CharIN Megawatt Charging System: 4th Event Summary Report

Isaac Tolbert, Namrata Kogalur, Jonathan Martin, and Andrew Meintz

National Renewable Energy Laboratory

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National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
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Foreword

The Charging Interface Initiative (CharIN) is a group of professionals from multiple industries promoting the development, standardization, and interoperability of charging systems for electrified vehicles. The CharIN Megawatt Charging System (MCS) Task Force is undertaking efforts to develop a new high-power charging standard for heavy-duty vehicle electrification.

The National Renewable Energy Laboratory (NREL), in Golden CO, hosted a CharIN MCS evaluation event from 25 May 2023 through 24 January 2024 to evaluate proprietary prototype designs from multiple manufacturers. Industry representatives Amphenol, Daimler, Stäubli, and TE Connectivity provided hardware for testing and evaluation.

Preface

The MCS evaluation event activities were funded under two agreements: Technical Services Agreement #TSA-19-16406 between Alliance/NREL and CharIN and Funds In Agreement #FIA-15-01813 between Alliance/NREL and CEC. These agreements charged NREL with conducting the following evaluations:

- Functional evaluations of the thermal performance of participant manufacturers' connector and port systems

This report satisfies requirements specified in the named agreements that NREL develops an aggregation method for a non-proprietary summary report (e.g., a pass/fail summary of all 1000A tests) to each participant manufacturer.

List of Acronyms

CEC	California Energy Commission
CharIN	Charging Interface Initiative
DUT	Device Under Test
FIA	Funds In Agreement
NREL	National Renewable Energy Laboratory
MCS	Megawatt Charging System
MER	Mechanical Evaluation Rig
RTD	Resistance Temperature Detector
TSA	Technical Services Agreement

Executive Summary

This summary report documents aggregated and anonymized CharIN Megawatt Charging System (MCS) device performance data collected by NREL from 25 May 2023 through 24 January 2024.

During this event, evaluations of pre-production, molded connectors and inlets were conducted to characterize the devices' compliance to the drafted IEC 63379 and SAE J3271 MCS standards. The event consisted of three main evaluation categories: thermal interoperability evaluations, mechanical evaluations, and reference device evaluations. The purpose of these evaluations was to characterize the performance of MCS connectors and inlets in support of the development of the MCS standards. This is an iterative process, in which each manufacturer is actively improving the interpretation and implementation of their MCS design. As a result, the prototypes under evaluation during this event may not contain all refinements that would be present in the eventual finished products.

Thermal interoperability evaluations consisted of loading each connector and inlet pair to the maximum current for each evaluation level (350A/1000A/3000A) and then allowing sufficient time for the device under test (DUT) to achieve steady state temperature, as defined by IEC 62196 as three successive readings, spaced at 10-minute intervals with no change in temperature greater than 2K. Once at least 30 minutes of steady-state data had been collected, a force of 100N was applied to the connector in the -X, +Y, +X, -Y directions for at least 2 minutes, in succession, as defined by IEC 62196 – referred to hereafter as the "misalignment evaluation." These evaluations were performed on both "new" components, as well as "aged' components, which had undergone an accelerated aging process, which included subjection to no-load endurance testing and thermal cycling per the procedure outlined in IEC 62196-1 Ed 4, clauses 23.3 and 34.3. This aging process was performed by the hardware provider prior to components being received by NREL.

Mechanical evaluations characterized the insertion/withdrawal force and pin contact sequence of each connector and inlet pair; additionally, the touch safety of each device was characterized via use of the jointed test finger defined by IEC 60529.

Finally, the reference device evaluations characterized the performance of the connectors when connected with a reference inlet design at 1500A or 3000A, at an ambient temperature of 40C. Some additional evaluations were conducted to validate the performance of the reference device when compared to simulated results.

Overall, the evaluated devices performed well and demonstrated the viability of the MCS standard. Of the 20 new and aged connector/inlet combinations evaluated for thermal interoperability, 18 combinations were found to be compliant with the thermal interoperability criteria of the standard (i.e., less than 60K temperature rise on the DC+ and DC- contacts at steady-state rated current). Similarly, 14 of the 20 connector/inlet combinations were found to be compliant with the misalignment evaluation, with half of the non-compliant results coming from aged devices. During insertion, withdrawal, and touch-safety evaluations, it was found that approximately half of the devices were able to mate/unmate with approximately 100N of force, and some devices were at least partially compliant with the touch-safety criteria, with several

inlets reaching full touch-safety compliance. This demonstrates the general ability of the MCS standard to meet the described insertion/withdrawal force. Additionally, this work suggests that individual manufacturers may need to further refine some of these pre-production components to fully meet the touch safety requirements and insertion/withdrawal force requirements. Finally, during reference inlet device evaluations, all evaluated connectors were found to be compliant at the standard ambient evaluation temperature of 40°C, and the reference device temperatures showed a good match with previously-simulated results, providing crucial validation of the MCS reference inlet design.

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1 Thermal Interoperability Evaluation

1.1 Overview

The objective of the CharIN MCS thermal evaluation is to run current with all functional prototypes in a shorted condition on the inlet using a high-current low-voltage power supply. This document is the aggregated report on the ability of equipment to reach desired current (either 350A, 1000A, or 3000A) while maintaining compliance with the MCS thermal limits (60K max temperature rise at the DC contacts, and 100°C maximum overall temperature). Three test currents (formerly designated Level 1/2/3 in previous events, but now referred to by the current level) were defined by the CharIN Taskforce for this evaluation event as summarized in Table 1. NREL used the same thermal evaluation bench that was used for all Event 2 and Event 3 thermal evaluations.

Table 1. Functional Evaluation Configurations

Hardware Configurations	
350A	350 amp capable, no active cooling for connector or inlet
1000A	1000 amp capable, combines actively-cooled connector with uncooled inlet
3000A	3000 amp capable, combines actively-cooled connector with cooled inlet

1.2 Prototype Equipment

The thermal interoperability test bench was set up to evaluate a connector and inlet system. The connector, consisting of a cable approximately 2m in length provided by the participant and terminated at one end with an MCS connector with socket terminals and terminated at the other end with electrical connection lugs, was bolted to an NREL-provided bus bar and instrumented with up to 14 thermocouples. Transducers were also provided to enable data collection from optional participant-provided Pt1000 Resistance Temperature Detector (RTD) sensors. Before being placed under test, the connector would be mated to a participant-provided inlet with shorted terminals or electrical connection lugs that would then be bolted to an NREL-provided bus bar, with a cable length of approximately 0.75m. The inlet was instrumented with up to 13 thermocouples. Current was supplied at low voltage to the connector/inlet device under test (DUT) from a Magna-Power MSD16-3600 power supply. During testing, the DUT experienced a voltage drop of less than 10VDC. Thermocouple locations at the connector/inlet interface are detailed in Figure 1.

1.3 Setup

The MCS evaluation bench was set up to record instrumentation of thermal performance for participant manufacturers' connector and inlet systems up to 350A without active cooling, and 3000A with active cooling. Table 2 summarizes equipment used to capture data during thermal interoperability evaluations. MCS evaluation bench layout and construction details are depicted in Figure 2 and Figure 3. Figure 4 depicts a simplified diagram of the MCS connector cooling system (used for current levels at or above 1000A) and Figure 5 depicts a simplified diagram of the MCS inlet cooling system (used for current levels at 3000A).

Heat generated during the test was removed from actively-cooled systems by NREL's Research Chilled Water system, utilizing a water/propylene glycol coolant with a 30% nominal propylene glycol concentration. The NREL Research Chilled Water system was setup to provide a nominal flow rate of 13.5 L/min to the Connector and 3.5 L/min to the Inlet. The coolant supply temperature was set to a nominal value of roughly 10°C. NREL provided 1" male NPT leakproof quick-connect fittings to interface with manufacturer-supplied cooling systems. In this event, all manufacturers of actively-cooled charging equipment provided secondary heat exchangers and/or pumping equipment to transfer heat from their own proprietary cooling medium(s) to the NREL-provided Research Chilled Water.

Table 2. Equipment Used for MCS Thermal Evaluation Data Capture

Type	Description
Oscilloscope	Yokogawa DL850E
Oscilloscope	Yokogawa DL850
Analog Voltage Input Module (x7)	Yokogawa 701260
Analog Voltage Input Module	Yokogawa 720210
Temperature/Voltage Input Module (x2)	Yokogawa 720221
Thermocouples	T-Type, special limits of error, no calibration
Resistance Temperature Detectors (RTDs)	Pt1000-type, manufacturer-provided (optional)
RTD measuring transducer (x2)	Phoenix Contact MACX MCR-T-UI-UP-2811394
Flow Meter (x2)	Max Machinery, Inc. G045 Gear Flow Meter

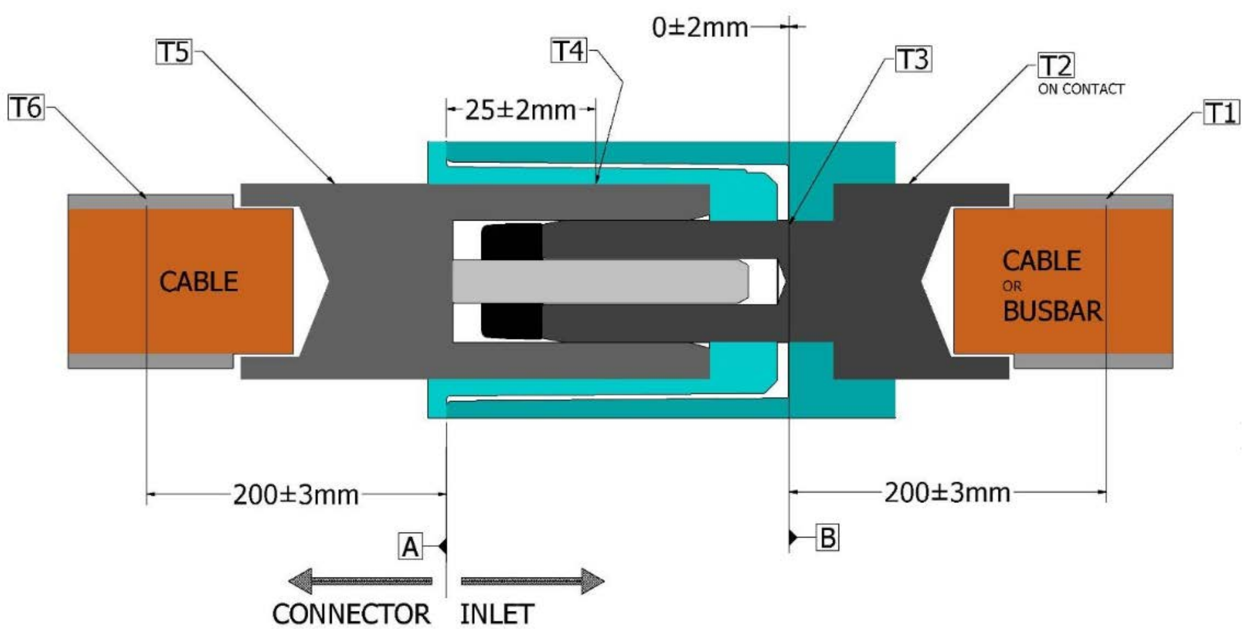


Figure 1. Thermocouple locations at the connector/inlet interface

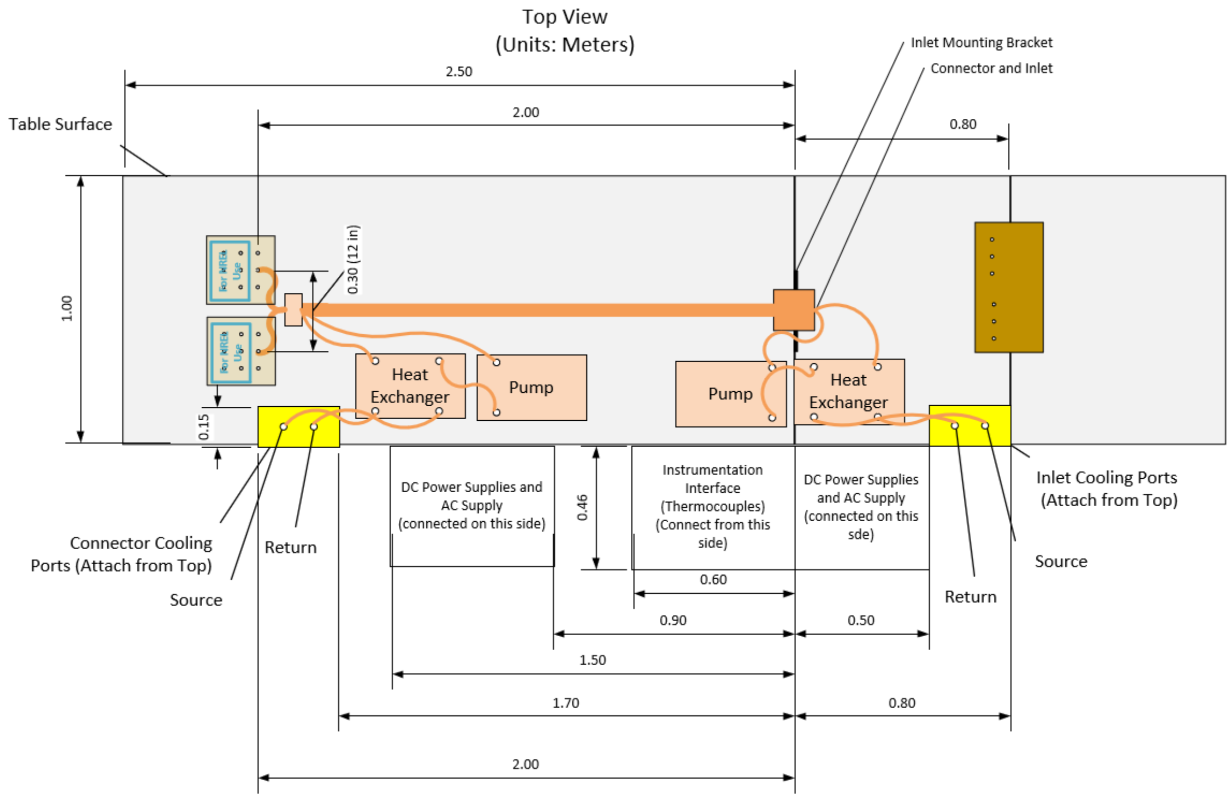


Figure 2. CharIN Thermal Interoperability Evaluation Bench Layout

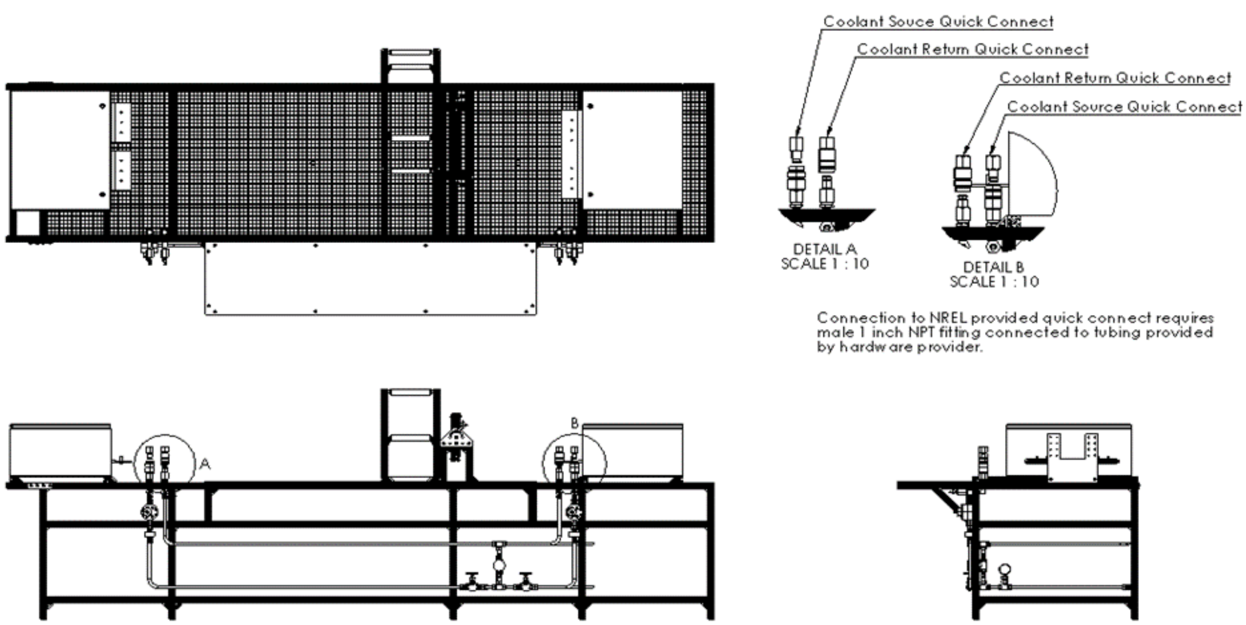


Figure 3. CharIN Thermal Interoperability Evaluation Bench and Cooling System Dimensioned Plan and Elevation Views

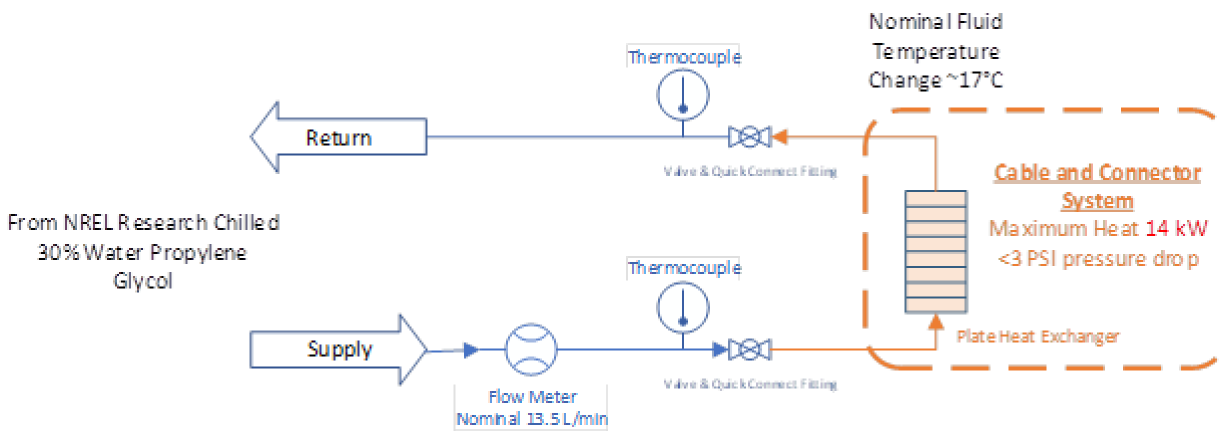


Figure 4. Simplified MCS 1000A-3000A Connector Cooling System Diagram

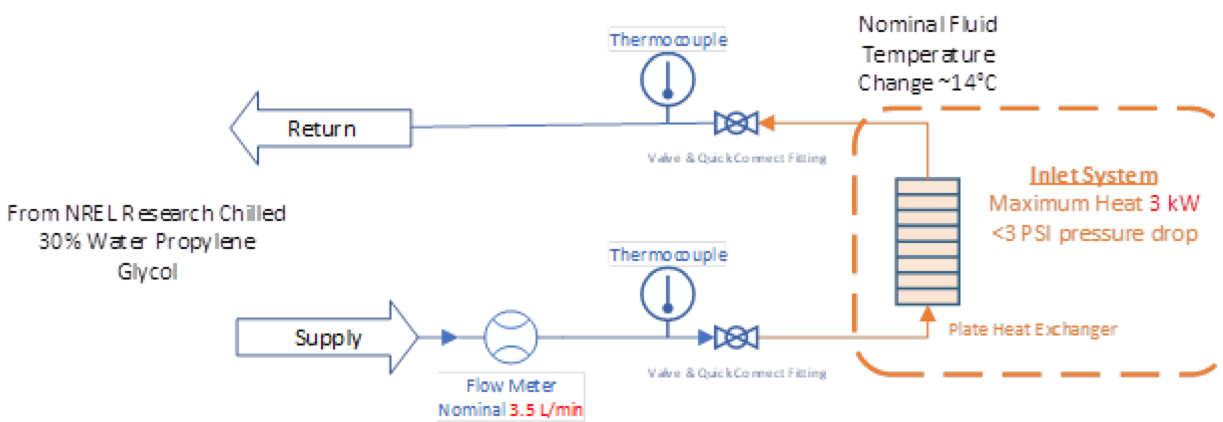


Figure 5. Simplified MCS 3000A Inlet Cooling System Diagram

Figure 6 shows the fixture used to perform misalignment testing mounted on the MCS evaluation bench. A 100N weight was hung from the fixture, applying the sideloading force to the DUT's lateral or vertical axes (4 total directions). Figure 7 shows the side view of the force alignment frame, with adjustable rollers and connector mounting apparatus.

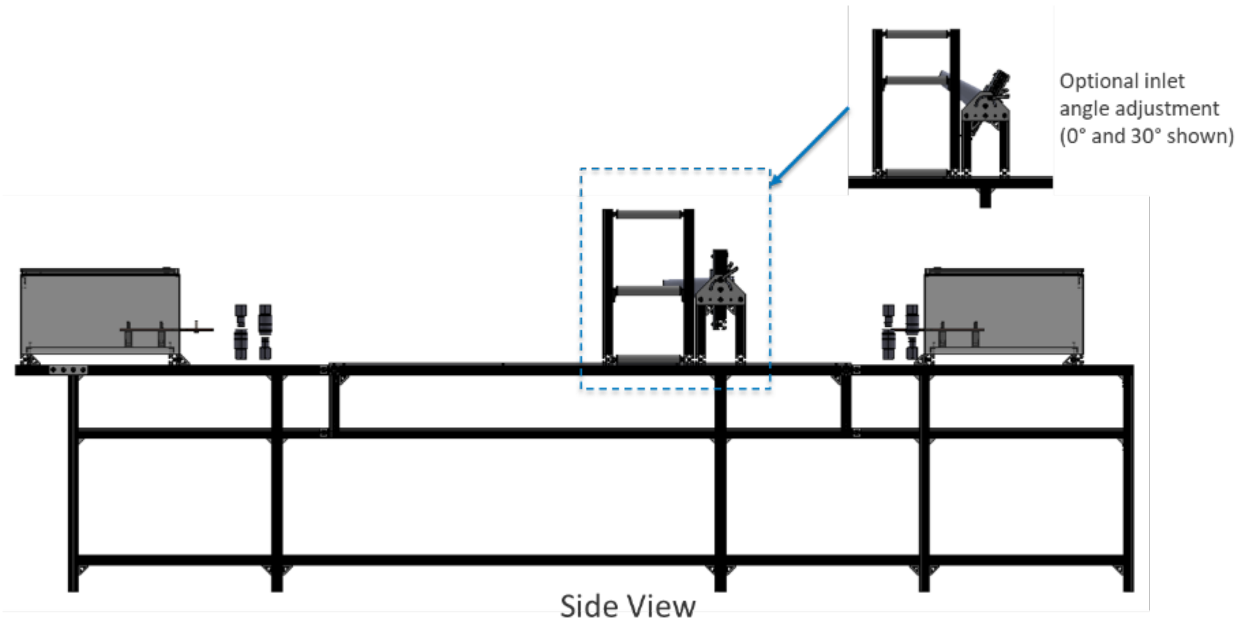


Figure 6. Force application frame with inlet attachment frame mounted on test bench.

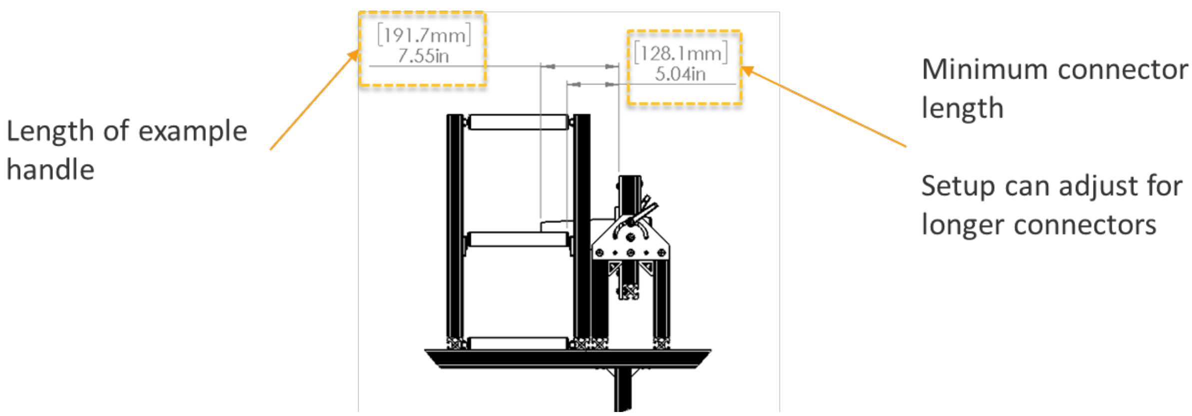


Figure 7. Side view of force alignment frame.

Plexiglass safety guards were installed on the test bench to prevent an operator from inadvertently contacting energized or hot DUT components, as shown in Figure 8 (CAD) and Figure 9 (photo).

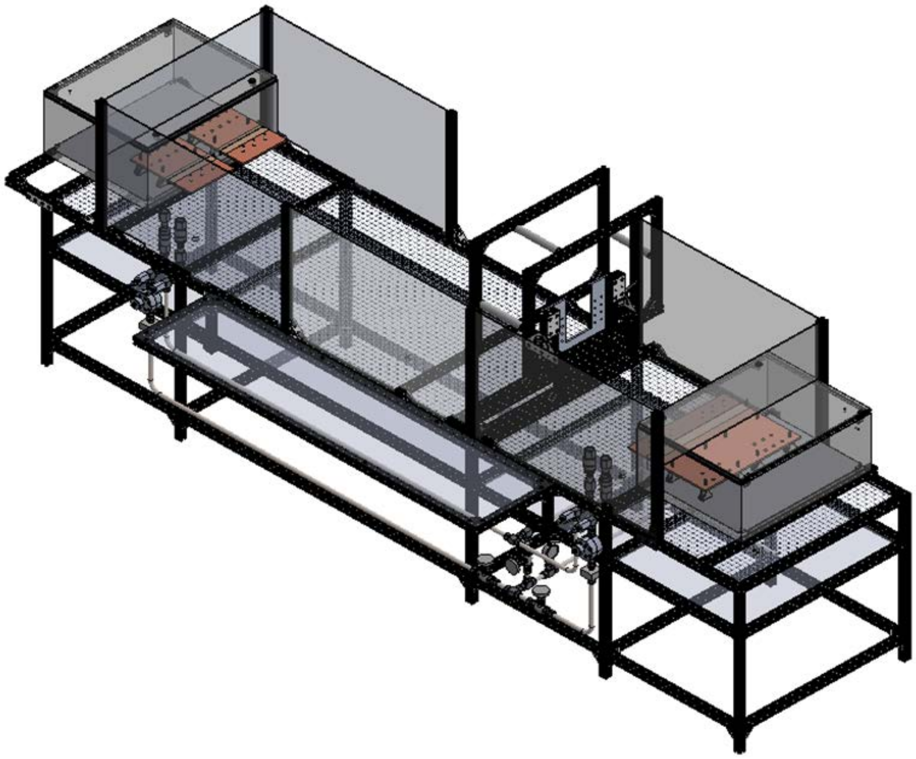


Figure 8. MCS Thermal Interoperability Evaluation Bench Safety Guards.

Figure 9. MCS Thermal Interoperability Evaluation Bench Setup with Safety Guards.

1.4 Results

Tests at each level (350A, 1000A, and 3000A) were run until the DUT was determined to be at steady state temperature, per the IEC 62196-1 definition. After installation, the DUT was energized with 25A of current supplied by the Magna-Power power supply. Expected system response was observed and accuracy of all instrumentation was confirmed. Supplied current was successively stepped up in 25A increments, pausing after each increment to observe the expected system response and check instrumentation until reaching 150A, at which point the DUT resistance was measured. Then, current was increased until the steady-state rated current was achieved.

Table 3, Table 4, Table 5, Table 6, and Table 7 list the measured resistances at 150A for all DUTs, categorized by current level and connector age, while Table 8 summarizes the overall minimum, mean, and maximum DUT resistances at 150A by current level and connector age.

Table 3. MCS DUT Resistance at 150A (350A New)

DUT	Resistance
Connector A / Inlet B	1.13 mΩ
Connector A / Inlet C	1.15 mΩ
Connector A / Inlet D	0.99 mΩ
Connector A / Inlet E	0.91 mΩ

Table 4. MCS DUT Resistance at 150A (1000A New)

DUT	Resistance
Connector F / Inlet I	1.64 mΩ
Connector F / Inlet J	1.60 mΩ
Connector F / Inlet L	1.59 mΩ
Connector G / Inlet I	2.24 mΩ
Connector G / Inlet J	2.26 mΩ
Connector G / Inlet K	2.24 mΩ
Connector G / Inlet L	2.29 mΩ
Connector H / Inlet I	2.03 mΩ
Connector H / Inlet J	1.90 mΩ
Connector H / Inlet K	1.87 mΩ
Connector H / Inlet L	1.97 mΩ

Table 5. MCS DUT Resistance at 150A (1000A Aged)

DUT	Resistance
Connector M / Inlet N	1.86 mΩ
Connector M / Inlet O	2.41 mΩ

Table 6. MCS DUT Resistance at 150A (3000A New)

DUT	Resistance
Connector P / Inlet R	0.88 mΩ
Connector Q / Inlet R	1.90 mΩ

Table 7. MCS DUT Resistance at 150A (3000A Aged)

DUT	Resistance
Connector S / Inlet T	0.91 mΩ

Table 8. MCS Min/Mean/Max* DUT Resistance at 150A

DUT Rating Class	350A	1000A (New)	1000A (Aged)	3000A (New)
Minimum	0.91 mΩ	1.59 mΩ	1.86 mΩ	0.88 mΩ
Mean	1.04 mΩ	1.97 mΩ	2.14 mΩ	1.39 mΩ
Maximum	1.15 mΩ	2.29 mΩ	2.41 mΩ	1.90 mΩ

*Due to only one aged 3000A sample being provided and evaluated, only the "new" 3000A devices were included in Table 8.

For each DUT, the temperature coefficient of resistance was calculated on the hottest measured DUT temperature using the voltage/current measurements collected at maximum steady-state current levels (350A, 1000A, and 3000A). Ohm's Law was used to compute the resistance profile from the recorded current and voltage traces while the DUT was actively loaded. This resistance profile was plotted against the hottest corresponding temperature trace of the DUT. Measured steady-state resistances are plotted with respect to temperature as scatter plots, with a calculated temperature coefficient of resistance plotted as a trend line.

Figure 10 shows the temperature coefficients of resistance determined from 350A testing with new connectors and new inlets.

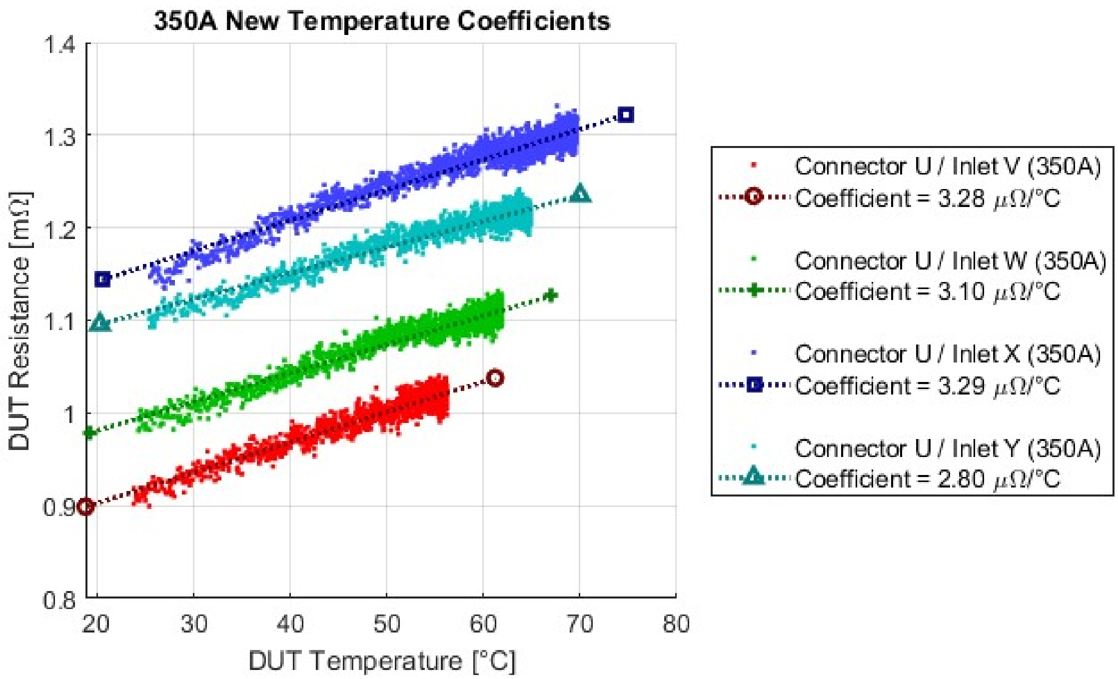


Figure 10. MCS 350A New Connector/Inlet Temperature Coefficients of Resistance

Figure 11 depicts the temperature coefficients of resistance determined from 1000A test data with new connectors and new inlets, while Figure 12 depicts temperature coefficients of resistance determined from aged devices at 1000A.

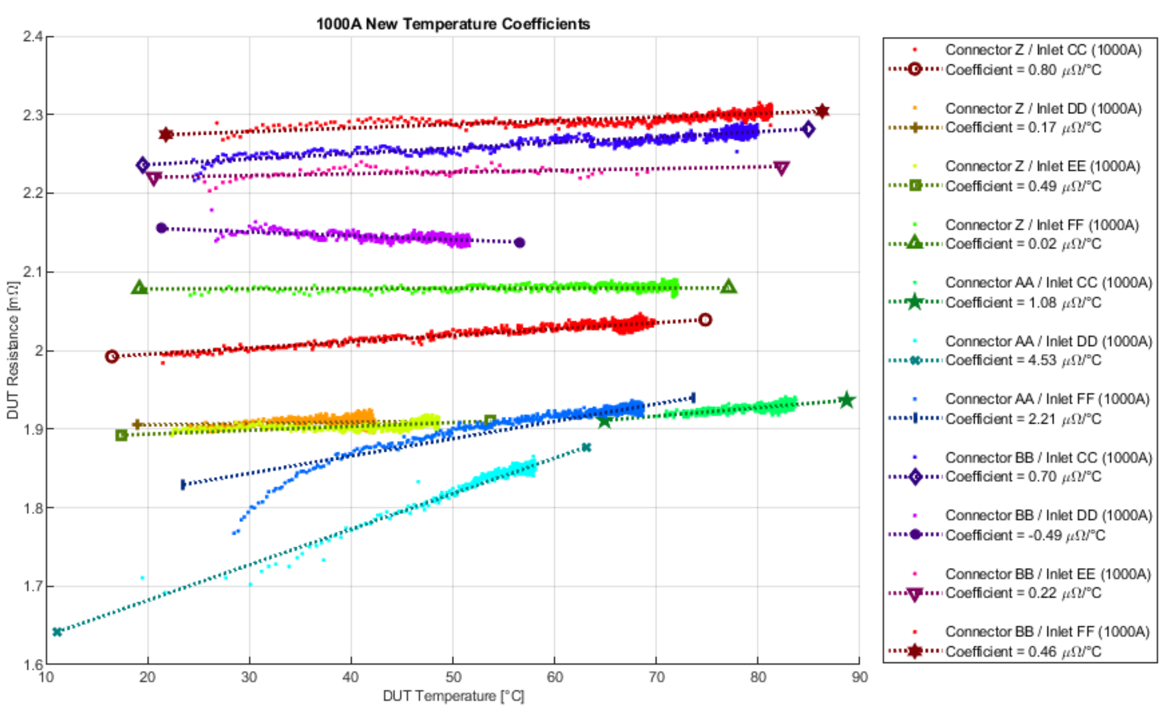


Figure 11. MCS 1000A New Connector/Inlet Temperature Coefficients of Resistance

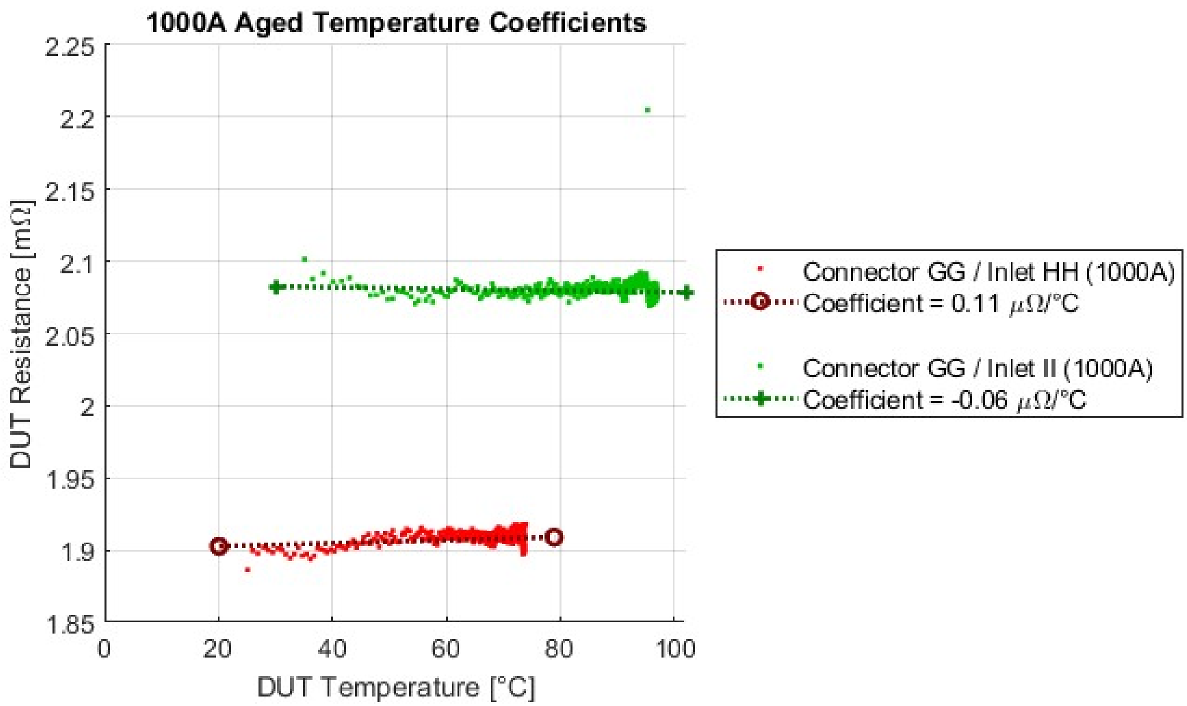


Figure 12. MCS 1000A Aged Connector/Inlet Temperature Coefficients of Resistance

Figure 13 depicts the temperature coefficients of resistance determined from 3000A test data with new connectors and new inlets, while Figure 14 shows the temperature coefficients of resistance of aged 3000A devices.

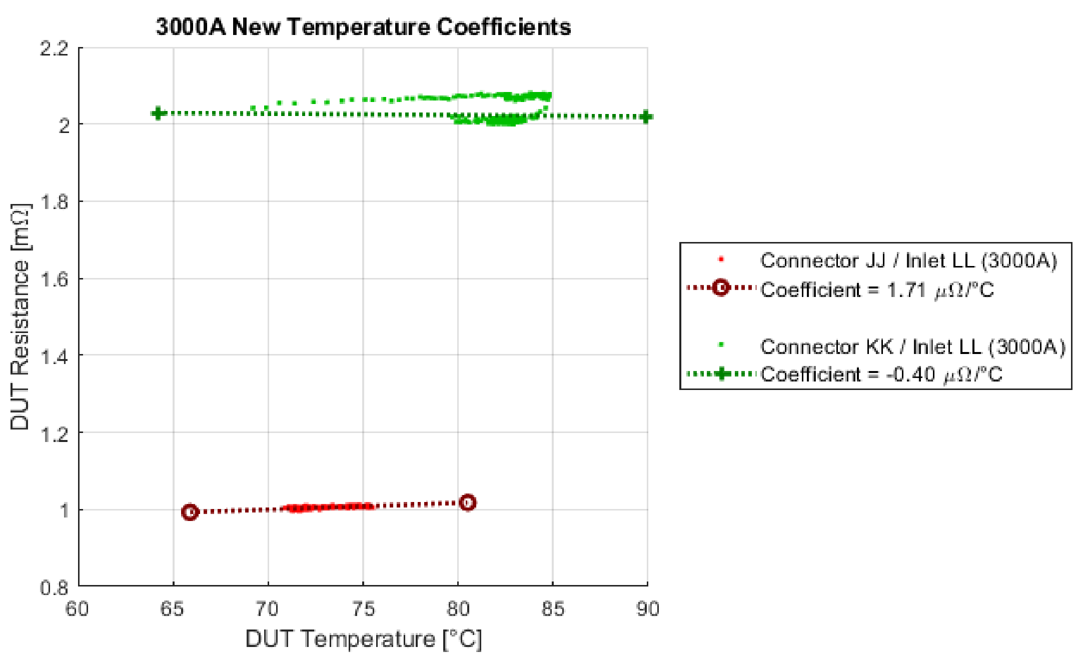


Figure 13. MCS 3000A New Connector/Inlet Temperature Coefficients of Resistance

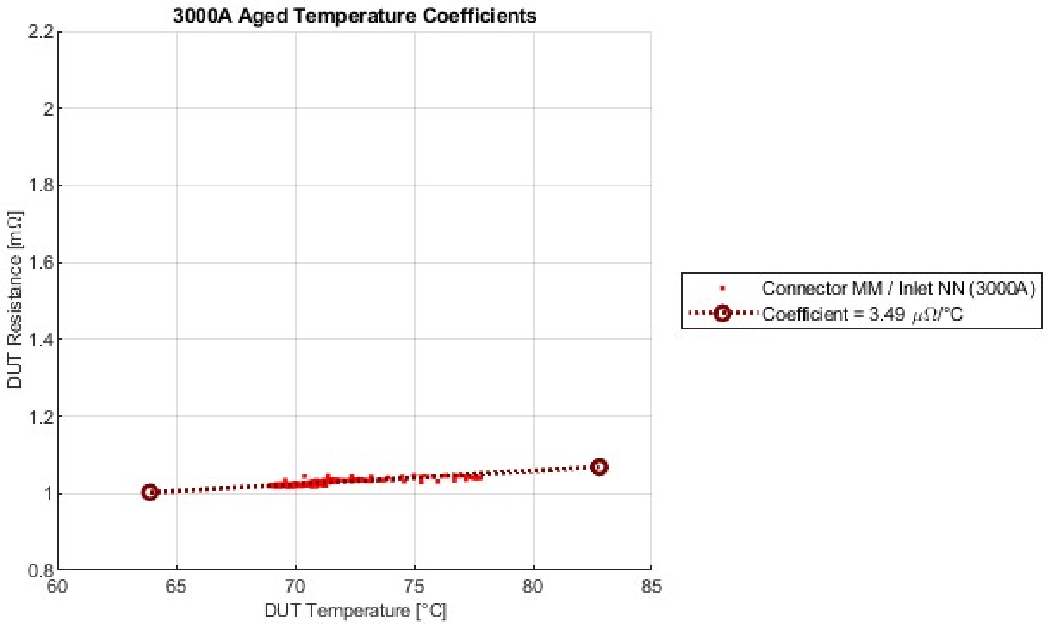


Figure 14. MCS 3000A Aged Connector/Inlet Temperature Coefficient of Resistance

*Due an issue with the NREL Research Chilled Water (RCW) system, the 3000A Aged interoperability evaluation was performed with an RCW temperature approximately 5°C below the usual temperature of approximately 12°C.

Each DUT was evaluated according to whether the DUT could maintain the maximum steady-state current load (350A, 1000A, or 3000A) without:

(1) Either of the HVDC *contact* thermocouples (T3 for the inlet, T4 for the connector, respectively, as shown in Figure 1) exceeding the 60 K temperature rise limit as specified in IEC 62196-1:(CDV2015)/UL2278 (outline document),
(2) *Any* of the thermocouples exceeding the manufacturer-specified temperature limits, or
(3) *Any* of the thermocouples exceeding the CharIN Task Force temperature target of 100°C.

The results are summarized in Table 9, Table 10, Table 11, Table 12, and Table 13, with maximum temperature rise reported at the hottest of the two contacts. The identity of the hottest contact (connector or inlet) is not reported in these tables to preserve manufacturer anonymity.

Table 9. MCS 350A Steady-State Test Outcomes

DUT	Max. Contact Temperature Rise (K)	Contact Temp Rise Pass/Fail (60K Limit)	Test Outcome (100 °C Limit)
Connector U / Inlet V	20.8	Compliant	Compliant
Connector U / Inlet W	32.9	Compliant	Compliant
Connector U / Inlet X	43.3	Compliant	Compliant
Connector U / Inlet Y	35.2	Compliant	Compliant

Table 10. MCS 1000A New Steady-State Test Outcomes

DUT	Max. Contact Temperature Rise (K)	Contact Temp Rise Pass/Fail (60K Limit)	Test Outcome (100 °C Limit)
Connector Z / Inlet CC	31.0	Compliant	Compliant
Connector Z / Inlet DD	15.0	Compliant	Compliant
Connector Z / Inlet EE	23.4	Compliant	Compliant
Connector Z / Inlet FF	41.9	Compliant	Compliant
Connector AA / Inlet CC	49.3	Compliant	Compliant
Connector AA / Inlet DD	22.2	Compliant	Compliant
Connector AA / Inlet FF	36.9	Compliant	Compliant
Connector BB / Inlet CC	47.5	Compliant	Compliant
Connector BB / Inlet DD	28.6	Compliant	Compliant
Connector BB / Inlet EE	65.1	Non-Compliant	Compliant
Connector BB / Inlet FF	52.2	Compliant	Compliant

* Due to a mating issue, Connector AA and Inlet EE were not tested together.

Table 11. MCS 1000A Aged Steady-State Test Outcomes

DUT	Max. Contact Temperature Rise (K)	Contact Temp Rise Pass/Fail (60K Limit)	Test Outcome (100 °C Limit)
Connector GG / Inlet HH	45	Compliant	Compliant
Connector GG / Inlet II	72	Non-Compliant	Compliant

Table 12. MCS 3000A New Steady-State Test Outcomes

DUT	Max. Contact Temperature Rise (K)	Contact Temp Rise Pass/Fail (60K Limit)	Test Outcome (100 °C Limit)
Connector JJ / Inlet LL	47.5	Compliant	Compliant
Connector KK / Inlet LL	58.6	Compliant	Compliant

Table 13. MCS 3000A Aged Steady-State Test Outcomes

DUT	Max. Contact Temperature Rise (K)	Contact Temp Rise Pass/Fail (60K Limit)	Test Outcome (100 °C Limit)
Connector MM / Inlet NN	45.2 (non-normalized) 50.2 (normalized)*	Compliant	Compliant

*Note: Due to an issue with the NREL Research Chilled Water (RCW) system, the 3000A Aged interoperability evaluation was performed with an RCW temperature approximately 5°C below the usual temperature of approximately 12°C. For easier comparison with other evaluations, the 3000A Aged test max contact temperature was normalized to the standard RCW temperature of 12°C, and both normalized and non-normalized temperatures are presented here.

After reaching steady-state temperature, as defined by IEC 62196-1, the DUTs were subjected to a misalignment evaluation, per IEC 62196-1. A 100N load was applied to the connector for approximately 3 minutes in each of 4 directions in the following sequence: -X, -Y, +X, +Y. This sequence was repeated 3 times, and the DUTs were monitored for temperature variations exceeding ± 5 K, per IEC 62196-1. DUTs with temperature measurements with variance greater than ± 5 K from their steady-state value were marked as 'Fail.' Misalignment testing was performed at the maximum current level the DUT was able to hold during steady-state testing (listed in parentheses in each table). The maximum resistance rise of each DUT during misalignment was also noted, comparing the resistance of the DUT before misalignment loading was applied to the maximum resistance after misalignment loading was applied. One to three locking pins were inserted prior to the misalignment evaluation, depending on manufacturer specification.

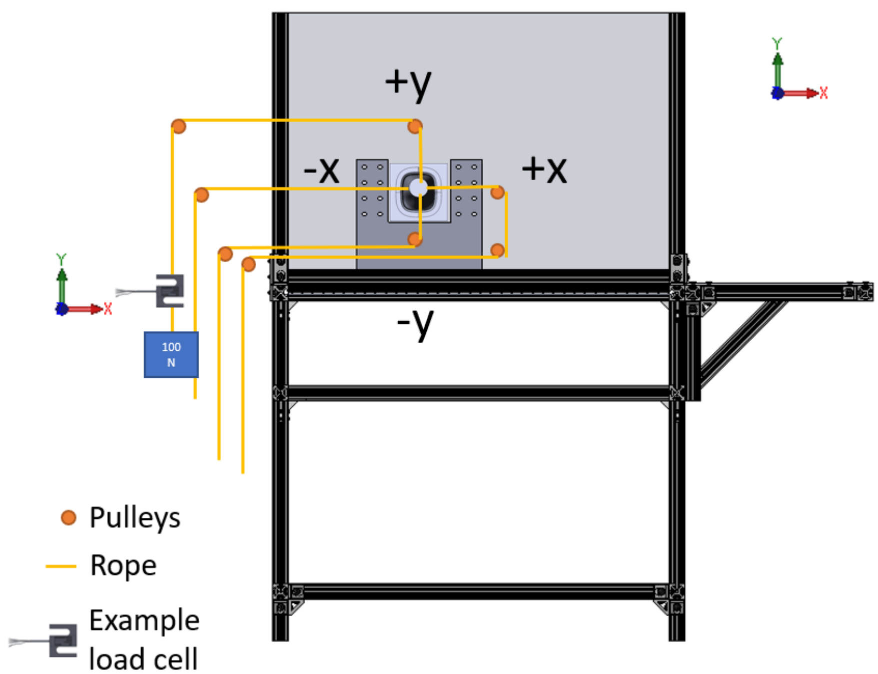


Figure 15. Layout of misalignment test setup with 100N load, facing towards the inlet from the connector end of bench

Table 14, Table 15, and Table 17 summarize the performance of "new" DUTs during misalignment testing at 350A, 1000A, and 3000A. Table 16 and Table 18 summarize the performance of "aged" DUTs at 1000A and 3000A during misalignment testing.

Table 14. MCS 350A Misalignment Test Outcomes

DUT (New)	Test Outcome	Max Resistance Rise (mΩ)	Max Contact Temperature Rise (°C)
Connector U / Inlet V	Compliant	0.014	1.76
Connector U / Inlet W	Compliant	0.003	1.92
Connector U / Inlet X	Compliant	0.007	0.96
Connector U / Inlet Y	Compliant	0.015	1.37

Table 15. MCS 1000A Misalignment Test Outcomes

DUT (New)	Test Outcome	Max Resistance Rise (mΩ)	Max Contact Temperature Rise (°C)
Connector Z / Inlet CC	Compliant	0.013	4.11
Connector Z / Inlet DD	Compliant	0.010	3.92
Connector Z / Inlet EE	Compliant	0.004	2.00
Connector Z / Inlet FF	Non-Compliant	0.012	6.22
Connector AA / Inlet CC	Non-Compliant	0.002	5.76
Connector AA / Inlet DD	Compliant	-0.001	1.46
Connector AA / Inlet FF	Compliant	0.009	4.63
Connector BB / Inlet CC	Compliant	-0.019	2.70
Connector BB / Inlet DD	Compliant	-0.003	1.22
Connector BB / Inlet EE	Compliant	0.074	4.76
Connector BB / Inlet FF	Non-Compliant	0.005	8.03

Table 16. MCS 1000A Aged Misalignment Test Outcomes

DUT (Aged)	Test Outcome	Max Resistance Rise (mΩ)	Max Contact Temperature Rise (°C)
Connector GG / Inlet HH	Non-Compliant	0.018	5.61
Connector GG / Inlet II	Non-Compliant	0.097	44.3

Table 17. MCS 3000A New Misalignment Test Outcomes

DUT (New)	Test Outcome	Max Resistance Rise (mΩ)	Max Contact Temperature Rise (°C)
Connector JJ / Inlet LL	Compliant	0.003	4.89
Connector KK / Inlet LL	Compliant	0.009	3.32

Table 18. MCS 3000A Aged Misalignment Test Outcomes

DUT (Aged)	Test Outcome	Max Resistance Rise (mΩ)	Max Contact Temperature Rise (°C)
Connector MM / Inlet NN	Non-Compliant	0.008	15.61

2 Reference Device Evaluation

2.1 Overview

In order for future MCS connector designs to be more effectively evaluated by industry, development of a “reference device” has been spearheaded by the IEC PT63379 working group. The intent of such a reference device is to serve as a standard inlet that can provide a baseline, minimally-acceptable thermal performance for evaluating connector compatibility in future industry evaluation and device certification efforts. Two prototype reference devices were evaluated during Event 4: a 1500A reference device, and a 3000A reference device, pictured below in Figure 16 and Figure 17 respectively. Reference device evaluations consisted of two types of characterizations. During the first characterization, connectors were run at either 1500A or 3000A, depending on their current rating, until the devices reached steady state, with similar cooling levels as were used in the interoperability evaluations. The second type of characterization was performed with only certain connectors, and consisted of running the device at rated current, then adjusting the cooling level until the reference inlet pin temperatures reached a target level of 100°C (at 40°C ambient), or 85°C (at 25°C ambient). Each evaluation was performed at 40°C, and repeated at 25°C, to help evaluate the necessity and performance implications of the 40°C ambient temperature test requirement.

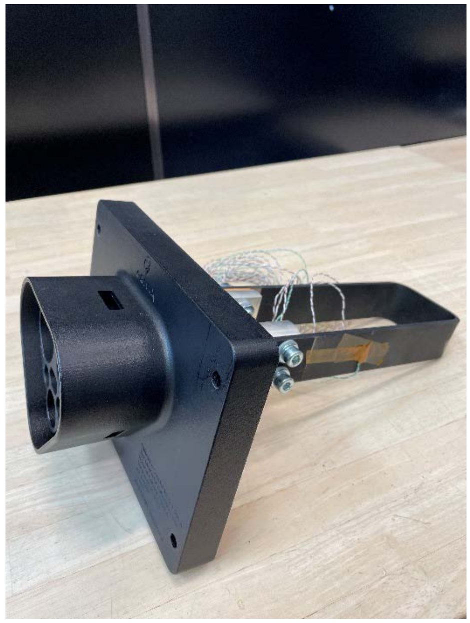


Figure 16: 1500A Reference Device

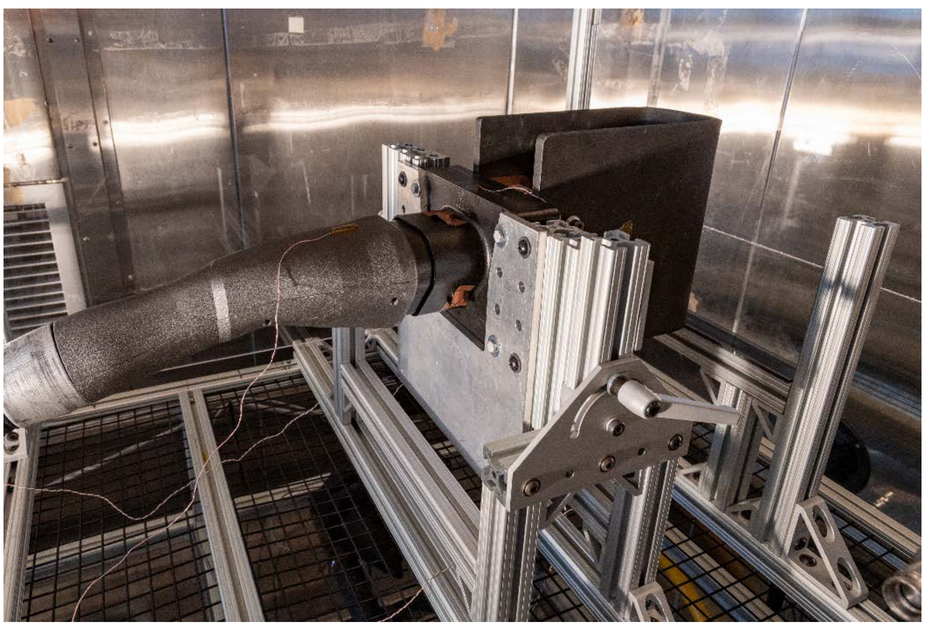


Figure 17: 3000A Reference Device with Connector Attached

2.2 Setup

In order to achieve a 40°C ambient temperature, the thermal interoperability test bench was modified and moved into an Espec thermal chamber with specifications listed in Table 19. In order to fit into the chamber, the bench was shortened and the inlet shorting box and instrumentation shelving was removed. The Plexiglass safety guards remained in place around the perimeter of the bench to provide some blockage of the airflow around the DUT. For 3000A reference device tests, a support bar was placed laterally across the extreme rear of the device to provide mechanical support, as seen in Figure 17.

Due to space constraints within the chamber, most supporting equipment was placed on the chamber exterior, and pass-through ports were utilized to provide power and cooling connections. The Magna-Power DC supply, oscilloscopes, and participant cooling pumps/heat exchangers were all placed outside of the chamber, with coolant tubing and electrical cabling passed through to the bench, as shown in Figure 18. Figure 19 and Figure 20 show the test bench placed within the thermal chamber.

Table 19. Espec Thermal Chamber Specifications

Specifications	
Dimensions	85"W x 142.5"D x 144"H
Volume	1005 ft^3 (28.4 m^3)

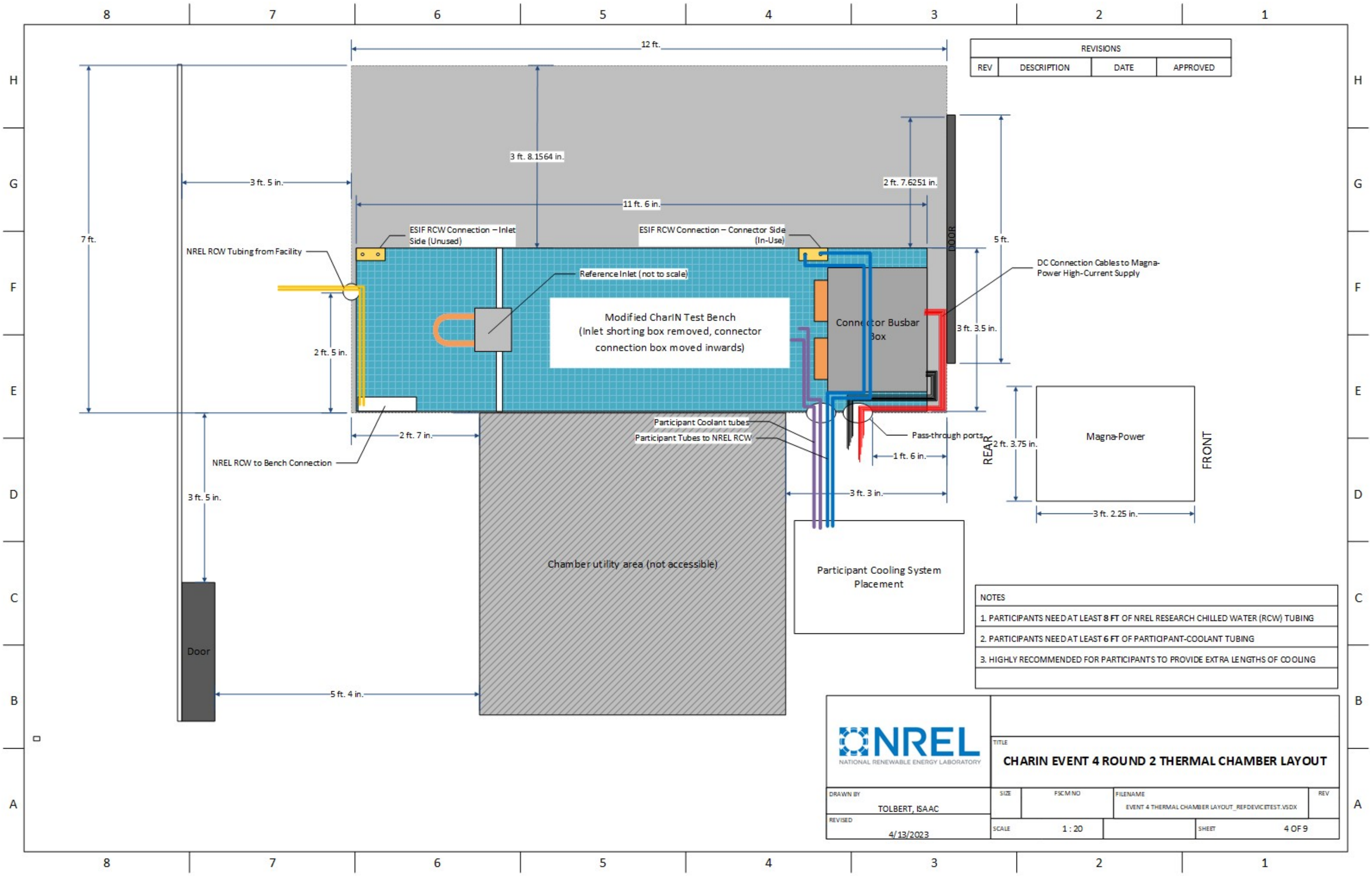


Figure 18: Schematic of thermal chamber and test bench setup, showing cooling and electrical connections

Figure 19: Exterior view of thermal chamber and evaluation bench

Figure 20: Evaluation bench within thermal chamber

A handheld Kestrel 2000 anemometer was used to measure airflow around the reference inlet with the chamber airflow running and the plexiglass guarding in place. The lateral airflow (front-to-back and side-to-side) was measured to be less than 40fpm, below the lowest measurable limit of the anemometer. The vertical airflow was measured to be roughly 50fpm from bottom-to-top. Since the primary way the reference devices cool themselves is via a “chimney effect”, utilizing thermal convection to move heated air vertically through the U-shaped busbar, it was decided to not add any additional guarding in the vertical direction, so as to preserve the integrity of the chimney effect.

To further minimize the effect of chamber airflow on the DUT temperatures, an additional step was taken. To begin the evaluation, the chamber airflow was turned on, and the chamber was allowed to come to the nominal 40°C ambient temperature. With the chamber at the appropriate temperature and chamber airflow running, current was then applied to the DUT. Once the DUT began to approach a steady-state temperature, chamber airflow was turned off such that only the insulation of the chamber and heat of the DUT maintained the required temperature. This was required to avoid the chamber's airflow impacting the reference device temperatures, but as a result, the ambient temperature could rise above or fall below the 40°C nominal setpoint in certain instances. This is examined further in the "Results" and "Discussion" sections. During 25°C evaluations, the chamber was turned off and the chamber door left open, as the lab ambient temperature was very near to 25°C, and this avoided adverse airflow effects from running the chamber.

Due to the placement of the thermal chamber, much longer tubing runs were required to connect the DUTs to the NREL Research Chilled Water system. These longer tubing runs resulted in a lower-than-expected flow rate to the connector cooling systems, of roughly 11.5-12 LPM, as opposed to the 13.5 LPM used during the interoperability evaluations This meant that some devices may have had slightly less cooling power provided during reference device evaluations than during their ambient interoperability evaluation.

Prior to delivery to NREL, the reference devices were instrumented with several T-type thermal sensors, as listed in Table 20.

Table 20. Reference Device Temperature Sensor Locations

Sensor Name	Location
TP1 (+/-)	Inlet DC+/DC- Pins
TP2 (+/-)	Inlet DC+/DC- Pin Collars
TB1	Rear of Inlet Busbar

2.3 Results

The reference device steady-state temperature results are shown the following tables. Table 21 and Table 22 show the results of the 1500A reference device evaluations, while Table 23 and Table 24 show the results of the 3000A reference device evaluations. If a connector was rated for less than 1500A or 3000A continuous, the device was tested with the reference inlet for the participant's informational purposes only, but the results of those evaluations are not included in the below tables for fairness and clarity. For this evaluation, compliance was determined by the devices' ability to keep the reference inlet pin temperatures below 100°C (60K over ambient), to accurately represent the intended evaluation use case and compliance criteria for future industry-led connector evaluations with reference inlets.

Unfortunately, due to a miscommunication between the NREL evaluation team and a hardware provider, the cooling parameters of Connector KK were set too low, leading to reduced cooling power and a lower-than-expected performance of the connector, and non-compliant results in the 25°C ambient evaluations (Table 24). However, even with the reduced cooling power, this connector achieved the temperature limit goals and was compliant at 40°C ambient (Table 23). These results are examined further in the Discussion section. Cooling parameters for each device were maintained at the same level between 40°C and 25°C ambient temperature tests. Additionally, even though Connector BB and Connector KK each were non-compliant at 25°C, their performance when used in the reference device simulation validation (Tables 25-28) demonstrate their ability to meet the 85°C limit at 25°C ambient, when run with some additional cooling power.

Table 21. 1500A Reference Device Steady-State Outcomes (40°C Ambient)

DUT	Max Temperature Rise Over Ambient (Inlet Contacts)	Max Temperature (Inlet Contacts)	Inlet Contact (100°C Limit)
Connector Z / 1500A Reference Inlet	44.1	83.7	Compliant
Connector BB / 1500A Reference Inlet	54.8	94.7	Compliant

Table 22. 1500A Reference Device Steady-State Outcomes (25°C Ambient)

DUT	Max Temperature Rise Over Ambient (Inlet Contacts)	Max Temperature (Inlet Contacts)	Inlet Contact (85°C Limit)
Connector Z / 1500A Reference Inlet	NOT TESTED	NOT TESTED	NOT TESTED
Connector BB / 1500A Reference Inlet	64.5	91.1	Non-Compliant

*Connector Z was not tested with the 1500A reference inlet at 25°C due to time/resource constraints.

Table 23. 3000A Reference Device Steady-State Outcomes (40°C Ambient)

DUT	Max Temperature Rise Over Ambient (Inlet Contacts)	Max Temperature (Inlet Contacts)	Inlet Contact (100°C Limit)
Connector JJ / 3000A Reference Inlet	45.4	87.1	Compliant
Connector KK / 3000A Reference Inlet	50.1	95.5	Compliant

*Connector KK cooling values set lower than manufacturer design.

Table 24. 3000A Reference Device Steady-State Outcomes (25°C Ambient)

DUT	Max Temperature Rise Over Ambient (Inlet Contacts)	Max Temperature (Inlet Contacts)	Inlet Contact (85°C Limit)
Connector JJ / 3000A Reference Inlet	49.4	75.2	Compliant
Connector KK / 3000A Reference Inlet	60.9	87.7	Non-Compliant

*Connector KK cooling values set lower than manufacturer design.

Separately from this event, the 1500A and 3000A reference devices' performance was simulated as part of the IEC PT63379 working group efforts, and simulation results were provided to NREL by a partner within the IEC PT63379 working group effort. To assist in validating the performance of the reference device, a subset of connectors were evaluated with the reference devices at rated current levels, and then the cooling flow rates of the connectors were adjusted until a target inlet pin operating temperature was reached. The pin temperatures were allowed to stabilize for at least 10 minutes after the final cooling flow adjustment, and the pin, collar, and busbar temperatures of the reference inlets were recorded to compare against the provided simulated "target" values. These tests were performed at both 25°C and 40°C ambient temperature conditions to help evaluate the performance of the device at two separate ambient temperatures and provide useful data for determining the necessity of the 40°C ambient temperature requirement for future evaluation efforts.

Comparisons of the 1500A and 3000A reference device temperatures to the simulated target temperatures at 40°C and 25°C ambient are provided in Table 25, Table 26, Table 27, and Table 28. Connector BB was used for the 1500A reference device temperature comparison, while Connector KK was used for the 3000A reference device temperature comparison.

Table 25. 1500A Reference Device Temperature Comparison – Target vs. Actual (40°C Ambient)

Sensor Name	Target (40 °C Ambient)	Actual (38.1 °C Ambient)
Sensor TP1 (+/-)	100	102 (TP1+) 97.7 (TP1-)
Sensor TP2 (+/-)	110	112.1 (TP2+) 106.1 (TP2-)
Sensor TB1	144	146.8

Table 26. 1500A Reference Device Temperature Comparison – Target vs. Actual (25°C Ambient)

Sensor Name	Target (25 °C Ambient)	Actual (27.7 °C Ambient)
Sensor TP1 (+/-)	85	79.5 (TP1+) 90.9 (TP1-)
Sensor TP2 (+/-)	95	91.7 (TP2+) 98.1 (TP2-)
Sensor TB1	129	133.3

Table 27. 3000A Reference Device Temperature Comparison – Target vs. Actual (40°C Ambient)

Sensor Name	Target (40 °C ambient)	Actual (48 °C ambient)
Sensor TP1 (+/-)	100	100.1 (TP1+) 100.0 (TP1-)
Sensor TP2 (+/-)	87	88.7 (TP2+) 89.1 (TP2-)
Sensor TB1	77	78.2

Table 28. 3000A Reference Device Temperature Comparison – Target vs. Actual (25°C Ambient)

Sensor Name	Target (25 °C Ambient)	Actual (27.5 °C Ambient)
Sensor TP1 (+/-)	85	85.2 (TP1+) 84.5 (TP1-)
Sensor TP2 (+/-)	72	73.4 (TP2+) 73.6 (TP2-)
Sensor TB1	62	62.4

2.4 Discussion

Several interesting aspects of the reference device performance were noted which should be considered for future MCS evaluation/device certification efforts.

The first aspect is the significant effect of chamber airflow on the reference device temperatures. The reference device test specification in IEC PT63379 specifies that the test environment should be free from forced convection and maintained at a temperature of 40°C, with a tolerance of +/- 5°C. With the chamber airflow running and guards in place to mitigate lateral airflow, and a relatively minor vertical airflow (which had to be left unguarded to allow the device's chimney effect to function), it was found that chamber airflow could cause a cooling effect of roughly 4-7 °C on the reference device busbar, which could potentially cause lower-than-expected temperatures on the device pins and affect evaluation results.

During these evaluations, the airflow effect as described above was mitigated by turning off the chamber airflow once the device began to approach its steady-state temperature. However, this is not a perfect solution. Depending on the configuration of the reference devices, connectors, and applied current, the ambient temperature within the chamber could vary significantly once airflow had been turned off. For example, during the 3000A evaluation, the higher resistive heat load generated by a 3000A current could result in the chamber temperature increasing dramatically – during one 40°C ambient evaluation, an ambient temperature rise of up to 8°C was observed (which put the chamber temperature above the prescribed 45°C maximum limit). Conversely, a 1500A test may not generate enough of a resistive heat load to fully maintain the ambient chamber temperature at 40°C after airflow is turned off.

Secondly, it can be seen that, counterintuitively, several devices were compliant in the reference device evaluations at 40°C ambient, but were non-compliant when the evaluations were repeated at 25°C ambient. (As mentioned previously, the 3000A Connector KK were inadvertently run at a lower-than-designed cooling value due to a miscommunication during both the 40°C and 25°C evaluations.) It should be noted that the compliance condition is set at a 100°C limit on the inlet contacts at 40°C ambient test temperature, and the inlet contact limit is set at 85°C with an ambient test temperature of 25°C. For passively-cooled connectors, it is established practice in industry to perform a temperature rise test at an ambient temperature between 25°C and 40°C, and then correct the result to the maximum ambient environmental temperature of 40°C. However, with actively cooled connectors, such as the 1500A and 3000A devices examined in these evaluations, the cooling system partially masks the ambient temperature's effect. Thus, it can be seen from the results that the reference inlet contact temperatures are not completely linearly related 1:1 with the evaluation's ambient temperature. If the pin contact and ambient temperatures were linearly related 1:1, it would be expected that, at the same current level with the same DUTs, there would be a pin contact temperature increase of 15°C between evaluations performed at 25°C and 40°C (as would generally be expected for passively-cooled components). However, during the evaluations, it was seen that inlet contact temperatures only increased between 3.6°C and 11.9°C between evaluations run at 25°C and 40°C, respectively, at the same current rating. This implies that the 85°C pin temperature limit at 25°C ambient actually presents a more difficult target to the connector than the 100°C pin temperature limit at 40°C ambient. In other words, a connector that passes the reference evaluation at 25°C ambient would likely pass the evaluation at 40°C, if the same cooling parameters were utilized. Future evaluation efforts should consider this lack of a 1:1 relationship between the inlet contact temperature and the ambient test temperature when setting ambient temperature conditions and compliance criteria.

Another effect that was noticed during some reference evaluations was a temperature imbalance between the inlet's positive and negative DC pins. In the ideal case, this temperature imbalance would be minimal (and it was, during some evaluations – sometimes less than 1°C). However, for some DUT combinations, it was seen to be as high as 10°C or more. The exact cause was not found during this event.

3 Mechanical Evaluations

3.1 Overview

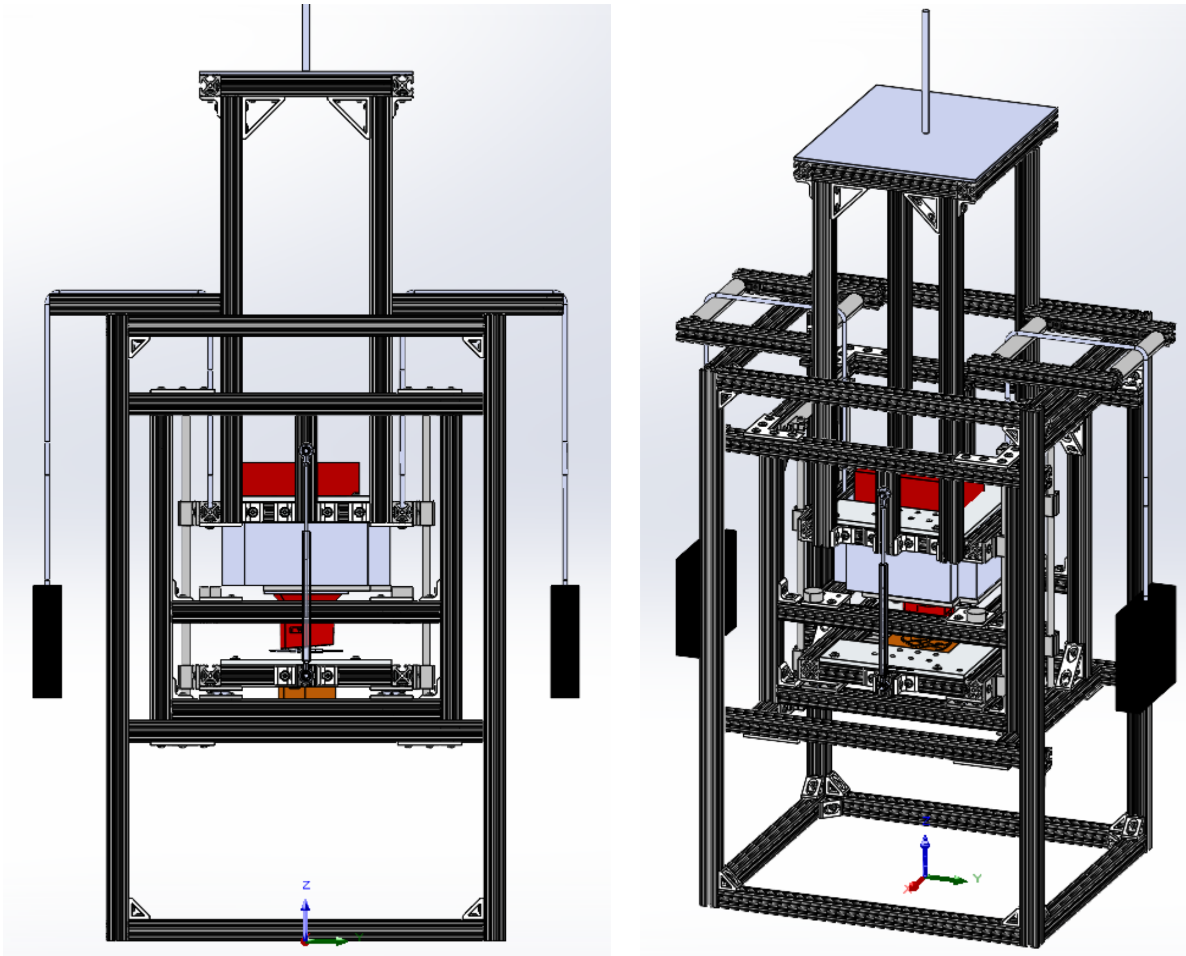
In order to characterize the mechanical aspects of the MCS devices, several mechanical evaluations were conducted. These included insertion, withdrawal, and touch-safety evaluations. Insertion and withdrawal evaluations consisted of performing insertion/withdrawals with all combinations of inlets in a "round-robin" format, while measuring insertion/withdrawal forces and the DUT pin connection/disconnection sequence. Touch-safety evaluations consisted of using an IEC test finger, described in IEC 60529, to probe the DC+ and DC- pins of each connector and inlet while checking for continuity. These evaluations, like the thermal interoperability and reference device evaluations, were conducted with molded components to more accurately represent the forces that would be experienced by actual production-intent devices.

3.2 Insertion and Withdrawal Evaluations

Insertion evaluations examined the insertion characteristics, based on IEC 62196-1, Section 16.15. Some modifications to the IEC 62196-1 test setup and procedure were made to more efficiently perform the test within NREL's setup.

3.2.1 Mechanical Evaluation Rig Setup

The evaluations were performed by mounting the connector and inlet vertically with the Mechanical Evaluation Rig (MER), shown in Figure 21. The connector was mounted near the bottom of the rig, with the inlet placed above. For the insertion evaluations, the connector was fixed in place, with the inlet placed above it on a movable platform, which allowed the inlet to move downwards during the mating process. For withdrawal evaluations, the inlet was fixed in place, with the connector attached to a movable platform below it, allowing the connector to move downwards to unmate from the inlet. For each evaluation, force and distance sensors characterized the forces observed at various points during the insertion/withdrawal process, while wiring attached to each of the DUTs' seven pins (DC+, DC-, PE, PHY1, PHY2, CP, PP) measured continuity between the connector and inlet during the mating/unmating process.



(a) (b)

Figure 21: (a) Mechanical Evaluation Rig (side view); (b): Mechanical Evaluation Rig (orthogonal view)

To accurately capture the forces involved and distances between mating components, several sensors were used:

Table 29. Equipment Used for MCS Mechanical Evaluation Data Capture

Type	Description
Oscilloscope	Yokogawa DL950
Analog Voltage Input Module (x4)	Yokogawa 720250
Analog Voltage Input Module (x4)	Yokogawa 720268
Power Supply	Agilent E3632A
Linear Position Transducer (x3 for insertion) Linear Position Transducers (x2 for withdrawal)	Celesco CLP-150
Force Transducer (x3)	Interface LBM-250
Force Transducer Multi-Channel Bridge Amplifier	Interface BSC4A-C14

While three linear transducers were used to characterize the position of the mating components during the insertion evaluations, due to limitations in the physical configuration of the MER, the number of linear position transducers was reduced to two during the withdrawal evaluations.

3.2.2 Insertion Evaluation Procedure

During setup of the insertion evaluations, the connector and inlet were slowly mated until the first pins began to make contact (this was usually the PE pin). This distance was noted as the "point of first contact." Once this point had been established, the inlet was unmated and raised 10mm to the starting point for the evaluation. This point was chosen for several reasons. First, by choosing a consistent starting point each time, each DUT combination would have a similar amount of mechanical momentum when the insertion weights were applied. Second, by placing the devices 10mm above the point of first contact, the devices were prevented from building up an excessive amount of mechanical momentum before mating began.

To begin the evaluation, approximately 90N of weight was applied to the top of the platform, without jolting, and the inlet was allowed to mate with the connector. If electrical continuity was established between all seven pins of the connector and inlet, an attempt was made to insert the inlet locking pins to secure the connector and inlet together and confirm full mechanical mating. Otherwise, a 10N weight was dropped onto the weight stack from a height of 5cm, for a total force of 100N. Connectors and inlets which mated at this point or before, showing full electrical continuity on all pins, were judged to have passed. Otherwise, the test was judged to have failed the insertion force test. For DUT combinations which failed the 100N insertion force criteria, weight was added in 22.4N (5lb) increments, without dropping or jolting, until full electrical and mechanical mating was achieved.

3.2.3 Withdrawal Evaluation Procedure

The withdrawal evaluations began with each connector and inlet pair fully mated, as confirmed by the insertion of the inlet's locking pin. Similar to the insertion evaluations, the withdrawal evaluations began with the application of approximately 90N of weight to the top of the platform, without jolting, in an attempt to unmate the devices. If the devices did not unmate, a 10N weight was dropped onto the weight stack from a height of 5cm, for a total applied force of 100N. Devices which unmated at this point (all pins electrically disconnected) were judged to have passed the withdrawal test. For DUT combinations which failed the 100N withdrawal force criteria, weight was added in 22.4N (5lb) increments, without dropping or jolting, until the full electrical and mechanical disconnection was achieved.

3.2.4 Insertion and Withdrawal Evaluation Results

In total, three connector samples and four inlet samples were evaluated together in "round robin" format, for a total of 12 DUT combinations (however, one DUT combination, Connector RR/Inlet TT, could not be fully mated due to a mechanical incompatibility, so there were only 11 "full" DUT combination evaluations).

Additionally, there were difficulties with the connector clamp provided by the manufacturer for Connector PP. The tapered shape of the connector handle was simple enough to secure against insertion forces. However, the high tolerances in the manufacturer's 3-D printed form-fitting clamp, used to attach the connector to the MER, meant that a compressible material had to be used to fill the resulting gap between the clamp and the connector. This compressible material allowed the connector to move with respect to its clamp during the withdrawal tests, up to approximately 20 mm. This meant that a data processing correction was needed in order to accurately characterize this device's performance in comparison to other DUTs.

To create a corrected data set of distance between connector PP and the inlets during the withdrawal tests, the average pin contact distances during the connector PP withdrawal tests (across all inlets) was mapped to the average pin contact distances across the connector PP insertion tests. A polynomial curve was fit to this data, and used to create a set of corrected distances for Connector PP. A separate correction curve was created for each inlet. While the correction curve was not perfect, it better aligned the withdrawal force and pin disconnection data better with the corresponding insertion force and pin connection data, allowing for a more accurate comparison by reducing the effect of the connector shifting within its holder.

Figure 22 illustrates the insertion and withdrawal forces with respect to the mating distance, while Figure 23 illustrates the pin connection/disconnection sequence observed during the insertion and withdrawal tests, as observed at different distances during the mating/unmating process. In both figures, the 0mm position indicates a full mechanical mate, with the front face of the connector and bottom interior face of the inlet touching. Devices are listed as compliant with the 100N insertion/withdrawal force criteria if electrical contact on all 7 pins was made/broken with less than 100N of force (averaged across three evaluation runs). To minimize the effect of potential measurement error and inconsistency, each DUT combination was evaluated multiple times, and the three best/most consistent evaluation runs were chosen for analysis. Table 30 summarizes the number of devices which were compliant with the insertion/withdrawal force criteria.

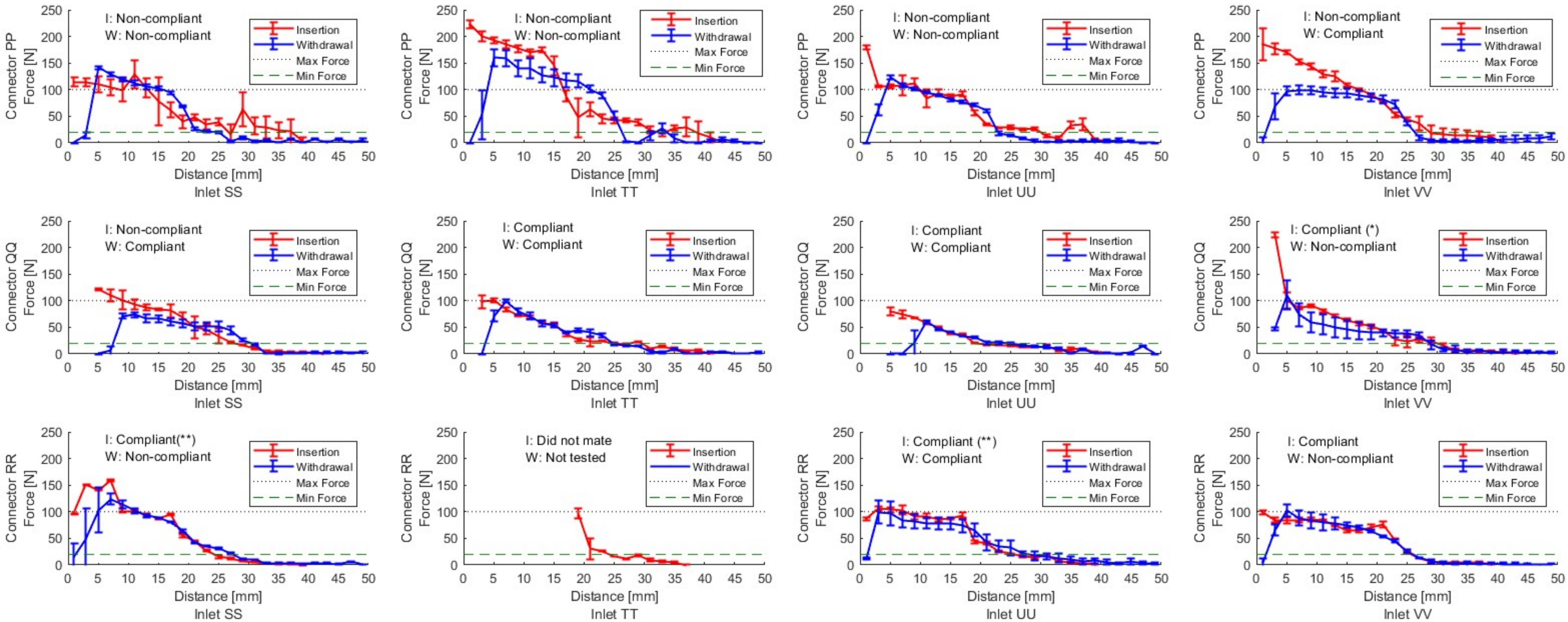


Figure 22: Insertion and Withdrawal Force vs. Distance

Position "0mm" indicates a complete mechanical mate. (I.e. insertion process starts at 50mm and ends at 0mm, while withdrawal process starts at 0mm and ends at 50mm.) Error bars on plot represent spread of observed forces across 3 separate evaluation runs.

Connector RR and Inlet TT were not evaluated for withdrawal forces, as they could not be fully mated.

**Note: Combination QQ and VV are listed as insertion force-compliant despite force spike at <5mm, as electrical contact was made with all 7 pins prior to this at less than 100N force.*

***Note: Combination RR/UU and RR/SS are listed as insertion-force compliant, despite transient force spikes over 100N during insertion process evaluation. Actual applied force was less than 100N in both cases (as can be seen by forces stabilizing at <100N at full mating, distance = 1mm).*

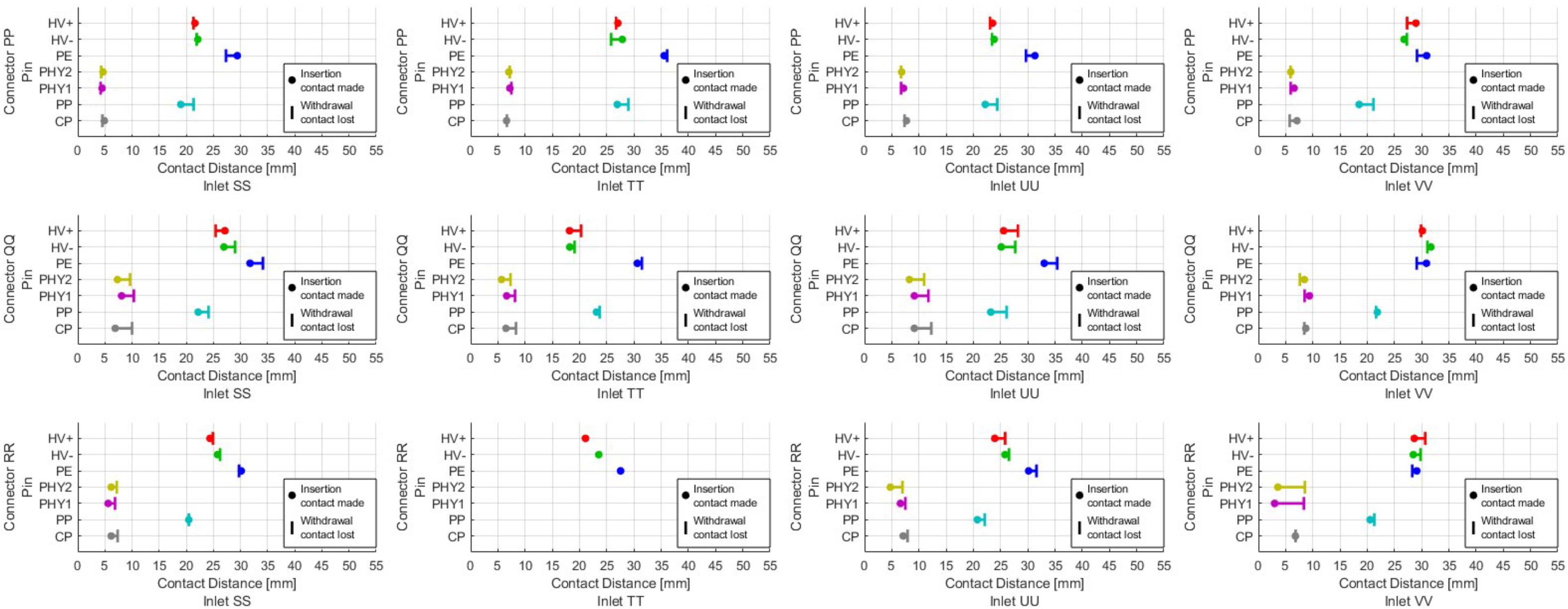


Figure 23: Insertion and Withdrawal Pin Contact Sequence

**Connector RR and Inlet TT were not evaluated for withdrawal pin disconnect sequencing, as they could not be fully mated. Position “0mm” indicates a complete mechanical mate. (I.e. insertion starts at 50mm and ends at 0mm, while withdrawal starts at 0mm and ends at 50mm.) Circular designators indicate pin connection point during insertion, while vertical bars indicate pin disconnection point during withdrawal.*

Table 30. Insertion/Withdrawal Force Summary

Type	Total Compliant DUT Combinations
Insertion Force (<100N)	6 (of 11)
Withdrawal Force (<100N)	5 (of 11)

3.2.5 Insertion and Withdrawal Evaluation Discussion

From Figure 22, it can be seen that roughly half of the evaluations were compliant with the insertion/withdrawal force criteria, with 6 combinations meeting the insertion force criteria of less than 100N, and 5 combinations meeting the withdrawal force criteria of less than 100N. Three combinations were compliant with both the insertion and withdrawal criteria. This suggests that more refinement is needed for these pre-production devices to fully comply with the 100N force requirement, but does demonstrate that the MCS standard is capable of meeting this insertion/withdrawal force target. Several refinements were identified from this evaluation and reported to the manufacturers to improve insertion/withdrawal force performance.

In Figure 23, it can be seen that the pin connection and disconnection sequence was generally consistent and correct across most DUTs. On insertion, only 1 of 11 DUT combinations experienced a significant pin connection sequence issue, with DC- connecting slightly before protective earth (PE). On withdrawal, only 2 of 11 DUT combinations experienced a significant pin disconnection sequence issue, with PE disconnecting before one or both of the DC pins. In the Figure 23, it can be seen that several devices experienced minor connection/disconnection sequence errors, with the PHY1/2 connecting slightly after (or disconnecting slightly before) the CP pin, but these errors were generally small, often with a difference of 0.5mm or less, placing most of these occurrences within the margin of error of the MER.

For full understanding of these results, and informing future evaluation efforts, several limitations of the insertion/withdrawal evaluations should be noted. First, the MER relied on a system of rollers and rope-suspended counterweights to apply the prescribed force while counteracting the weight of the rig and DUTs, which introduced noticeable mechanical losses into the system through friction. While this could be countered through real-time adjustments during the evaluation and through data post-processing techniques, these losses could introduce noticeable variability between evaluation runs.

Additionally, the connector and inlet were each rigidly mounted in place, with no flexibility to adjust the insertion/withdrawal angle or tweak the devices' alignment as they were inserted. To adjust for this limitation, each device was fully mated together before the final DUT mounting bolts were tightened, in order to ensure that the devices were in their most optimal position for mating (or as near as could be reasonably achieved). However, even with this technique, the limitation of the rigid mounting structure meant that devices could not be adjusted or tweaked during insertion, as a real human would instinctively do to find the path of least resistance.

3.3 Touch-Safety Evaluation

3.3.1 Touch-Safety Evaluation Setup

Touch safety evaluations were performed using an IEC 60529 test finger. The test finger was attached to a force gauge using a custom mounting assembly which allowed a wire attached to the conductive portion of the finger to be passed through. This wire was attached to a multimeter, and the other end of the multimeter was attached to the DC+ and DC- contacts of the DUT. The probe was then inserted into the DC+ and DC- pins of the DUT with up to 10N of force, in a variety of different orientations, around the entire circumference of each respective pin. The 3 primary finger insertion orientations were:

1. "Straight in" – The finger was inserted in parallel with the DC pin/receptacle, with no inward or outward tilt.
2. "Angled outwards" – The finger was angled outwards, towards the outer contact surface of the DC pin/receptacle.
3. "Angled inwards" – The finger was angled inwards, towards the center of the DC pin/receptacle.

Each of these angles were repeated along the entire circumference of the DC+ and DC- contacts. To conclude the test, a final pass was made around the circumference of the DC+/- contacts, while varying the insertion angle and orientation of the finger. If the DUT successfully prevented connection between the DC+/- contacts and the test finger with up to 10N of insertion force, the device was determined to have passed. If the test finger was able to make contact with the conductive portion of the pins with less than 10N of force, the device was determined to have failed.

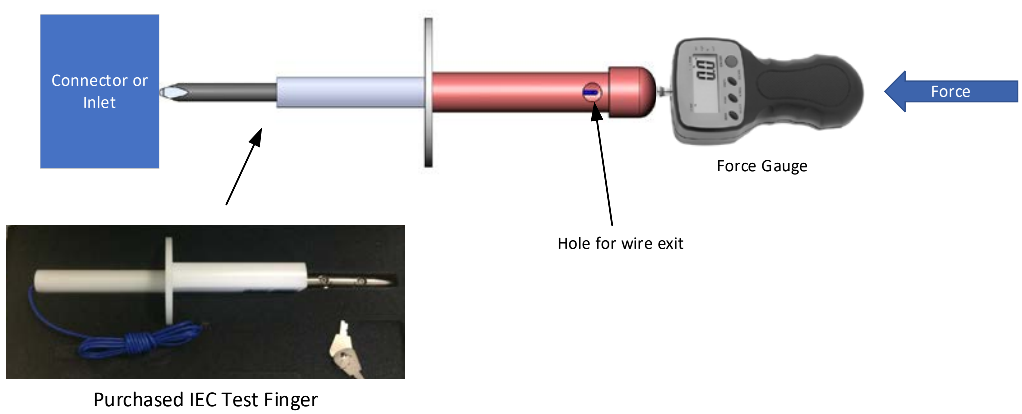


Figure 24: IEC Touch-Safety Finger Setup

3.3.2 Touch-Safety Evaluation Results

The touch-safety evaluation results with each respective insertion angle are listed in tables below. Table 31 lists the touch-safety evaluation results for each connector manufacturer, while Table 32 lists the evaluation results for each inlet manufacturer.

Table 31: Connector Touch-Safety Evaluation Results

DUT	Test Outcome In Probing Direction		
	Straight In	Angled Outwards	Angled Inwards
Connector WW	Non-Compliant	Non-Compliant	Compliant
Connector YY	Non-Compliant	Non-Compliant	Compliant
Connector XX	Compliant	Non-Compliant	Compliant

Table 32: Inlet Touch-Safety Evaluation Results

DUT	Test Outcome In Probing Direction		
	Straight In	Angled Outwards	Angled Inwards
Inlet ZZ	Non-Compliant	Non-Compliant	Non-Compliant
Inlet AAA	Compliant	Compliant	Compliant
Inlet BBB	Compliant	Compliant	Compliant
Inlet CCC	Non-Compliant	Non-Compliant	Non-Compliant

3.4 Mechanical Evaluations Discussion

From the above results, it can be seen that some work remains to refine the mechanical characteristics of these connector and inlets devices to fully comply with the 100N insertion/withdrawal force requirement. Discarding one DUT combination which could not mate, of the 11 remaining DUT combinations, 6 combinations were fully compliant with the insertion force requirement, while only 5 combinations were compliant with the withdrawal requirement. This suggests that further mechanical refinement is needed to bring the evaluated samples fully into compliance, but the results do demonstrate that the 100N insertion/withdrawal force criteria is attainable with the MCS design.

While slightly more combinations were compliant with the insertion evaluation (electrical contact on all pins with less than 100N force) than were compliant with the withdrawal evaluation (disconnection with less than 100N force) (6 combinations on insertion vs. 5 on withdrawal, respectively), as a whole, the forces required to complete the action were generally lower on withdrawal. To look at the results more broadly, 10 of the 11 DUT combinations successfully withdrew with 150N of force or less, while only 7 combinations successfully fully inserted to make electrical contact on all 7 pins with 150N of force or less. One potential explanation for this is that the rigid mounting structure of the MER (as mentioned previously) meant that there was no ability for the devices to naturally move and angle themselves slightly, as would happen during a human-performed insertion – when the devices were brought to their initial position for insertion, minor shifts in the device mounting plates during movement could have slightly thrown off the mating angle, increasing required insertion force. For withdrawal testing, since devices were first fully mated, then secured firmly into their mounting plates, without any movement before beginning the test, it's possible that they began the test in a more advantageous position, leading to lower overall forces needed. More investigation is needed to fully understand this behavior.

Of the touch safety evaluations, none of the connectors and only 2 of the 4 inlets were fully compliant in keeping a conductive finger, applied with up to 10N of force, away from the conductive surfaces of the DC+/- pins. Further development may be needed to improve this behavior, especially on the connector devices, on which it can be seen that all connector samples were non-compliant when the test finger was angled towards the outside edges of the DC+/- pin. On some of the devices, there was noticeable movement and flexibility in the plastic touch protection pin mounted within each DC contact, which allowed the conductive finger to push aside the touch protection and make contact. On others, it seemed as if some of the touch-safety pins were slightly off-centered, allowing the finger to slip by uninhibited. It's possible that this was due to a manufacturing imperfection on these pre-production devices, or perhaps the pin had shifted as a result of the earlier mechanical and thermal evaluations. Further development to strengthen and improve the rigidity of the plastic touch-safety pins on individual devices is likely needed.

4 Summary Observations

Overall, the evaluations performed during this event demonstrated the viability of the MCS standard to support currents up to 3000A while meeting thermal and mechanical interoperability goals laid out by the CharIN MCS Task Force, SAE J3271, and IEC 63379 groups. The connectors demonstrated a strong thermal interoperability performance across the 350A, 1000A, and 3000A evaluations, with the majority of connectors and inlets meeting the thermal criteria, both while at steady-state and while under a misalignment load. This strong performance carried over to the 1500A and 3000A reference device tests, in which all evaluated 1500A- and 3000A-rated connectors were compliant with the thermal performance criteria at an ambient temperature of 40°C. Additionally, the performance of the reference devices themselves demonstrated a strong correlation with the simulated results generated by industry partners, which provided a crucial validation of the reference device design. Finally, while some work remains to further refine the devices' mechanical performance, several devices were fully compliant with the insertion/withdrawal force requirements and the touch-safety requirements, demonstrating a general ability of the MCS standard to meet these operational goals.