75.1
236.2
160.0
TITLE:
CCS1 DC Vehicle Inlet
DATE: 2025-04-29
ALL DIMENSIONS IN MM
TOLERANCES
.X ± 0.5
.XX ± 0.05
ANGLES ± 2°
SIZE: A3
SCALE: 1:2
SHEET 2 OF 11


236.2
ϕ10.0
160.0
22.9
137.2
22.9
213.4
20.0
TITLE:
CCS1 HOUSING
DATE: 2025-04-29
ALL DIMENSIONS IN MM
TOLERANCES
.X ± 0.5
.XX ± 0.05
ANGLES ± 2º
SIZE: A3
SCALE: 1:2
SHEET 3 OF 11
CHARGEX


236.2
ϕ10.0
160.0
22.9
160.0
110.0
22.9
236.2
20.0
102.6
31.0
20.0
TITLE:
PINS SUPPORT PLATE
DATE: 2025-04-29
ALL DIMENSIONS IN MM
TOLERANCES
.X ± 0.5
.XX ± 0.05
ANGLES ± 2º
SIZE: A3
SCALE: 1:2
SHEET 4 OF 11
CHARGEX

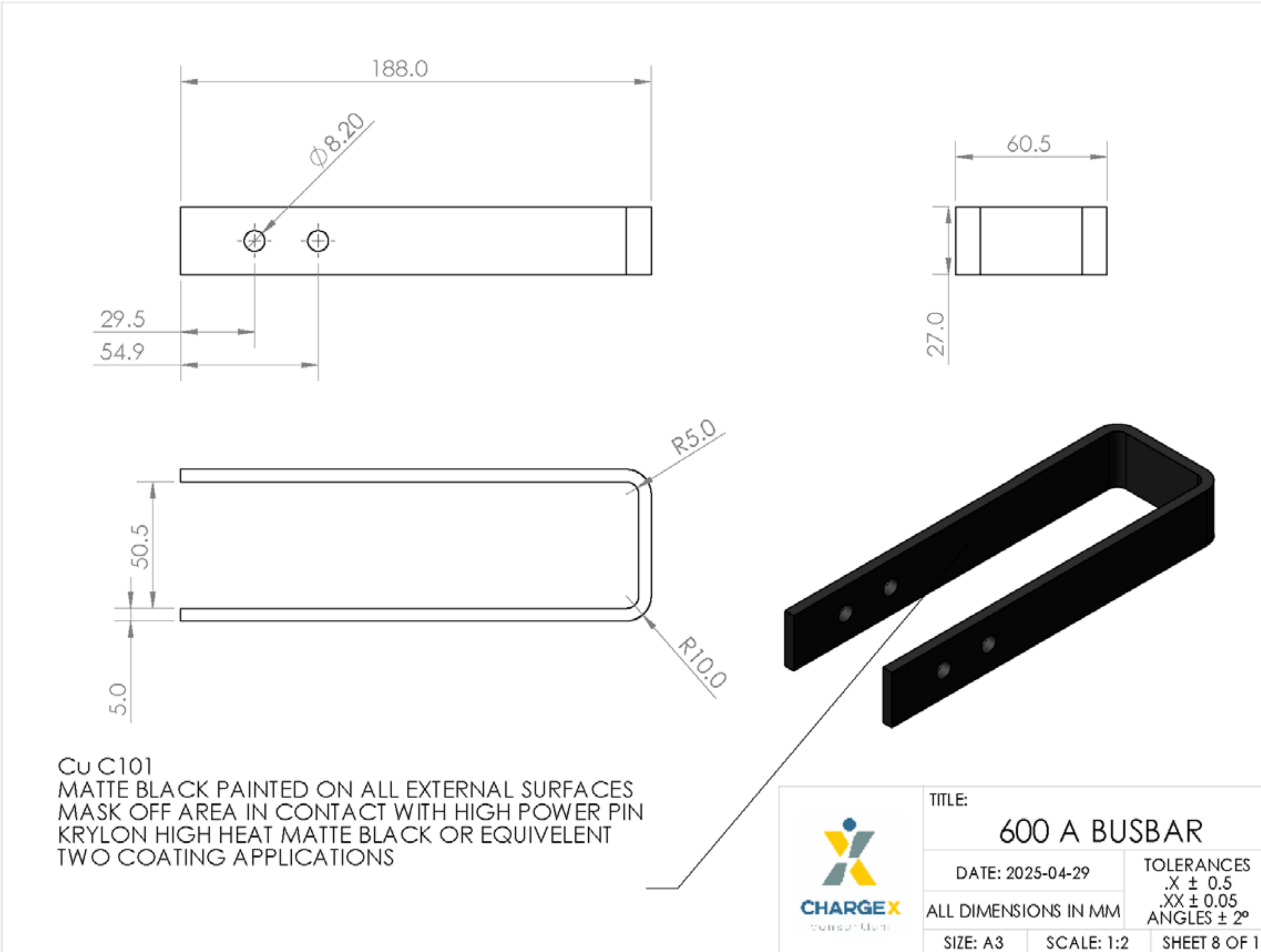

52°
2.2
65.0
40.0
7.0
11.9
TITLE:
LOCKING PIN
DATE: 2025-04-29
ALL DIMENSIONS IN MM
TOLERANCES
.X ± 0.5
.XX ± 0.05
ANGLES ± 2°
SIZE: A3
SCALE: 1
SHEET 5 OF 11
CHARGEX

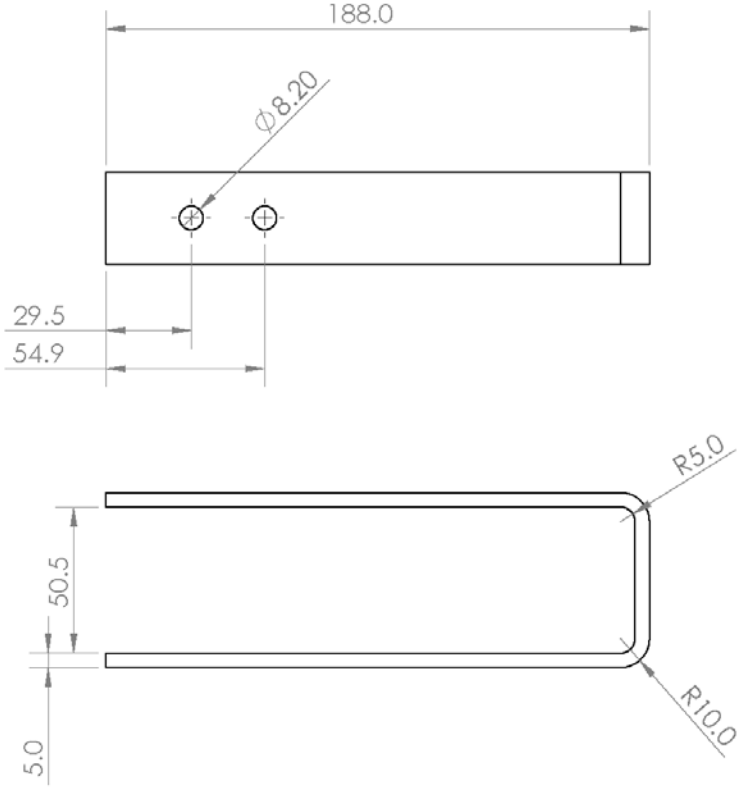

R22.2
24.0
Ø3.30
128.4
38.92
Ø8.2
40.0
14.6
12.0
191°
Ø7.26
Ø8.00
10.0
Ø3.5
12.5
Cu C101
FIRST PLATING LAYER: NI PER ASTM B689-97, 2-12 MICRON THICK. NO POST HEAT TREATMENT.
MUST USE SULFAMATE NICKEL
SURFACE FINISH: MATTE
SECOND PLATING LAYER: ELECTRODEPOSITED SILVER PER ASTM B700-08, TYPE I, 2-12 MICRON
THICK, GRADE B, CLASS N. MUST USE SILVER CYANIDE PROCESS.
SURFACE FINISH: BRIGHT
PLATING THICKNESS LIMIT SPLIT FINGER: NO LESS THAN 2 MICRON NI, 2 MICRON SILVER
PLATING THICKNESS LIMIT DC PIN: NO MORE THAN 12 MICRON NI, 12 MICRON SILVER
PLATING THICKNESS TEST REQUIREMENT: ADHESION THROUGH SCRIBE GRID TEST PER ASTM B571
CHARGEX
TITLE:
HIGH POWER PIN
DATE: 2025-04-29
ALL DIMENSIONS IN MM
TOLERANCES
.X ± 0.5
.XX ± 0.05
ANGLES ± 2º
SIZE: A3
SCALE: 1:1
SHEET 6 OF 11

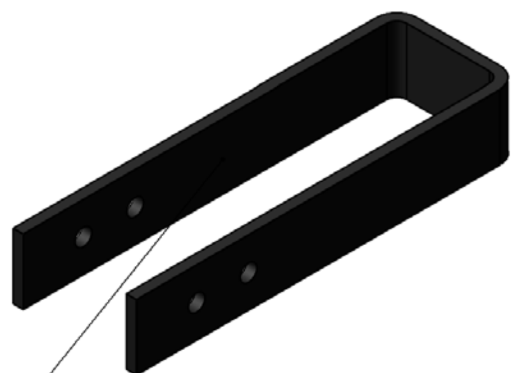


Cu C101
MATTE BLACK PAINTED ON ALL EXTERNAL SURFACES
MASK OFF AREA IN CONTACT WITH HIGH POWER PIN
KRYLON HIGH HEAT MATTE BLACK OR EQUIVELENT
TWO COATING APPLICATIONS

TITLE: 500 A BUSBAR		
DATE: 2025-04-29		TOLERANCES .X ± 0.5 .XX ± 0.05 ANGLES ± 2º
ALL DIMENSIONS IN MM		
SIZE: A3	SCALE: 1:2	SHEET 7 OF 11

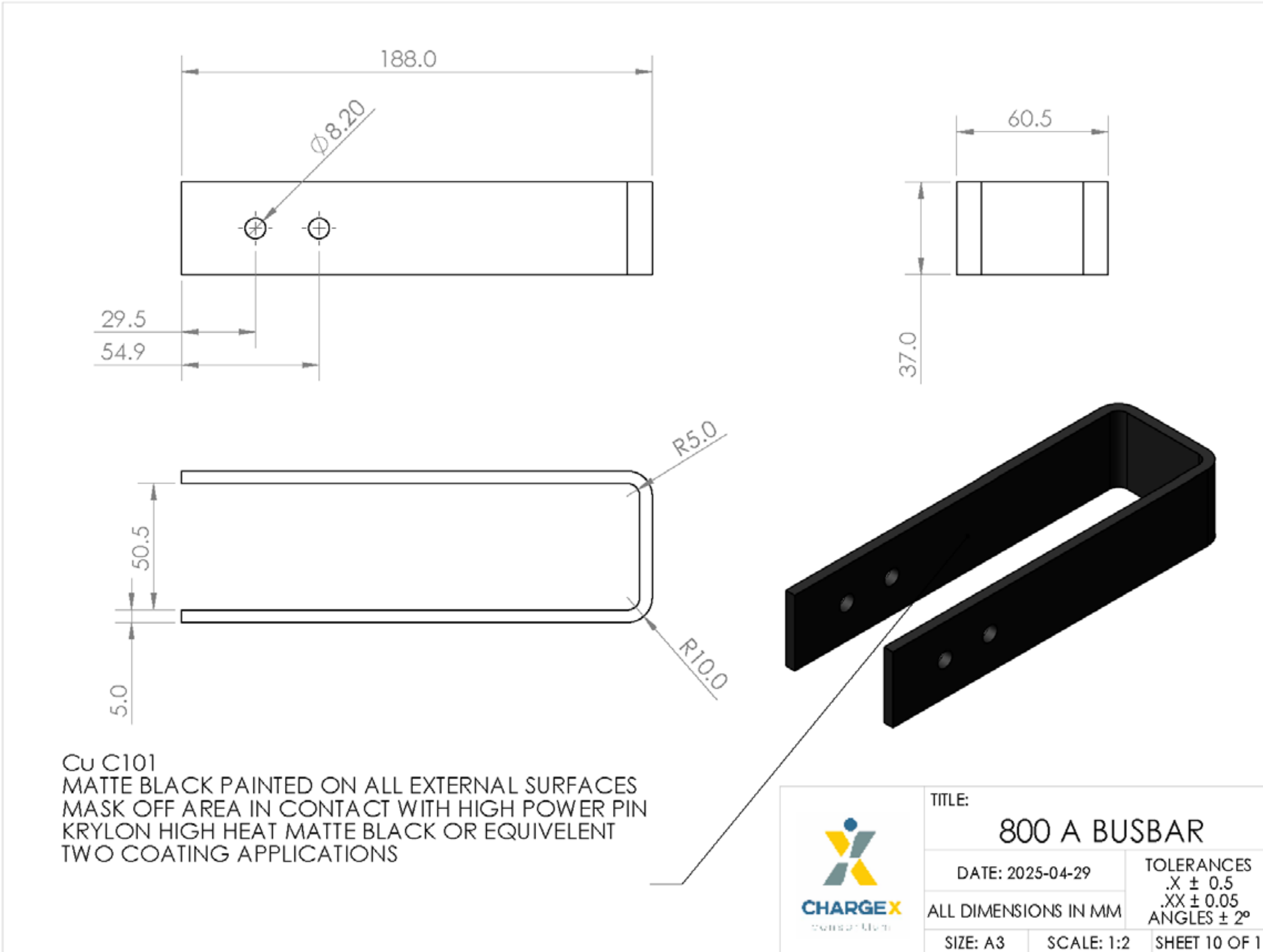

188.0
⌀8.20
60.5
29.5
54.9
27.0
R5.0
50.5
R10.0
5.0
Cu C101
MATTE BLACK PAINTED ON ALL EXTERNAL SURFACES
MASK OFF AREA IN CONTACT WITH HIGH POWER PIN
KRYLON HIGH HEAT MATTE BLACK OR EQUIVELENT
TWO COATING APPLICATIONS
CHARGEX
TITLE:
600 A BUSBAR
DATE: 2025-04-29
ALL DIMENSIONS IN MM
TOLERANCES
.X ± 0.5
.XX ± 0.05
ANGLES ± 2º
SIZE: A3
SCALE: 1:2
SHEET 8 OF 11





Cu C101
MATTE BLACK PAINTED ON ALL EXTERNAL SURFACES
MASK OFF AREA IN CONTACT WITH HIGH POWER PIN
KRYLON HIGH HEAT MATTE BLACK OR EQUIVELENT
TWO COATING APPLICATIONS

TITLE: 700 A BUSBAR		
DATE: 2025-04-29		TOLERANCES .X ± 0.5 .XX ± 0.05 ANGLES ± 2º
ALL DIMENSIONS IN MM		
SIZE: A3	SCALE: 1:2	SHEET 9 OF 11


188.0
⌀8.20
29.5
54.9
60.5
37.0
R5.0
50.5
5.0
R10.0
Cu C101
MATTE BLACK PAINTED ON ALL EXTERNAL SURFACES
MASK OFF AREA IN CONTACT WITH HIGH POWER PIN
KRYLON HIGH HEAT MATTE BLACK OR EQUIVELENT
TWO COATING APPLICATIONS
CHARGEX
TITLE:
800 A BUSBAR
DATE: 2025-04-29
ALL DIMENSIONS IN MM
TOLERANCES
.X ± 0.5
.XX ± 0.05
ANGLES ± 2º
SIZE: A3
SCALE: 1:2
SHEET 10 OF 11

Item	Description	Quantity	Material	Source	Part Number	Reference
1	Housing	1	PPS CF or Equivalent	3D Printed	NA	NA
2	Pins Support Plate	1	PPS CF or Equivalent	3D Printed	NA	NA
3	Locking Pin	1	PPS CF or Equivalent	3D Printed	NA	NA
4	High Power Pin	2	Cu 101, Ni/Ag Plating	Machined	NA	NA
5	500 A Busbar	1	Cu 101, Matte Black Paint	Machined	NA	NA
6	600 A Busbar	1	Cu 101, Matte Black Paint	Machined	NA	NA
7	700 A Busbar	1	Cu 101, Matte Black Paint	Machined	NA	NA
8	800 A Busbar	1	Cu 101, Matte Black Paint	Machined	NA	NA
9	Ground Pin	1	Cu 101, Ni/Ag Plating	Machined	NA	NA
10	Low Power Pin	2	Cu 101, Ni/Ag Plating	Machined	NA	NA
11	M8 x 1.25 mm Coarse Thread, 30 mm Long Hex Head Screw	4	Class 10.9 Stainless Steel	McMaster-Carr	91310A536	https://www.mcmaster.com/91310A536/
12	M8 Washer	4	18-8 Stainless Steel	McMaster-Carr	93475A270	https://www.mcmaster.com/93475A270/
13	M8 Spring Lock Washer	8	18-8 Stainless Steel	McMaster-Carr	91477A181	https://www.mcmaster.com/91477A181/
14	M8 x 1.25 mm Coarse Thread Hex Nut	4	18-8 Stainless Steel	McMaster-Carr	91828A410	https://www.mcmaster.com/91828A410/
15	M3.5 Washer	2	18-8 Stainless Steel	McMaster-Carr	93475A220	https://www.mcmaster.com/93475A220/
16	M1.6 Washer	6	18-8 Stainless Steel	McMaster-Carr	93475A190	https://www.mcmaster.com/93475A190/
17	No. 6 Screw Size Ring Terminal	1	Tin-Plated Cu, Nylon	McMaster-Carr	7113K265	https://www.mcmaster.com/7113K265/
18	No. 2 Screw Size Ring Terminal	2	Tin-Plated Cu, Nylon	McMaster-Carr	7113K263	https://www.mcmaster.com/7113K263/
19	1/16" Thick, 1/16" OD Neodymium Magnet	4	Nickel-Plated Neodymium	McMaster-Carr	5862K137	https://www.mcmaster.com/5862K137/
20	Watlow 1/8" D, 1" L, 24 V, 5 W Firerod Cartridge Heater	2	Inconel 600, MgO	Therm-X	C1A-9600	https://www.therm-x.com/watlow-1-8-diameter-cartridge-heaters.html
21	Adhesive Type K Thermocouple	3	Chromel +/ Alumel −, Polyimide	McMaster-Carr	3648K34	https://www.mcmaster.com/3648K34/
22	1/8" D Probe Type K Thermocouple	2	Chromel +/ Alumel −, SS	McMaster-Carr	3857K212	https://www.mcmaster.com/3857K212/

TITLE:

Bill of Materials

DATE: 2025-04-29

ALL DIMENSIONS IN MM

TOLERANCES
.X ± 0.5
.XX ± 0.05
ANGLES ± 2°

SIZE: A3 | SCALE: NA | SHEET 11 OF 11

About the ChargeX Consortium

The National Charging Experience Consortium (ChargeX Consortium) is a collaborative effort between Argonne National Laboratory, Idaho National Laboratory, National Renewable Energy Laboratory, electric vehicle charging industry experts, consumer advocates, and other stakeholders. The ChargeX Consortium's mission is to work together to measure and significantly improve public charging reliability and usability by June 2025. For more information, visit chargex.inl.gov.

DOE/GO-102025-6797 • August 2025

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INL Idaho National Laboratory

NREL