Pull Force Evaluation of CCS Insulated End Caps

CHARGEX consortium

JANUARY 2026

DOE/GO-102026-6942

Argonne NATIONAL LABORATORY

INL Idaho National Laboratory

NATIONAL LABORATORY OF THE ROCKIES

Disclaimer

This report was prepared for the U.S. Department of Energy under DOE Idaho Operations Office Contract No: AC07-05ID14517, U.S. Department of Energy M&O Contract No: DE-AC36-08GO28308, and U.S. Department of Energy Office of Science Laboratory Contract No: DE-AC02-06CH11357. Funding was provided by the Joint Office of Energy and Transportation

Acknowledgments

The National Charging Experience (ChargeX) Consortium is a collaborative effort between Argonne National Laboratory, Idaho National Laboratory, the National Laboratory of the Rockies (NLR), electric vehicle charging industry experts, consumer advocates, and other stakeholders. This report was produced by the ChargeX Consortium's Hardware Task Force. We would also like to acknowledge Joel Miscall and Lisa Stanley from NLR's Polymer Science and Engineering team for their assistance with the material analysis of the insulated end caps.

Authors

Saroj Shinde, Isaac Tolbert, Andrew Meintz, and Kristi Moriarty, National Laboratory of the Rockies

Contributors

Keith Beckstead (EVgo), and Kenneth Tennyson (Electrify America)

Executive Summary

This report assesses the sections in the International Electrotechnical Commission (IEC) 62196-1:2022 § 26.7 standard related to insulated end caps that explore the temperature variation effects on the end caps followed by the pull force. Further, it incorporates evaluations with modifications to IEC 62196-1:2022 § 26.7 to align with SAE J3400, accompanied by additional evaluations proposed by industry experts.

Poorly secured insulated end caps acting as debris in the charging connector have been identified as a contributing factor to increased fire and electric shock hazards. This work was initiated to understand if IEC 62196-1:2022 specifies sufficient mechanical pull force for the insulated end caps to prevent the end caps from becoming dislodged during normal use. To investigate this, the National Charging Experience (ChargeX) Consortium's Hardware Task Force purchased numerous Combined Charging System (CCS) charging inlets from original equipment manufacturer dealerships and subjected the end caps to different thermal preconditioning criteria followed by a pull-force evaluation. SAE J3400 North American Charging System (NACS) inlets were not included in the study due to the lack of diverse field data. Several electric vehicles, electric vehicle supply equipment, and connector manufacturers are present in the CCS market, whereas there is currently significantly less diversity in the NACS market. As a result, more data is available on the operation of CCS devices, so this study centered on the insulated end caps of the CCS charging inlet. The fundamental principles of the end caps for SAE J1772 CCS and SAE J3400 are equivalent, so this work is expected to be directly applicable to both standards. The DC pins used in this study have a similar diameter to SAE J3400 pins, and the relevant standards are defined based on pin size rather than connector geometry, irrespective of the influence of the geometry on pull forces induced on the pin caps. Additionally, data was collected from different charging network operators to understand the field failure prevalence and material properties of end caps that were found to be dislodged in charging connectors in the field.

NLR performed material analyses on the end caps and compared them with field debris to ensure coverage of inlet samples associated with dislodged end caps. Following this, insulated end caps from various charging inlets were evaluated under varying temperature and humidity conditions and pull-force testing. To increase the robustness of the pin caps and to reduce the incidence of them becoming dislodged in charging connectors, the pull force should be increased to a minimum of 150 N. This would align the evaluation with the field data, where more robust pin caps have shown a lower prevalence of being left in the connector than those that show a high prevalence of being left in the connector. Although this is an increase in force from 40 N in IEC 62196-1:2022, it is less than the 450 N included in the SAE J3400 Recommended Practice, which uses a different precondition requirement for aging and pull temperature. The study's results also indicated that pull temperature, especially when samples were soaked at higher temperatures than at room temperature, was more crucial for showing end cap separation than a longer preconditioning duration.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

Abbreviation	Description
CCS	Combined Charging System
ChargeX	National Charging Experience
CNO	charging network operator
DC	direct current
EV	electric vehicle
EVSE	electric vehicle charging system
FTIR	Fourier transform infrared spectroscopy
IEC	International Electrotechnical Commission
NACS	North American Charging System
NLR	National Laboratory of the Rockies
OEM	original equipment manufacturer
PBT	polybutylene terephthalate
PC	polycarbonate
PET	polyethylene terephthalate
TGA	thermogravimetric analysis

1. Introduction

As the deployment of electric vehicles (EVs) and electric vehicle supply equipment (EVSE) expands in the North American market, demand for fast-charging solutions is also increasing. Direct current (DC) fast chargers play a key role in enabling long-distance travel by providing much faster charging times, whereas alternating current (AC) chargers typically require longer dwell periods. Additionally, numerous automobile manufacturers are adopting the North American Charging Standard (NACS), increasing the surge of adapters in the market to allow compatibility between Combined Charging System (CCS) and NACS chargers.

To ensure broad compatibility, user safety, and a seamless charging experience across various EV models, a range of standards has been established. A critical component among these standards is having touch safety, which is important for protecting users from electric shock hazards. This touch safety in EV charging inlets is achieved using insulated end caps that are fitted onto the electrical pins (see Figure 1).

But there have been incidents where the DC pins' insulated end caps (which are used during DC fast-charging sessions), from either the EV charging inlet or a charging adapter, have been detached during the mating of the charging connector and the inlet. These occurrences have been documented for both legacy Tesla connectors and CCS systems. Figure 1 illustrates a CCS charging inlet with the insulated end caps intact on the DC pins, and Figure 2 shows a CCS charging inlet where the insulated end caps have been detached.

Figure 1. CCS charging inlet with the insulated DC pin end caps attached. *Photo by NLR*

Figure 2. CCS charging inlet with the insulated DC pin end caps detached. *Photo by NLR*

The secure retention of these insulated end caps is crucial, as they can become dislodged and become trapped within the EVSE charging connector, acting as debris. This situation could compromise the integrity of the connection, leading to improper contact with the EV pins. Such issues can result in overheating of the pins or arcing during the charging process, posing serious risks, including fire hazards and other electrical dangers. These incidents could necessitate the urgent replacement of the charging connector pin in the field to ensure continued safe operation.

For example, Figure 3 shows a side and top view of a CCS charging connector DC pin that is in good condition. Figure 4 shows a damaged EVSE connector DC pin; with the kind of damage that can result from pollution caused by a detached insulated end cap. The damaged connector pin shows effects from arcing and thermal damage.

Figure 3. Side and top view of a CCS connector DC pin. *Photos by NLR*

Figure 4. Side and top view of a damaged CCS connector DC pin. *Photos by NLR*

The standards International Electrotechnical Commission (IEC) 62196-1:2022 and UL 2251 specify these requirements for touch safety. IEC 62196-1 discusses a mechanical strength test for insulated end caps that involves subjecting the end caps to a temperature change test followed by a pull test; however, UL 2251 (the safety standard used in the United States that covers requirements for EV plugs, receptacles, connectors, and inlets) does not specify a testing requirement for these insulated end caps to ensure that they are not left in the connector after a charging session. SAE J3400 also includes a testing requirement for these insulated end caps to ensure that they can withstand the forces seen in the field, which is more strenuous than the IEC pull force evaluation. However, SAE does not require third party conformance evaluations as is required for UL listing of components. Manufacturers might choose not to complete these evaluations, and public data on this requirement is not well known. The pull evaluation included in SAE J3400 was suggested by a manufacturer that found that a more robust evaluation reduced the occurrence of dislodged pin caps.

To investigate this issue, the National Charging Experience (ChargeX) Consortium Hardware Task Force evaluated EV/EVSE charging systems, specifically connector and inlet interfaces, to assess pin cap performance under varying temperatures and applied forces simulating real-world conditions. Numerous CCS charging inlets were purchased from various original equipment manufacturer (OEM) suppliers and dealerships and then sent to UL Solutions for evaluation according to the defined procedure mentioned in the standards along with the additional evaluations recommended by industry experts and to align the evaluations with SAE J3400. SAE J3400 inlets were not included in the study due to the lack of diverse field data.

2. Sample Acquisition

Several OEM charging inlets and commercially available charging connectors were carefully selected for the insulated end cap evaluation. For this assessment, we acquired 9 CCS inlets each from 7 identified manufacturers, for a total of 63 inlet samples. Additionally, we sourced 22 charging connector samples from a commercially available equipment supplier. These charging connectors were paired with the various inlets for detailed evaluations, which were conducted by UL.

Table 1 and Table 2 provide specifications for the purchased inlets and connectors. Some inlet current ratings are estimates, derived from considerations of wire gauge and the maximum DC charging power capacity of the corresponding EV.

Table 1. Charging Inlet Samples

Inlet Manufacturer	Inlet Current Rating (A)	Wire Outer Diameter
A	310	13.8
B	250	12.4
C	230	11
D	200	11
E	200	11
F	200	11
G	100	8

Table 2. Charging Connector Samples

Connector Manufacturer	Connector Current Rating (A)	Quantity
Z	200	6
Z	40	14
Y	200	1
S	200	1

Each manufacturer was subjected to three evaluations, with each evaluation requiring three distinct charging inlet samples. This totaled 9 charging inlet samples per manufacturer (2 insulated end caps per inlet, for a total of 18 insulated end cap samples per manufacturer), ensuring a thorough and comprehensive evaluation process.

Given the extensive variety of EVs presently available in the market, a systematic approach was undertaken to select the charging inlet samples for the evaluations. Our initial step involved engaging with various OEM dealerships to gain insight into their procurement procedures and the availability of inlet samples. We approached various OEM dealerships to secure inlet samples from each, ensuring that each supplier for the charging inlets was distinct and could offer nine inlets for procurement. A primary criterion was that each inlet sample must feature DC charging pins or possess the capability for DC charging. To further refine our selection process, we consulted with the charging network operator (CNO) to understand the types of materials commonly observed as insulated end cap debris within the EVSE connector pin.

Following that, the National Laboratory of the Rockies (NLR) conducted a thorough material analysis of the charging inlet insulated end caps to identify the composition of the materials used. The objective was to finalize inlet samples that were readily available for purchase that can provide nine inlet samples within the required time frame and to ensure that the corresponding insulated end cap samples had similar material compositions to those found in the field by the CNOs. We made a conscious effort to include insulated end cap samples that have been commonly observed in the field. This decision should not be conflated with the identification of a causal relationship between the material properties in the design and a propensity for end caps to be dislodged; rather, this experimental design choice is to ensure coverage of inlets that have resulted in dislodged end caps being discovered in connectors in the field.

Table 3 presents the material properties of the insulated end cap material as determined by the Fourier transform infrared spectroscopy (FTIR) and thermogravimetric analysis (TGA) conducted on the insulated end cap samples by NLR. Table 4 displays the material compositions identified through the CNO analysis in the field correlated with the corresponding possible samples and their associated field-failure prevalence.

Table 3. Material Analysis on Insulated End Caps Performed by NLR

Inlet Manufacturer	FTIR Results	TGA Prediction	TGA Result Comments
A	Polyethylene terephthalate (PET) and polybutylene terephthalate (PBT)	Mix—majority PBT	Onset temps are close to PBT and PET, multiple weight-loss events
B	PET and polycarbonate (PC)	Mix—PBT and PC, majority PBT	Onset temps are close to PBT and PC, multiple weight-loss events, higher coke percentage (PC has high coke percentage.)
C	PET and PBT	PBT	Onset temp matches PBT, one weight-loss event, lower coke percentage loss versus PET (PET has higher coke amount [11%–20%].)
D	PET and PBT	PBT	Onset temps match PBT, one weight-loss event, lower coke percentage loss versus PET (PET has higher coke amount [11%–20%].)
E	Nylon 6,6	Copolymer	Initial water loss (characteristic of nylons), multiple weight-loss events
F	Nylon 6,6	Copolymer	Initial water loss (characteristic of nylons), multiple weight-loss events
G	Nylon 6,6	Copolymer	Initial water loss (characteristic of nylons), multiple weight-loss events

Table 4. Material Composition Comparison Incorporating CNO and NLR Data with Field Failure Prevalence

Insulated End Cap Material Composition Provided by CNOs	Field Failure Prevalence Provided by CNOs	Possible Corresponding Manufacturer Sample
PC/PBT GF5	High	Manufacturer B
PBT/PBT GF13	High	Manufacturer C
PBT/PBT GF13	Medium	Manufacturer D
PA 66/6	Medium	Manufacturer E
Nylon 6/6 GF33	Low	Manufacturer F
Nylon 6,6	Low	Manufacturer G
PBT	Very low	Manufacturer A

As shown in Table 4, and throughout the remainder of the report, manufacturer inlet/end cap sample names are color-coded: Red indicates high field failure prevalence, yellow indicates medium, and green indicates low or very low field failure prevalence.

CNOs provided data on the field failure prevalence of insulated end caps, which is summarized in Table 4. These prevalence data are categorized on a scale ranging from very high to very low. As shown in the table, observations from various sources indicate that Manufacturers B and C had the highest prevalence in the field, whereas Manufacturer A had the lowest. Manufacturer D exhibited low prevalence at one CNO and high prevalence at another, resulting in an overall classification of medium prevalence. Additionally, Manufacturer C showed medium prevalence at one CNO but very high prevalence at another, leading to its overall classification as high prevalence.

Figure 5. Insulated end cap with its associated pin structure. ***Photos by NLR***

Figure 6. Insulated end cap with its associated pin structure. ***Photos by NLR***

During our inspection of the insulated end cap samples, we observed numerous structures of insulated end caps from different suppliers. We identified two main designs of end caps: One type features a configuration where the end cap is inserted into a DC pin hole, as illustrated in Figure 5. The other type has an insulated end cap pressed and fitted onto the narrower pin head, as shown in Figure 6, which is the predominantly used type across the evaluated end cap samples. Note that some manufacturers, such as Manufacturer C, offered different structures of end caps among the 9 inlet samples i.e., the 18 insulated end cap samples that were collected. These samples included both configurations of insulated end caps shown in Figure 5 and Figure 6. Detailed descriptions of all the end caps, along with corresponding images, are provided in Appendix A, which also contains approximate measurements of the associated DC pin heads for reference. It is possible that the differing CNO reported prevalence is a result of this mechanical difference in the pin.

3. Evaluation Procedure and Results

Insulated end cap samples from various manufacturers were subjected to thermal cycling and pull-force testing to assess the insulated end cap failure characteristics. The evaluations are categorized into three main test groups, each with specific preconditioning steps followed by pull-force conditions, which are detailed in the following sections.

3.1 Evaluation 1 (IEC 62196-1)

Evaluation 1 is divided into three subevaluations: 1a, 1b, and 1c. Three inlet samples i.e., six insulated end cap samples from each manufacturer, were processed through Evaluation 1 in sequence from 1a to 1b to 1c. Evaluations 1a and 1b follow the criteria defined in IEC 62196-1:2022 § 26.7, whereas Evaluation 1c was added as an additional evaluation involving a 100°C soak followed by the pull force on the insulated end caps.

3.1.1 Evaluation 1a (Preconditioning)

In this evaluation, the charge connectors were mated with three untested inlets from each of seven manufacturers with insulated end caps. These mated charging inlet-connector samples were kept in the thermal chamber and subjected to the following procedure:

1. Initial chamber temperature: +25°C ±5 K (ambient)
2. Cool down to –30°C at 3 K/min.
3. Hold at –30°C for 1 hour after the temperature stabilizes.
4. Heat up to +100°C at 3 K/min.
5. Hold at +100°C for 1 hour after the temperature stabilizes.
6. Cool back to +25°C ±5 K at 3 K/min.
7. Steps 1 through 6 constitute one complete thermal cycle; repeat for five cycles total.

Note that the thermal chambers used at UL for the evaluations had a limitation, achieving temperature changes at a maximum rate of 1 K/min (the rate was still set to try to achieve 3K/min). After conducting the thermal cycles on all the inlet samples from each manufacturer, the inlet samples were mated with their unconditioned complementary accessories (i.e., the charging inlet samples were mated with their unconditioned charging connectors), and compliance was evaluated by making observations as shown in Table 5.

Table 5. Evaluation 1a Results

Sample	Observations on Insulated End Caps				
	Detach	Move, Loosen, or Detach to Extent That Sample Is Not Functional	Uninsulated Live Parts Become Accessible	Reduction of Creepage and Clearance	Any Other Evidence of Damage (Risk of Fire or Electric Shock)
A1 to A3	No	No	No	No	No
B1 to B3	No	No	No	No	No
C1 to C3	No	No	No	No	No
D1 to D3	No	No	No	No	No
E1 to E3	No	No	No	No	No
F1 to F3	No	No	No	No	No
G1 to G3	No	No	No	No	No

All samples from each manufacturer passed Evaluation 1a, as no damage was observed to any of the insulted end caps.

3.1.2 Evaluation 1b (Pull Test at Room Temperature)

After completing Evaluation 1a, the same inlet samples were subjected to the following procedure:

1. Soak samples for 2 hours at 22°C ±3°C.
2. After soaking, subject the insulated end cap assemblies to a pull test per Table 16 from IEC 62196-1:2022, i.e., 40-N force was applied (for contacts >3 mm in diameter).
3. Apply force for 1 minute along the contact axis in the direction opposite the contact.

After conducting the thermal soak and application of the pull force on all the insulated end cap samples from each manufacturer, the samples were mated with their unconditioned complementary accessories (i.e., the charging inlet samples were mated with their unconditioned charging connectors), and compliance was evaluated by making observations documented in Table 6.

Table 6. Evaluation 1b Results

Sample	Observations on Insulated End Caps				
	Detach	Move, Loosen, or Detach to Extent That Sample Is Not Functional	Uninsulated Live Parts Become Accessible	Reduction of Creepage and Clearance	Any Other Evidence of Damage (Risk of Fire or Electric Shock)
A1 to A3	No	No	No	No	No
B1 to B3	No	No	No	No	No
C1 to C3	No	No	No	No	No
D1 to D3	No	No	No	No	No
E1 to E3	No	No	No	No	No
F1 to F3	No	No	No	No	No
G1 to G3	No	No	No	No	No

All samples from each manufacturer passed Evaluation 1b, as no damage was observed to any of them.

3.1.3 Evaluation 1c (Pull Test at Hot Temperature Until Failure)

After completing Evaluation 1b, the same samples were subjected to the following procedure:

1. Soak samples for 2 hours at 100°C ±3°C.
2. Perform initial pull test at 40 N (for contacts >3 mm diameter).
3. Increase force in 50-N increments until failure or a maximum of 450 N is reached.
4. Apply force for 1 minute along the contact axis in the direction opposite the contact.

The pullout forces for each insulated end cap, along with detailed descriptions of whether the end caps were pulled out during the force ramp-up or while holding at the test force level, are provided in Appendix B.

The report received from UL contained incomplete pull-force data for certain end cap samples. These incomplete data could not be recreated because the caps had already been removed. Specifically, in Evaluation 1c, the data for the insulated end cap sample E1 was incomplete. Generally, there should be six data points for the pull forces for each manufacturer (three inlet samples with two end caps each), but manufacturer E contains only four data points.

Figure 7 and Figure 8 shows the number of pullouts that happened at each force level across all the insulated end cap samples, and Figure 9 illustrates the distribution of the pull forces for each manufacturer using a box-and-whisker plot, which displays the data distribution based on a five-number summary, i.e., showing the median, quartile range, and extreme values. Appendix C discusses in detail how to interpret a box-and-whisker plot and shows an example. In Figure 9, the red dotted line represents the 450-N requirement included in the SAE J3400 Recommended Practice for insulated end caps.

Here are some observations from these graphs:

- Figure 7, shows when the pull force of 100 N was applied, 23 of 40 end cap samples (approximately 57.5%) were pulled out. At 50 N and 150 N, approximately 12.5% of the end cap samples were pulled out; at 40 N, 10% of the samples were pulled out. Only 5% of the samples were pulled out at 200 N, whereas at 300 N, only 2.5% were pulled out.

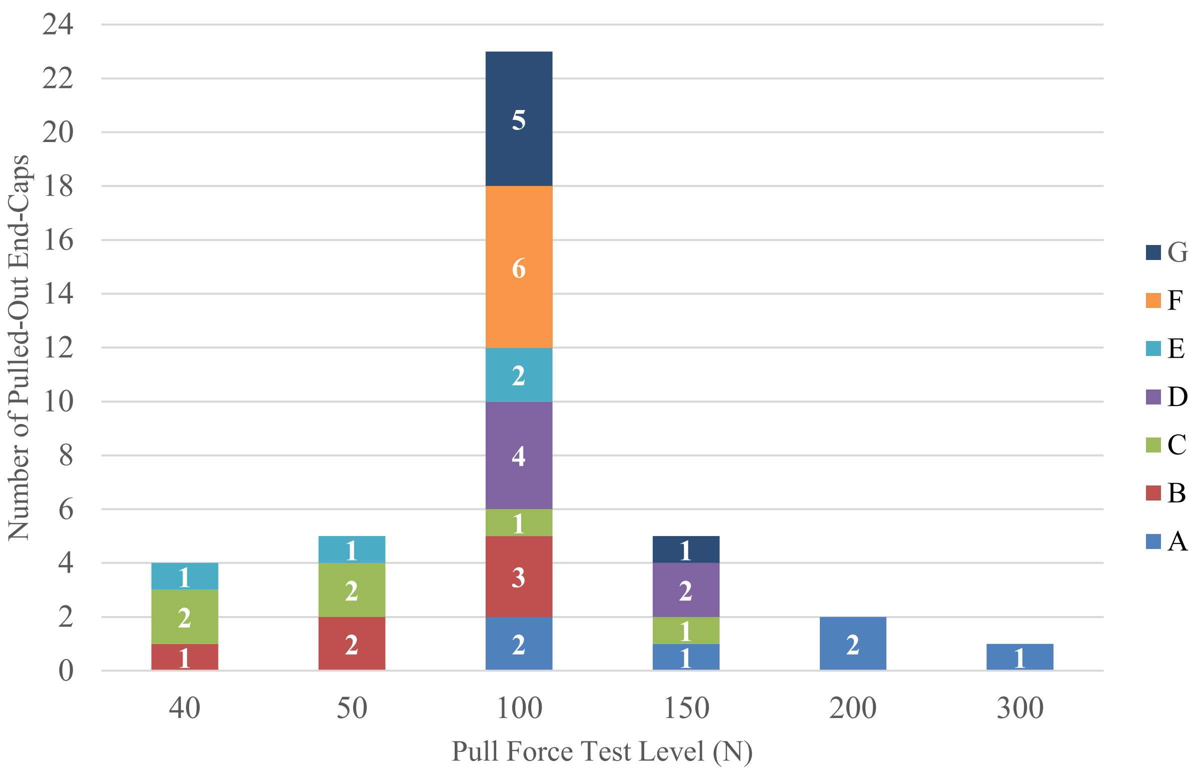


Figure 7. Number of pullouts at each force level: Evaluation 1c

- Some manufacturers exhibit a wide variation in pull-out forces between their end caps. For example, Manufacturer A's samples ranged from 87.75 N to 300 N, as shown in Figure 9.
- Although all samples passed the IEC 62196-1:2022 test (i.e., evaluations 1a and 1b), soaking them at an elevated temperature (100°C) revealed additional weakness. Certain samples could not withstand a 40-N force, and their end caps detached at a very low force (e.g., samples B1 to B3, C1, E3), as shown in Figure 9 and detailed in Appendix B.

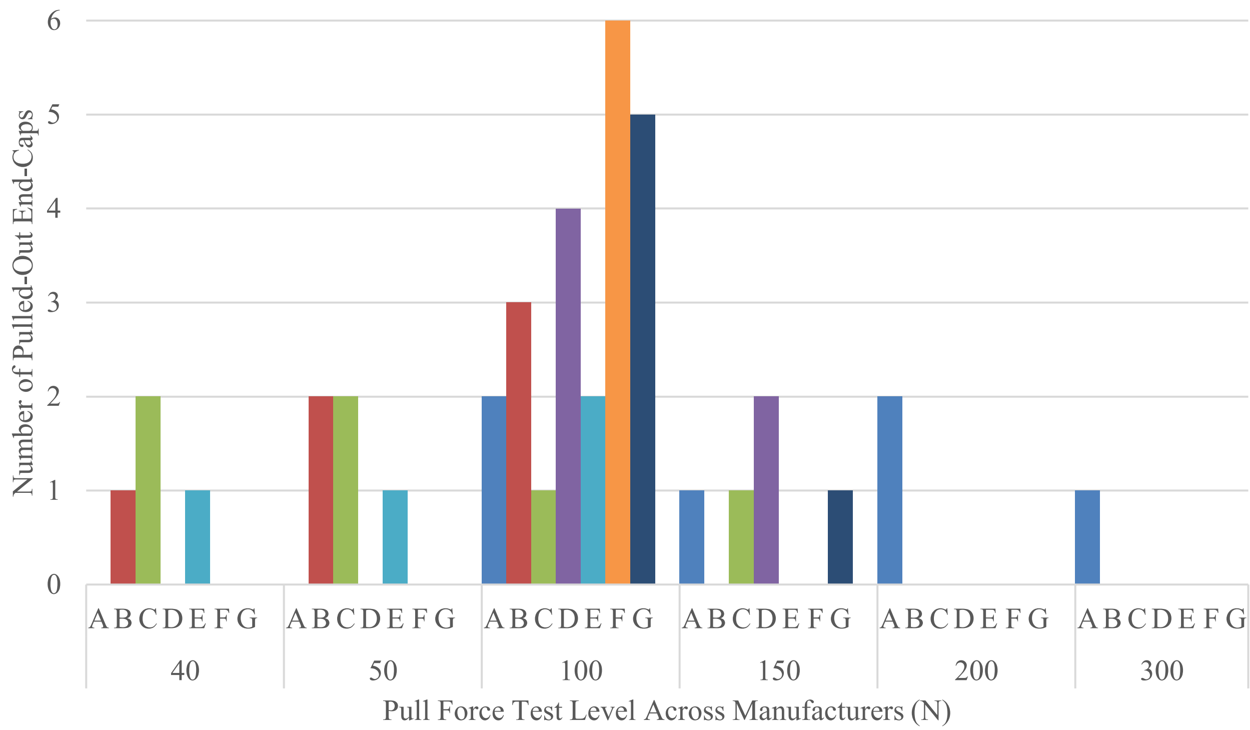


Figure 8. Number of pullouts at each force level across the manufacturers: Evaluation 1c

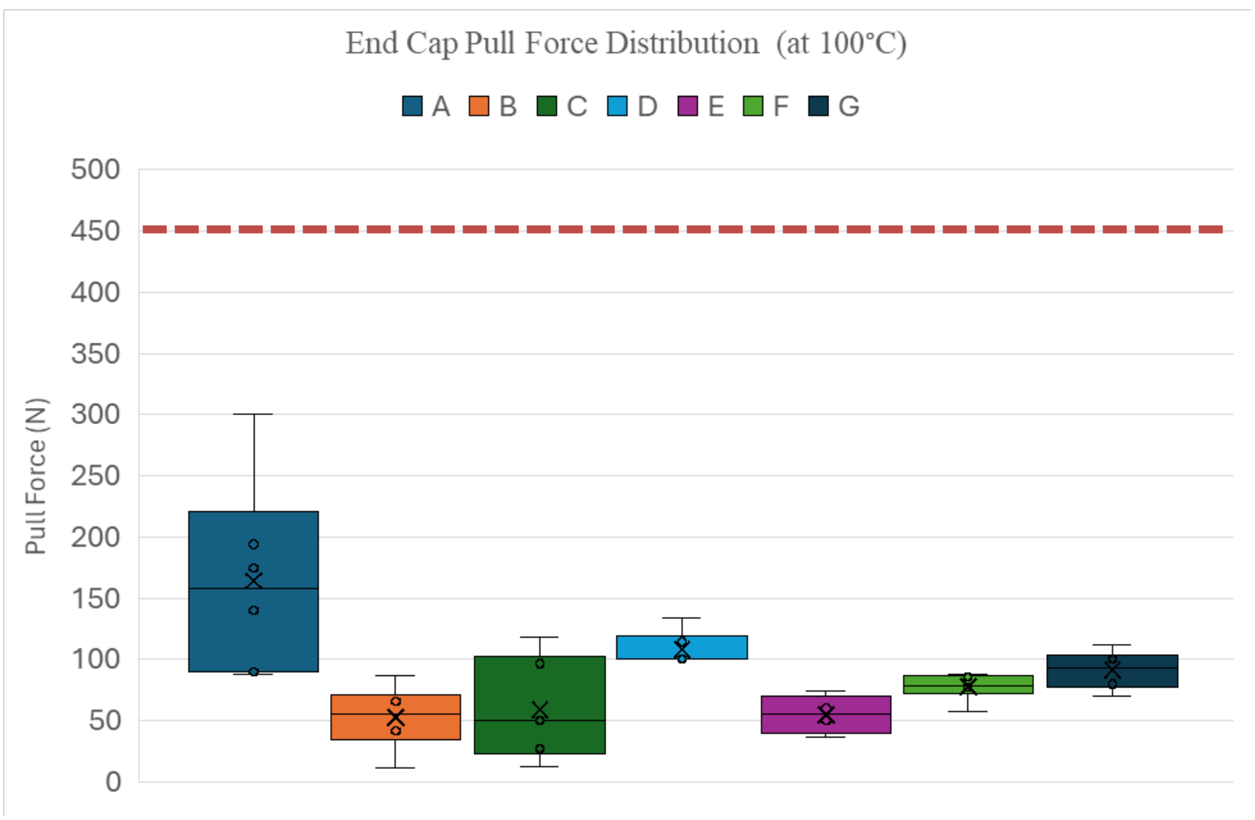


Figure 9. Pull-force distribution observed across all manufacturers: Evaluation 1c

3.2 Evaluation 2 (SAE J3400)

Evaluation 2 is divided into two sub-evaluations: 2a and 2b. Three inlet samples from each manufacturer, i.e., six end cap samples, were processed through Evaluation 2 in sequence from 2a to 2b. Evaluation 2 follows the criteria defined in IEC 62196-1:2022 § 26.7.2 with some modifications, which align the procedure with the SAE J3400 Recommended Practice requirements.

3.2.1 Evaluation 2a (Preconditioning)

In this evaluation, vehicle connectors were mated with three untested inlets from each of seven manufacturers with insulated end caps. These mated samples were kept in the thermal chamber and subjected to the following procedure:

1. Initial chamber temp: +25 C ±5 K (ambient)
2. Cool down to –30°C at 3 K/min.
3. Hold at –30°C for 1 hour after the temperature stabilizes.
4. Heat up to +100°C at 3 K/min.
5. Hold at +100°C for 1 hour after the temperature stabilizes.
6. Cool back to +25°C ±5 K at 3 K/min.
7. Steps 1 through 6 constitute one complete thermal cycle; repeat for five cycles total.
8. After completing five cycles, soak the mated inlets at 85°C and 85% relative humidity for 500 hours.

After conducting the thermal cycles on all the samples from each manufacturer, the samples were mated with their unconditioned complementary accessories (i.e., the charging inlet samples were mated with their unconditioned charging connectors), and compliance was evaluated by making observations documented in Table 7.

All samples from each manufacturer passed the evaluation, as no damage was observed to any of them.

Table 7. Evaluation 2a Results

Sample	Observations on Insulated End Caps				
	Detach	Move, Loosen, or Detach to Extent That Sample Is Not Functional	Uninsulated Live Parts Become Accessible	Reduction of Creepage and Clearance	Any Other Evidence of Damage (Risk of Fire or Electric Shock)
A4 to A6	No	No	No	No	No
B4 to B6	No	No	No	No	No
C4 to C6	No	No	No	No	No
D4 to D6	No	No	No	No	No
E4 to E6	No	No	No	No	No
F4 to F6	No	No	No	No	No
G4 to G6	No	No	No	No	No

3.2.2 Evaluation 2b (Pull Test at Room Temperature Until Failure)

After completing Evaluation 2a, the same samples were subjected to the following procedure:

1. Soak samples for 2 hours at 22°C ±3°C.
2. Apply an initial pull force of 40 N. Document the observed damage, if any.
3. Increase the force in 50-N increments until failure or a maximum of 450 N is reached.
4. Apply force for 1 minute along the contact axis in the direction opposite the contact.

The pull forces for each insulated end cap along with detailed descriptions of whether the end caps were pulled out during the force ramp-up or while holding at the test force level are provided in Appendix B.

Figure 10 and Figure 11 show the variations in pull forces across all 21 inlet samples, 3 inlet samples each from 7 manufacturers with end caps on the DC+ and DC- pins. Figure 12 illustrates the distribution of the pull forces for each manufacturer using a box-and-whisker plot. Here are some observations from these graphs:

- Figure 10 shows that when a pullout force of 100 N was applied, 13 of 42 end cap samples (approximately 30.95%) were pulled out, whereas at 150 N, 28.57% end caps were pulled out. At 200 N, 14.28% caps were pulled out. At 300 N, 11.9% were pulled out. Only 2.38% of the samples were pulled out at 40 N and 250 N, whereas at 300 N, only 2.5% were pulled out.
- The SAE J3400 Recommended Practice requires applying a pull force of 450 N for 1 minute; however, Figure 12 shows that all the insulated end caps get detached before reaching a force of 450 N, and none of the samples satisfy the requirement mentioned in SAE J3400.
- Figure 12 shows that some manufacturers exhibit a wide variation in pull forces between their end caps. For example, Manufacturer C's samples ranged from 18 N to 154 N.

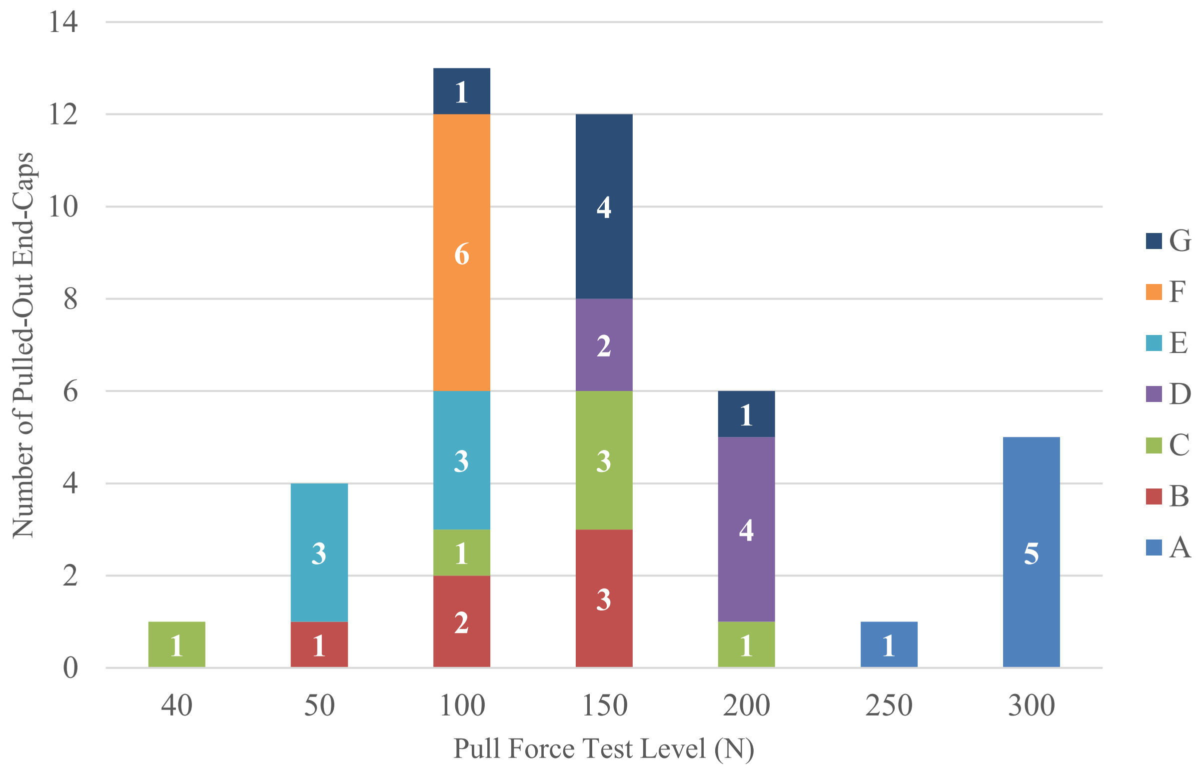


Figure 10. Number of pullouts at each force level: Evaluation 2b

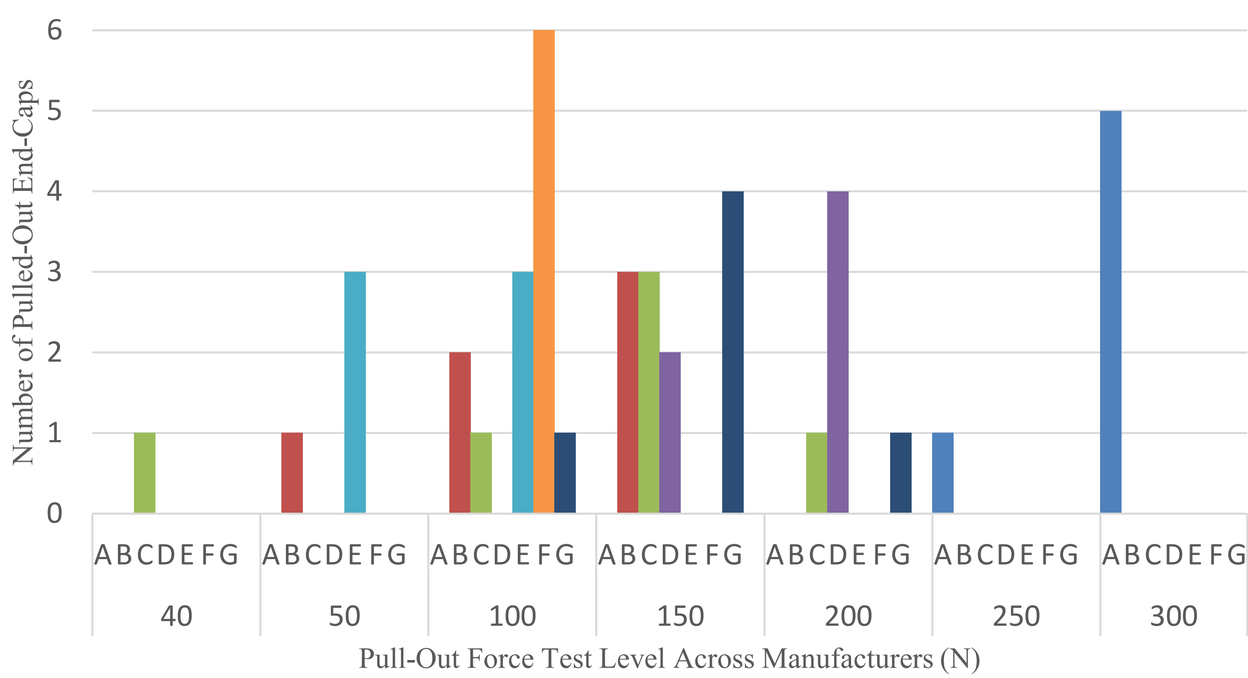


Figure 11. Number of pullouts at each force level across the manufacturers: Evaluation 2b

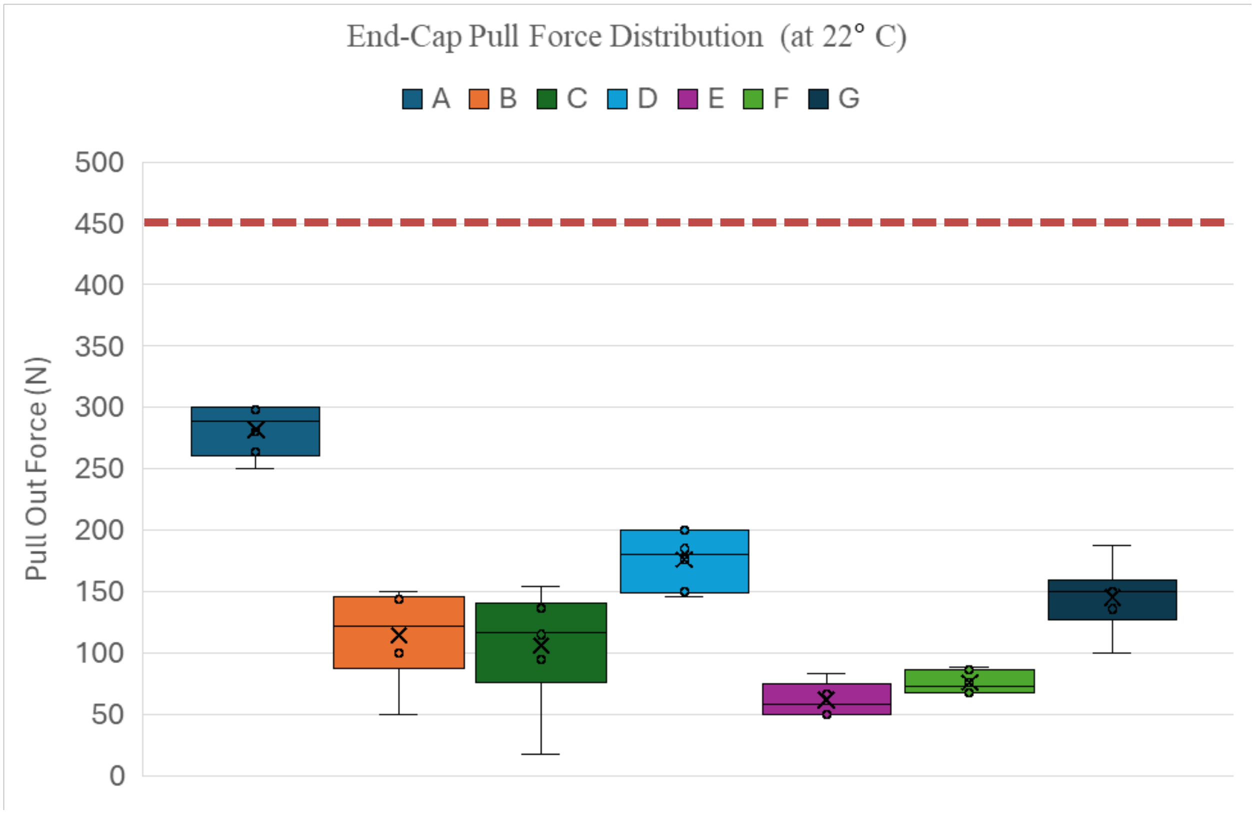


Figure 12. Pull-force distribution observed across all manufacturers: Evaluation 2b

3.3 Evaluation 3 (Experimental Procedure)

Evaluation 3 is divided into two subevaluations: 3a and 3b. Three inlet samples from each manufacturer, i.e., six end cap samples, were processed through Evaluation 3 in sequence from 3a to 3b. Evaluation 3 follows the criteria defined in IEC 62196-1:2022 § 26.7.2 with some modifications. Modifications are listed in blue.

3.3.1 Evaluation 3a (Preconditioning)

In this evaluation, unmated and untested vehicle inlets from each of seven manufacturers were kept in the thermal chamber and subjected to the following procedure:

1. Initial chamber temp: +25°C ±5 K (ambient)
2. Cool down to –30°C at 3 K/min.
3. Hold at –30°C for 1 hour after the temperature stabilizes.
4. Heat up to +110°C at 3 K/min.
5. Hold at +110°C for 1 hour after the temperature stabilizes.
6. Cool back to +25°C ±5 K at 3 K/min.
7. Steps 1 through 6 constitute one complete thermal cycle; repeat for 100 cycles total.
8. After 100 thermal cycles, subject the unmated inlets to an additional soak at 85°C/85% relative humidity for 500 hours.

After conducting the thermal cycles on all the samples from each manufacturer, the samples were mated with their unconditioned complementary accessories (i.e., the charging inlet samples were mated with their unconditioned charging connectors), and compliance was evaluated by making observations documented in Table 8.

All samples from each manufacturer passed the evaluation 3a, as no damage was observed to any of them.

Table 8. Evaluation 3a Results

Sample	Observations on Insulated End Caps				
	Detach	Move, Loosen, or Detach to Extent That Sample Is Not Functional	Uninsulated Live Parts Become Accessible	Reduction of Creepage and Clearance	Any Other Evidence of Damage (Risk of Fire or Electric Shock)
A7 to A9	No	No	No	No	No
B7 to B9	No	No	No	No	No
C7 to C9	No	No	No	No	No
D7 to D9	No	No	No	No	No
E7 to E9	No	No	No	No	No
F7 to F9	No	No	No	No	No
G7 to G9	No	No	No	No	No

3.3.2 Evaluation 3b (Pull Test at Hot Temperature Until Failure)

After completing Evaluation 3a, the same samples were subjected to the following procedure:

1. Soak for 2 hours at 100°C ±3°C.
2. Apply an initial pull force of 40 N. Document the observed damage, if any.
3. Increase force in 50-N increments until failure or a maximum of 450 N is reached.
4. Apply force for 1 minute along the contact axis in the direction opposite the contact.

The pull forces for each insulated end cap along with detailed descriptions of whether the end caps were pulled out during the force ramp-up or while holding at the test force level are provided in Appendix B.

The report received from UL contained incomplete pull-force data for certain manufacturers. These incomplete datapoints could not be recreated because the caps had already been removed. Specifically, in Evaluation 3b, the data for inlet manufacturers C, D, and G were incomplete. Generally, there should be six data points for pull forces for each manufacturer (three inlet samples with two insulated end caps each), but manufacturer C and D contain five data points, whereas manufacturer G contains only four data points.

Figure 13 and Figure 14 show the variations in pull forces across all 21 inlet samples, three samples each from seven manufacturers with end caps on the DC+ and DC- pins. Figure 15 illustrates the distribution of the pull forces for each manufacturer using a box-and-whisker plot. Here are some observations from these graphs:

- Figure 13 shows that when a pullout force of 100 N was applied, 20 of 38 end cap samples (approximately 52.63%) were pulled out. At 150 N, 18.42% of the samples were pulled out; at 40 N, approximately 10.5% of the samples were pulled out; and at 50 N, 7.89% of the samples were pulled out. Only 5.28% of the samples were pulled out at 200 N, whereas at 250 N and 300 N, only 2.63% were pulled out.
- Figure 15 shows that some manufacturers exhibit wide variations in pull forces between their end caps. For example, Manufacturer A's samples ranged from 70 N to 296 N.

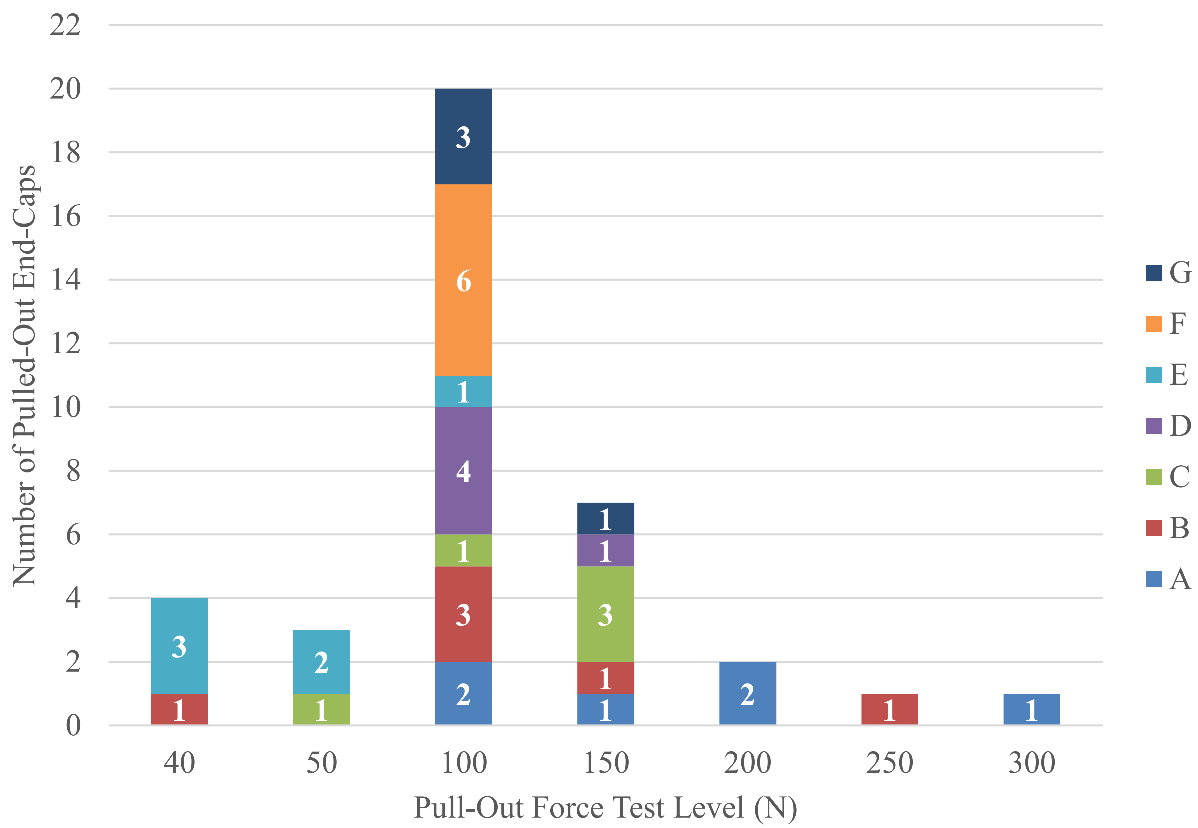


Figure 13. Number of pullouts at each force level: Evaluation 3b

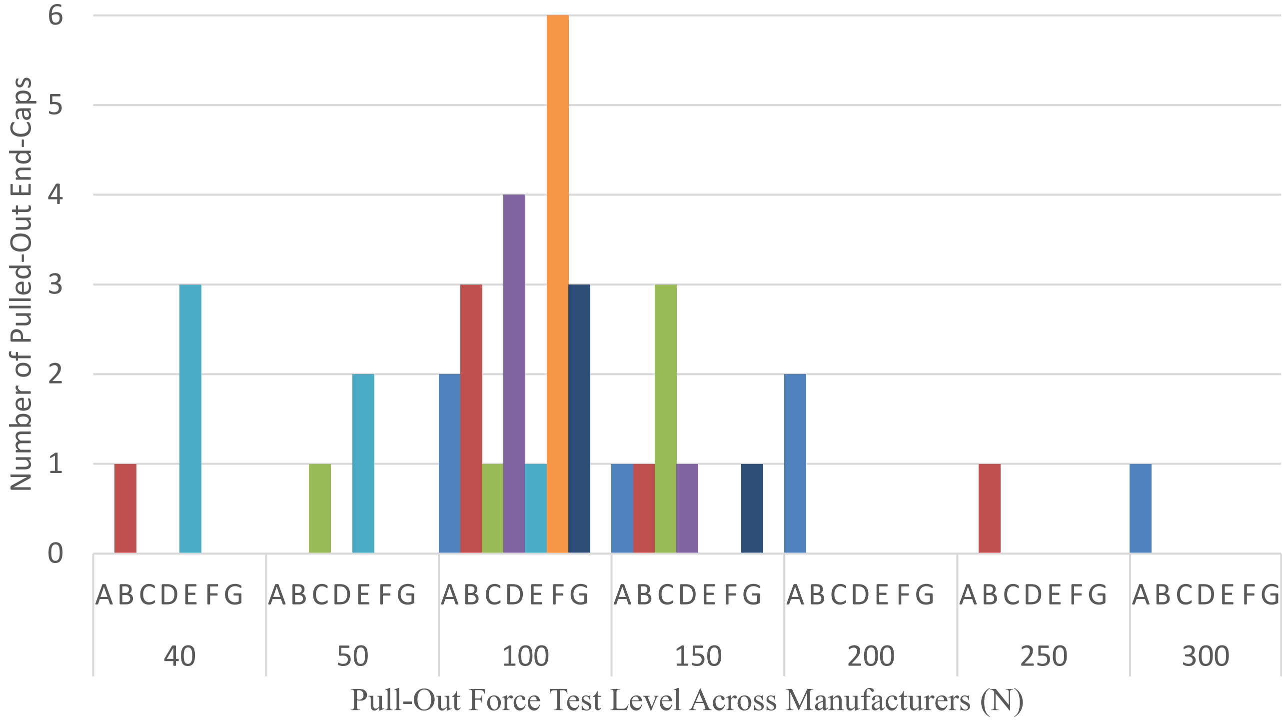


Figure 14. Number of pullouts at each force level across manufacturers: Evaluation 3b

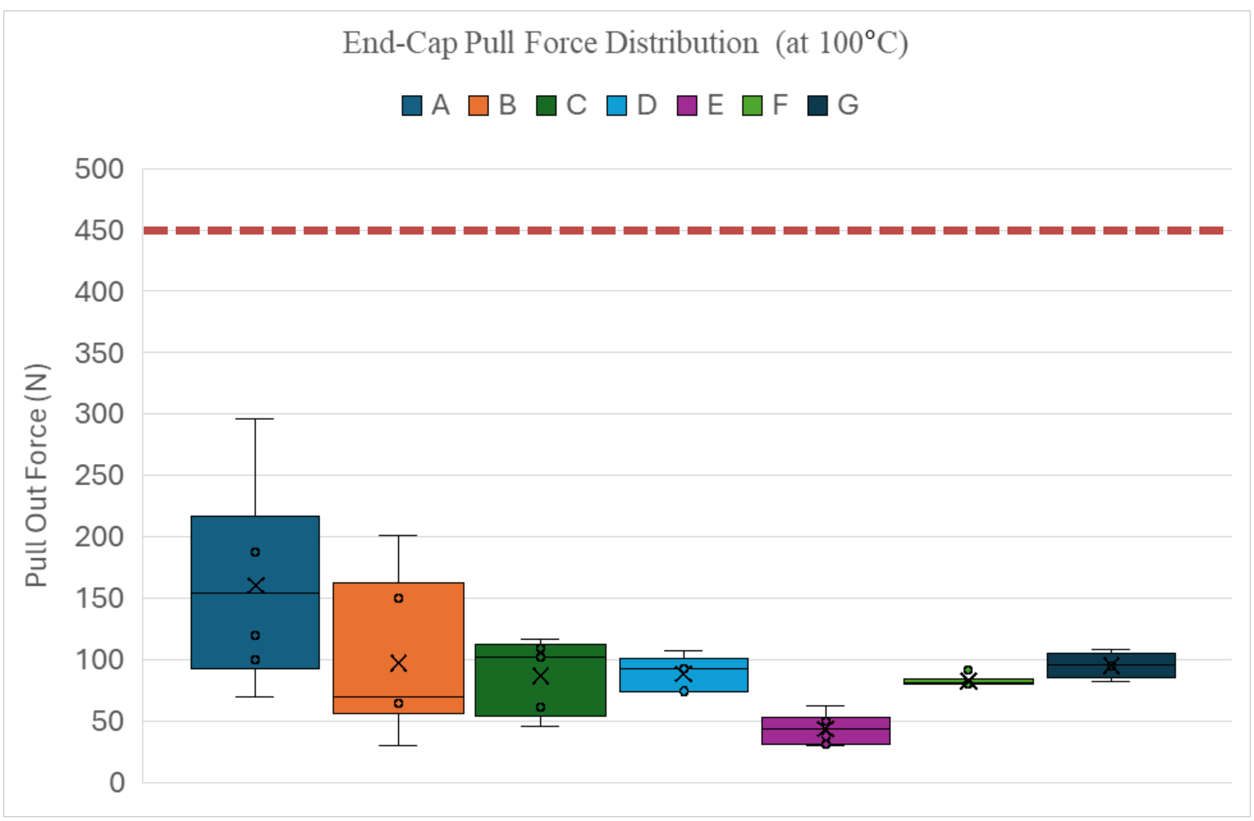


Figure 15. Pull-force distribution observed across all manufacturers: Evaluation 3b

4. Comparative Analysis

Figure 16 through Figure 22 show the distribution of the pull forces of the insulated end caps after each evaluation, i.e., evaluations 1c, 2b, and 3b.

Note that for evaluations 1c and 3b, the insulated end caps were immediately pulled out while hot (after soaking at 100°C), whereas for Evaluation 2b, the insulated end caps were pulled out at room temperature (after soaking at 22°C).

For all manufacturers except Manufacturer F, the median value of the pull forces for Evaluation 2 is higher than that for evaluations 1 and 3. In Evaluation 2, the samples were preconditioned by soaking them at a higher temperatures of 85°C with a higher humidity of 85% for approximately 500 hours; thus, Evaluation 2 can be considered a more stringent evaluation than Evaluation 1. Because of this, we expected to have a lower pull force for Evaluation 2 than Evaluation 1; however, the data suggests the opposite, with the pull force being lower in Evaluation 1. This difference could be due to variation in the temperature at the time of the pullout force application. In Evaluation 1, the pullout force was applied at 100°C while for Evaluation 2 it was conducted at ambient temperature. This suggests that the pull force tends to be lower at higher temperatures than ambient temperature.

Similarly, comparing evaluations 1 and 3, Evaluation 3 can be considered more stringent than Evaluation 1 because the samples were preconditioned to 100 hours of thermal cycling instead of five cycles, as mentioned in Evaluation 1, along with soaks at 85°C and 85% humidity for 500 hours. Based on this, we would expect to have a lower pull force in Evaluation 3 than Evaluation 1. Instead, the results are not consistent: In some cases, the median pull forces for Evaluation 3 are almost similar to Evaluation 1 (e.g., for Manufacturers F and G; Figure 21 and Figure 22), whereas in some cases, the median pull forces for Evaluation 1 are higher (e.g., for Manufacturers D and E; Figure 19 and Figure 20). This suggests that the longer-duration preconditioning seems to be less critical than the pull temperature in demonstrating insulated end cap separation in the test results.

According to Table 4, Manufacturers B and C exhibited the highest prevalence among the samples acquired. The line inside the box in the box-and-whisker plot represents the median value across the data samples. For evaluations 1c, illustrated in Figure 17 and Figure 18, the median value for Manufacturer B is 55.25 N, whereas for Manufacturer C, it is 50 N. This indicates that end cap samples pulled at high temperatures with approximately 50 N pull forces are observed as high-prevalence samples; however, when these same samples were pulled at room temperature with 40 N (as shown in Evaluation 1b), they were able to withstand the forces. This suggests that the 40 N force, as outlined in IEC 61296-1:2022, might be insufficient. In contrast, Table 4 indicates that Manufacturer A has the lowest prevalence among the acquired samples, with a median value of 157.5 N, as shown in Figure 16 for Evaluation 1c; therefore, to reduce the occurrence of pin cap pullout in the field, applying a force of 150 N instead of 40 N during pull-force evaluations could be more effective.

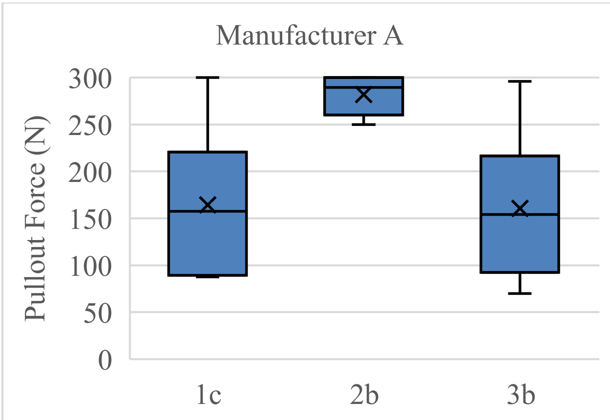


Figure 16. End cap pull-force distribution for Manufacturer A

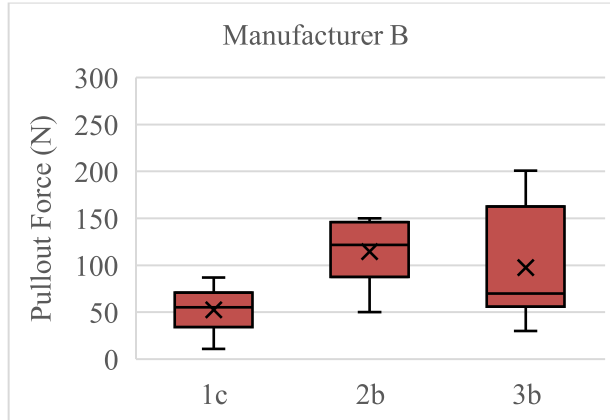


Figure 17. End cap pull-force distribution for Manufacturer B

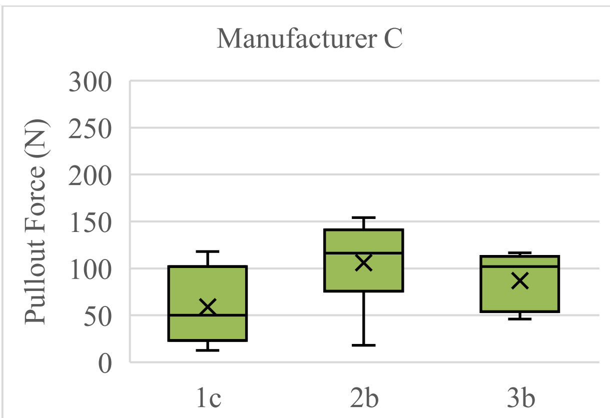


Figure 18. End cap pull-force distribution for Manufacturer C

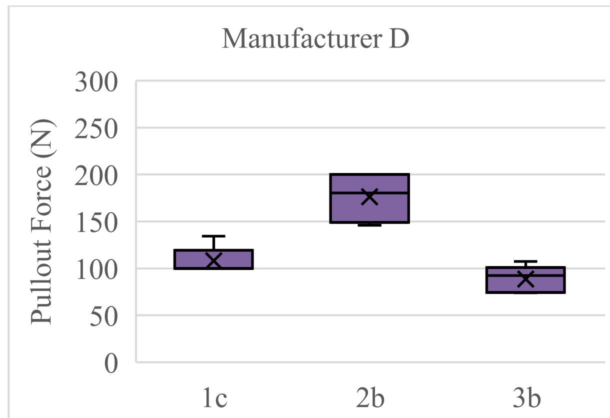


Figure 19. End cap pull-force distribution for Manufacturer D

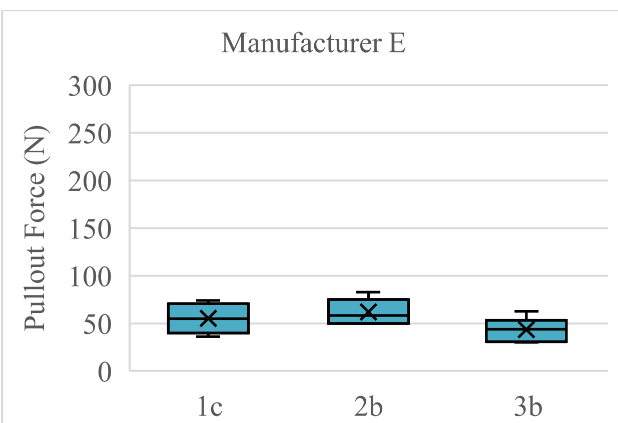


Figure 20. End cap pull-force distribution for Manufacturer E

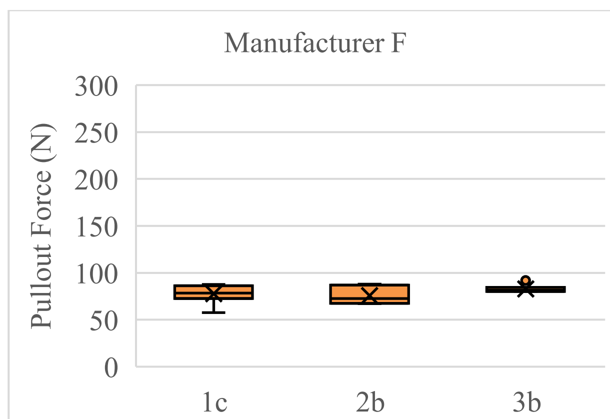


Figure 21. End cap pull-force distribution for Manufacturer F

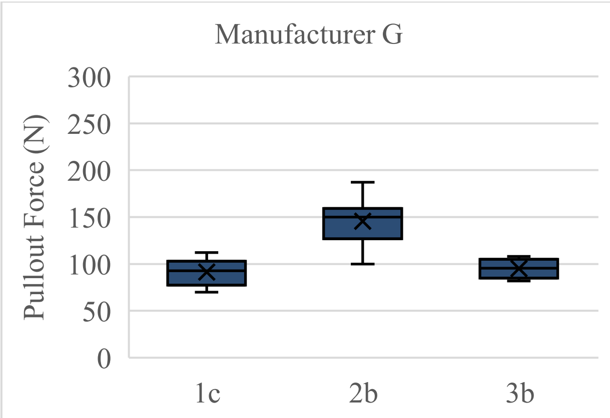


Figure 22. End cap pull-force distribution for Manufacturer G

For Manufacturer C, the acquired inlet samples revealed two distinct types of end caps attached to the DC pins on separate samples, which were not compatible with each other, as illustrated in Figure 23 and Figure 24. Charging inlet samples C1 and C2 contained Type A end caps (Figure 23), and the remaining inlet samples, C3 to C9, contained Type B end caps (Figure 24). To compare the performance of both end caps, we can refer to Evaluation 1c because this evaluation allowed both types of end caps to undergo the same testing conditions.

Figure 23. Type A insulated end cap for Manufacturer C. *Photo by NLR*

Figure 24. Type B insulated end cap for Manufacturer C. *Photo by NLR*

In Evaluation 1c, specifically for Manufacturer C, the distribution of the end cap pull forces indicated notable differences between the two types. As shown in Figure 25, the Type A end cap displayed a lower pull force than the Type B end cap. The median pull force for the Type B end cap is 107.4 N, whereas the Type A end cap has a median pull force of 38.5 N. Note that the Type A end cap had four data points, whereas the Type B end cap has only two. The force distribution of the Type A and Type B end caps from Manufacturer C is given in Figure 25.

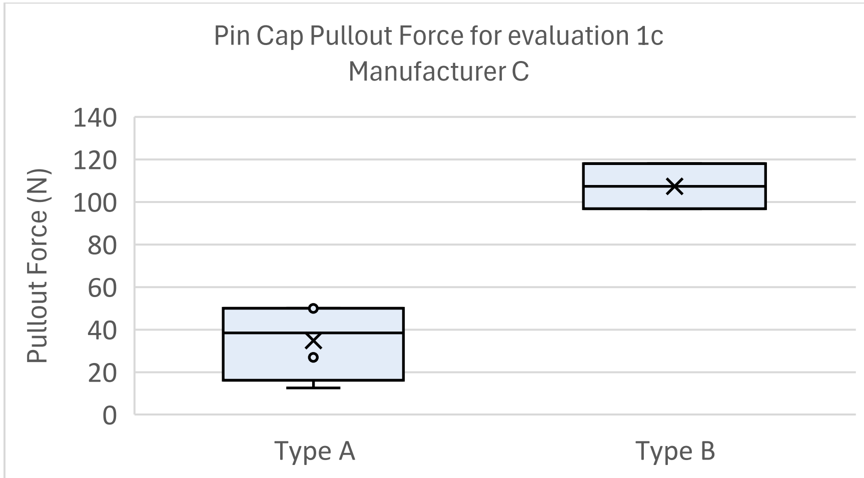


Figure 25. Pull-force distribution of Manufacturer C during Evaluation 1c for Type A and Type B insulated end caps

5. Conclusion

This study evaluates the performance of various insulated end caps used in OEM CCS inlets, with a particular focus on DC pin end caps, during DC charging sessions. The assessment centers on the pull-force withstand capability as specified in IEC 62196-1:2022 § 26.7 and SAE J3400 along with some for experimental purposes.

To gain insight into the types of insulated end cap materials commonly found as debris within the EVSE connector pins, NLR first collaborated with CNOs to gather field observations. Based on this information, various OEM insulated end cap samples were collected and analyzed at NLR. The results of the material analysis were then compared with debris observed in the field by CNOs, ensuring inclusion of insulated end cap samples that are frequently encountered in real-world scenarios.

Observations were made after conducting various temperature and humidity change evaluations, followed by the pull-force evaluation on the insulated end caps. Overall, the experimental data revealed significant variations in pull forces among end cap samples from the same manufacturer, potentially highlighting the need for tighter tolerance on the insulated end caps. The results also indicated that pull forces tend to decrease at higher ambient temperatures. Additionally, the duration of preconditioning appeared to be less critical than the pullout temperature in demonstrating insulated end cap separation in the test results.

The results indicate that all the end cap samples successfully passed the 40 N pull test according to IEC 62196-1:2022 § 26.7.2; however, when the same samples were subjected to soaking and pull force at a higher temperature of 100°C, some failed to withstand the 40 N pull test. Additionally, according to SAE J3400, end caps must withstand 450 N for 1 minute after undergoing thermal cycling. The results indicate that none of the samples met the required pull force of 450 N, which would classify them as noncompliant with SAE J3400.

After comparing the pull forces observed in the end cap samples, it is evident that those with the highest prevalence of being found in the field as end cap pollution demonstrate an average pull force of approximately 50 N at a temperature of 100°C (according to Evaluation 1c). In contrast, the samples with the lowest prevalence show a median pull force of 157 N. The specified pull force of 40 N, as mentioned in IEC 62196-1:2022 § 26.7, seems to be too low, and it should be increased to a minimum of 150 N to better align with robust end caps, which have shown a lower prevalence of being left in connectors in the field. Additionally, it is recommended that the samples be soaked at elevated temperatures, rather than at room temperature, before attempting to pull off the insulated end caps; therefore, the recommended criteria for insulated end cap evaluation should adhere to Evaluation 1—specifically, Evaluation 1a preconditioning followed by 1c (pull test at hot temperature), with a minimum pull force of 150 N set as the passing criteria.

Appendix A: Insulated End Cap and its Corresponding Pin Structure

Table A-1 shows the insulated end caps and their corresponding DC pin structures for all manufactures used for the evaluations. The pictures might show some cracks, scratches, or discoloration of the pins and the end caps because these were taken after all the evaluations were performed on the samples. All manufacturers had the same end cap structure for the nine inlet samples except the samples from Manufacturer C, which had two types of sample structures, as shown here.

Table A-1. Insulated End Caps and Their Corresponding DC Pin Structures for All Samples

Photos by NLR

Inlet Sample	End Cap		Corresponding DC Pin	
A1 to A9				
B1 to B9				
C1 and C2				
C3 to C9				

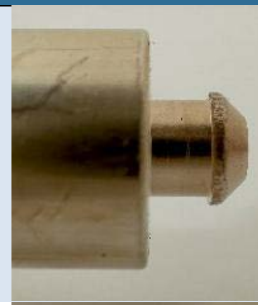
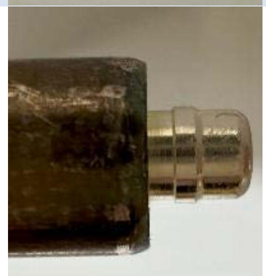
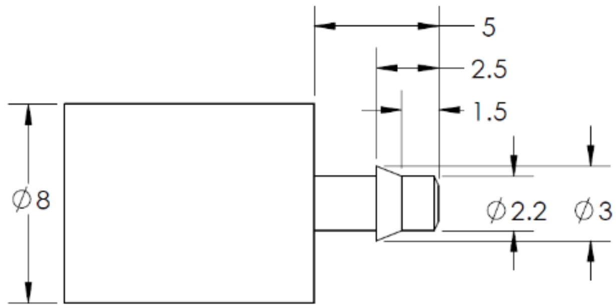
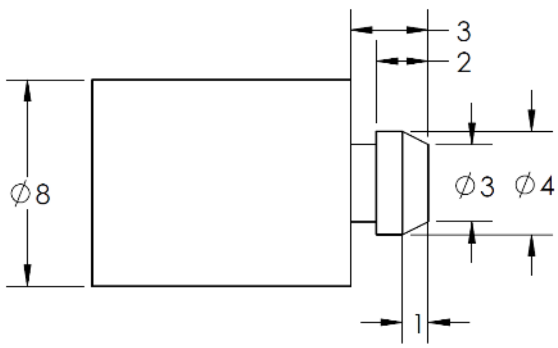
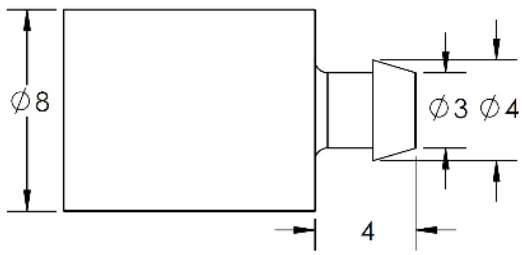
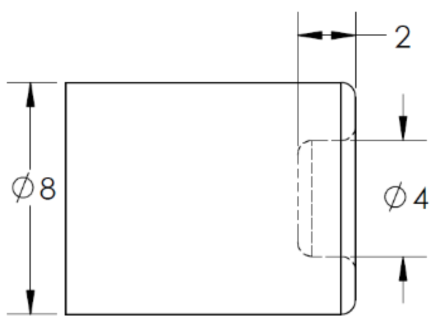
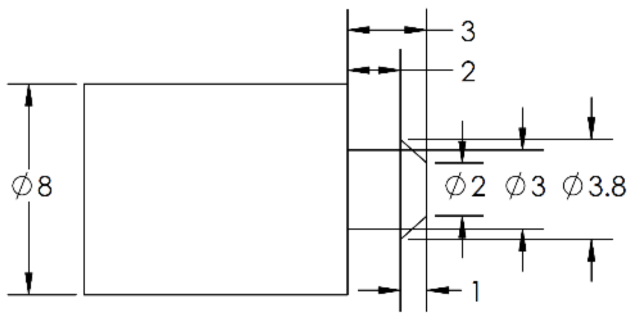
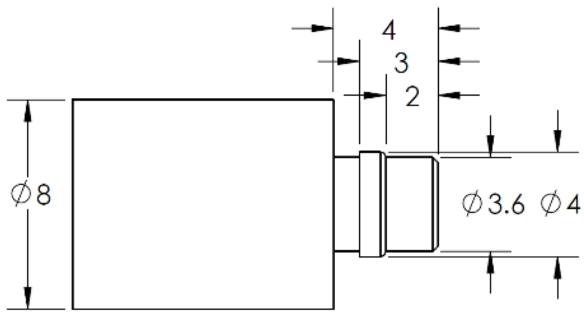
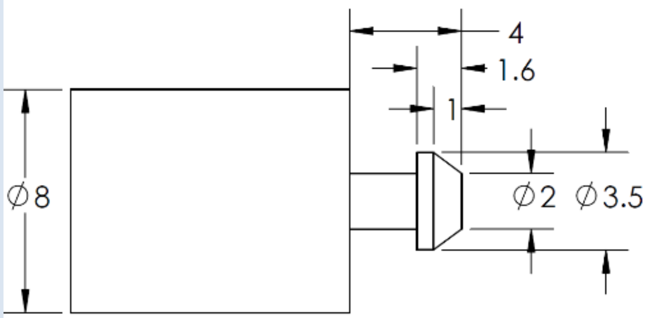
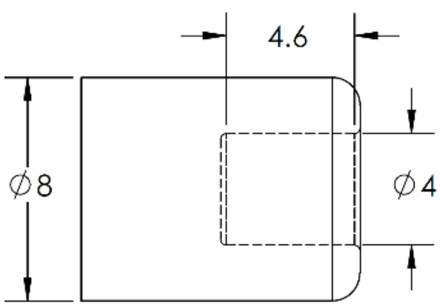
Inlet Sample	End Cap		Corresponding DC Pin	
D1 to D9				
E1 to E9				
F1 to F9				
G1 to G9				

Table A-2 presents the DC pin structures corresponding to the end caps for all manufacturers. The measurements were taken manually using a vernier caliper and should be considered for reference only. All the measurements are in millimeters.

Table A-2. DC Pin Structure Measurements

Photos by NLR

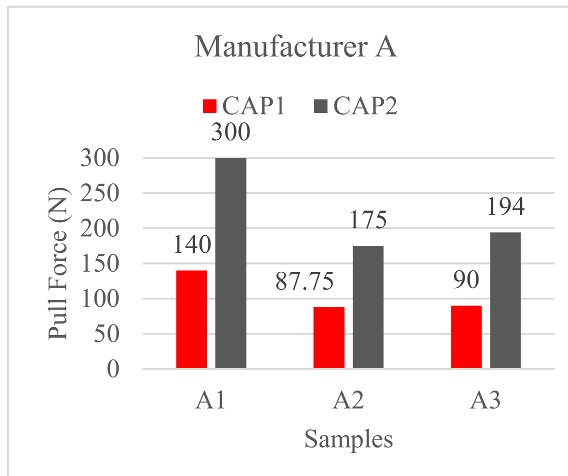
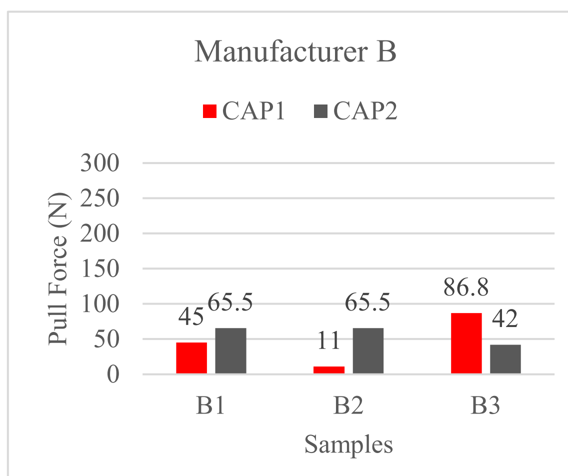
Inlet Sample	Pin Measurement (mm)	Pin Structure Picture
A1 to A9		
B1 to B9		
C1 and C2		
C3 to C9		

Inlet Sample	Pin Measurement (mm)	Pin Structure Picture
D1 to D9		
E1 to E9		
F1 to F9		
G1 to G9		

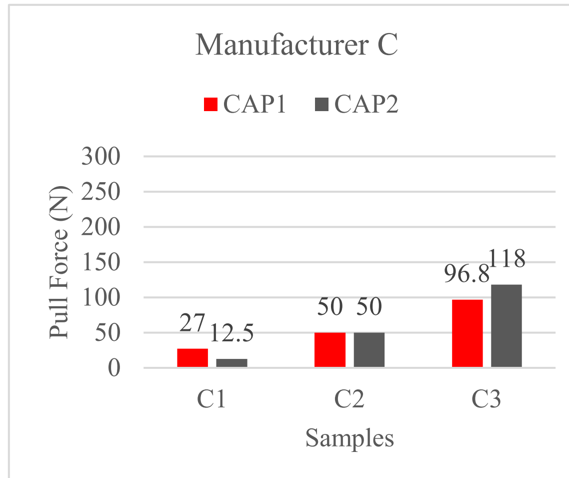
Appendix B: Pull-Force Values for Insulated End Caps After Evaluations 1c, 2b, and 3b

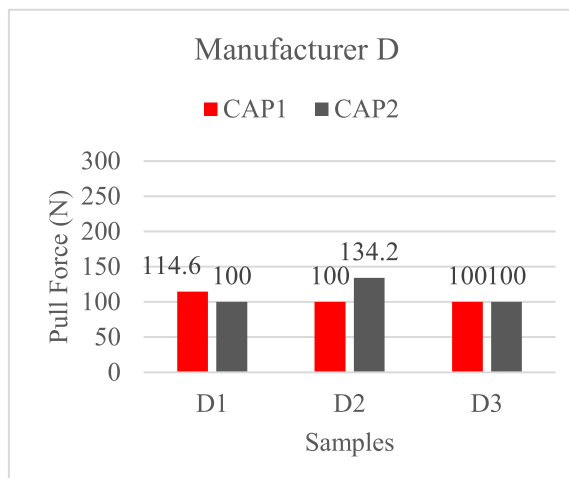
The pull forces for each insulated end cap that detached from the pin are recorded in Table B-1, Table B-2 and, Table B-3. The corresponding bar graph provides a visual representation of these forces for each inlet sample.

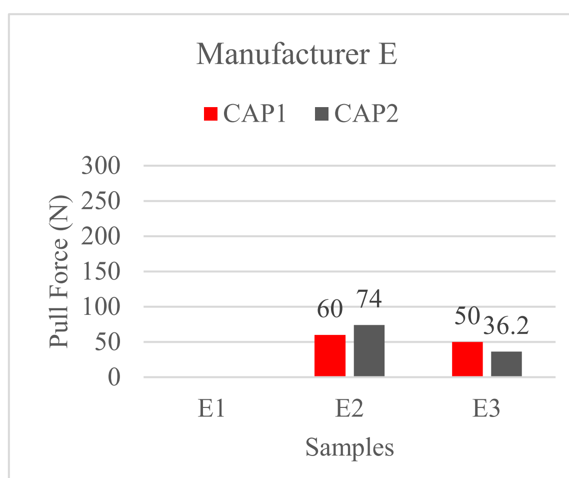
Table B-1. Evaluation 1c Results

Sample	Pin Cap	End Cap Pull Force (N)	Comments	
A1	CAP 1	140	Cap pulled out at 140 N while ramping to 150 N	
A1	CAP 2	300	Cap pulled at 300 N	
A2	CAP 1	87.75	Cap pulled out at 87.75 N while ramping to 100 N	
A2	CAP 2	175	Cap pulled out at 175 N while ramping to 200 N	
A3	CAP 1	90	Cap pulled out while ramping to 100 N	
A3	CAP 2	194	Cap pulled out while ramping to 200 N	
B1	CAP 1	45	Cap pulled out while ramping to 50 N	
B1	CAP 2	65.5	Cap pulled out while ramping to 100 N	
B2	CAP 1	11	Cap pulled out while ramping to 40 N	
B2	CAP 2	65.5	Cap pulled out while ramping to 100 N	
B3	CAP 1	86.8	Cap pulled out while ramping to 100 N	
B3	CAP 2	42	Cap pulled out while ramping to 50 N	

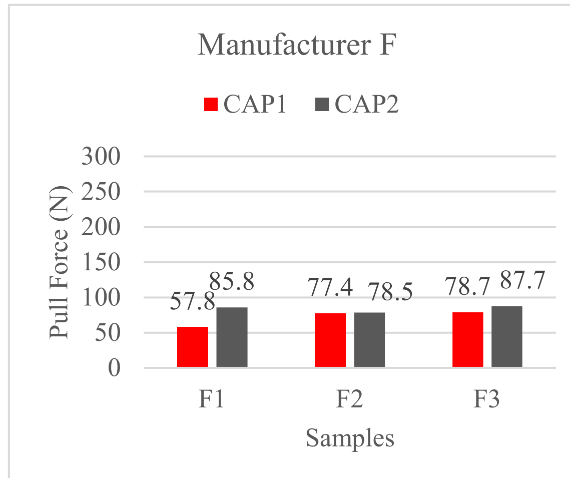
Sample	Pin Cap	End Cap Pull Force (N)	Comments
C1	CAP 1	27	Cap pulled out while ramping to 40 N
C1	CAP 2	12.5	Cap pulled out while ramping to 40 N
C2	CAP 1	50	Cap pulled out at 15 s with 50 N pull
C2	CAP 2	50	Cap pulled out at 10 s with 50 N pull
C3	CAP 1	96.8	Cap pulled out while ramping to 100 N
C3	CAP 2	118	Cap pulled out while ramping to 150 N
D1	CAP 1	114.6	Cap pulled out while ramping to 150 N
D1	CAP 2	100	Cap pulled out at 37 s with 100 N pull
D2	CAP 1	100	Cap pulled out at 40 s with 100 N pull
D2	CAP 2	134.2	Cap pulled out while ramping to 150 N
D3	CAP 1	100	Cap pulled out at 2 s with 100 N pull
D3	CAP 2	100	Cap pulled out at 2 s with 100 N pull
E1	CAP 1	-	Data not available
E1	CAP 2	-	Data not available
E2	CAP 1	60	Cap pulled out while ramping to 100 N
E2	CAP 2	74	Cap pulled out while ramping to 100 N
E3	CAP 1	50	Cap pulled out at 29 s with 50 N pull
E3	CAP 2	36.2	Cap pulled out while ramping to 40 N







Sample	Pin Cap	End Cap Pull Force (N)	Comments
F1	CAP 1	57.8	Cap pulled out while ramping to 100 N
F1	CAP 2	85.8	Cap pulled out while ramping to 100 N
F2	CAP 1	77.4	Cap pulled out while ramping to 100 N
F2	CAP 2	78.5	Cap pulled out while ramping to 100 N
F3	CAP 1	78.7	Cap pulled out while ramping to 100 N
F3	CAP 2	87.7	Cap pulled out while ramping to 100 N
G1	CAP 1	100	Cap pulled out at 25 s with 100 N pull
G1	CAP 2	70	Cap pulled out while ramping to 100 N
G2	CAP 1	85.7	Cap pulled out while ramping to 100 N
G2	CAP 2	100	Cap pulled out at 40 s with 100 N pull
G3	CAP 1	112.1	Cap pulled out while ramping to 150 N
G3	CAP 2	80	Cap pulled out while ramping to 100 N



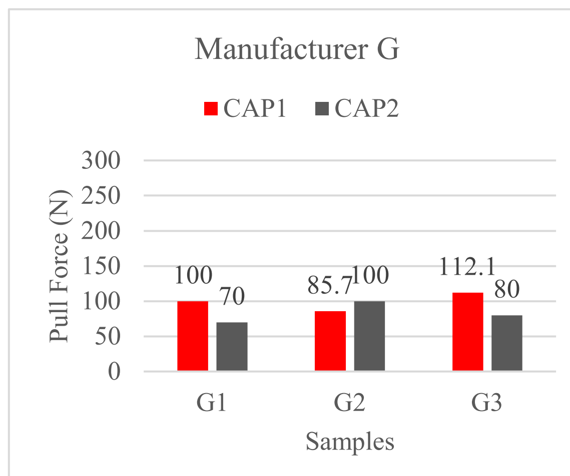
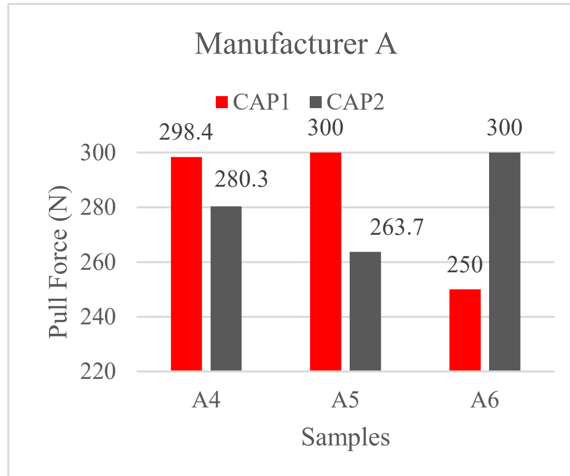
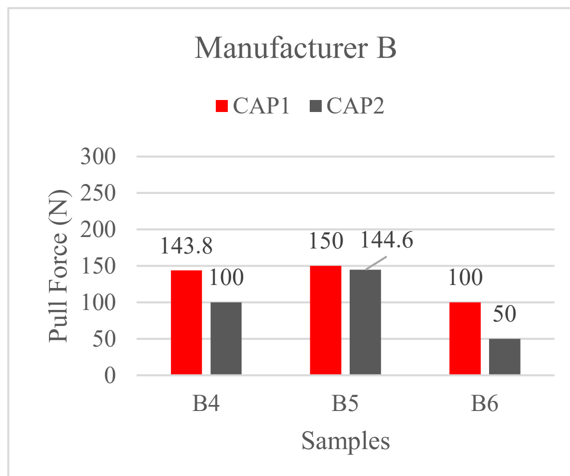
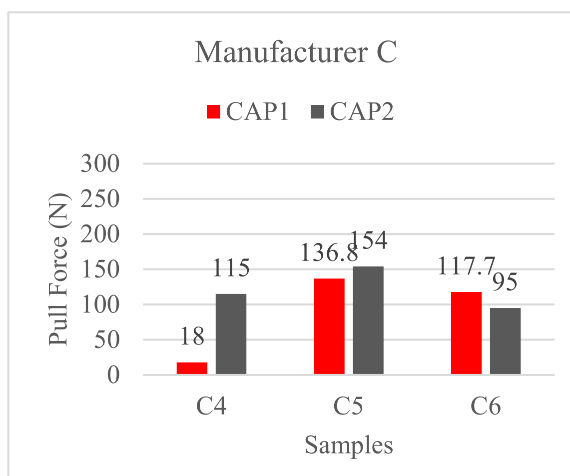


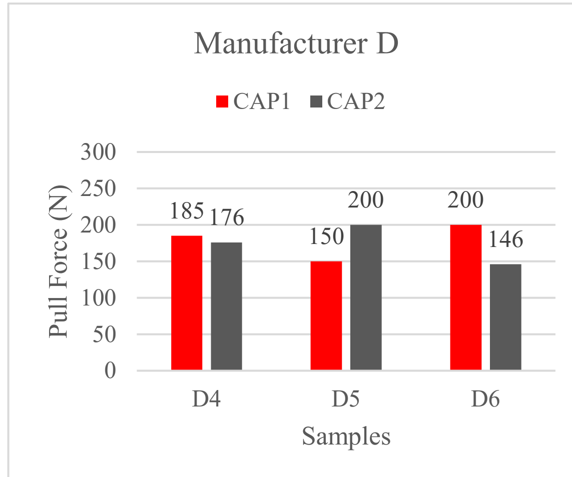
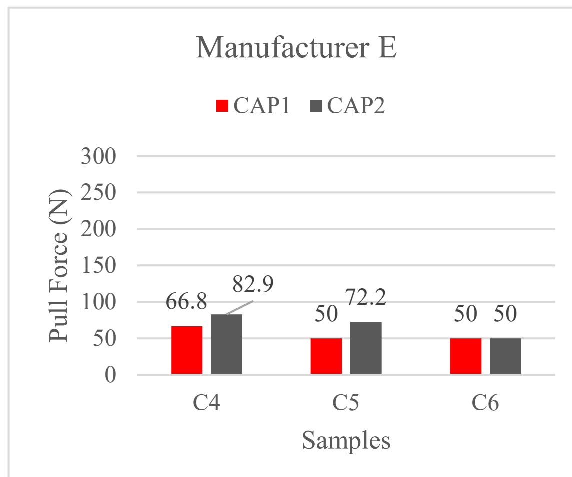
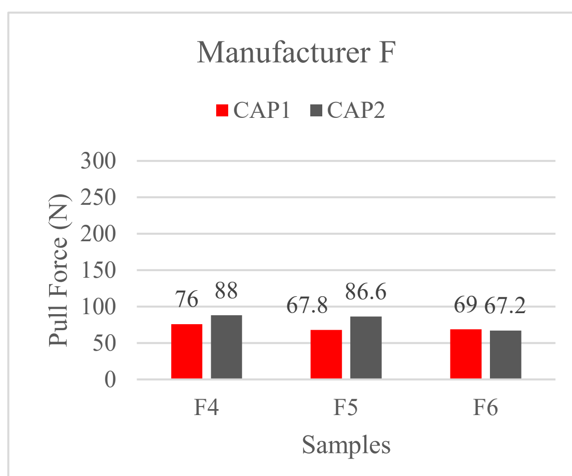
Table B-2. Evaluation 2b Results

Sample	Pin Cap	End Cap Pull Force (N)	Comments
A4	CAP 1	298.4	Cap pulled out while ramping to 300 N
A4	CAP 2	280.3	Cap pulled out while ramping to 300 N
A5	CAP 1	300	Cap pulled out at 300 N
A5	CAP 2	263.7	Cap pulled out while ramping to 300 N
A6	CAP 1	250	Cap pulled out at 15 s with 250 N pull
A6	CAP 2	300	Cap pulled out while ramping to 300 N
B4	CAP 1	143.8	Cap pulled out while ramping to 150 N
B4	CAP 2	100	Cap pulled out at 10 s with 100 N pull
B5	CAP 1	150	Cap pulled out at 10 s with 150 N pull
B5	CAP 2	144.6	Cap pulled out while ramping to 150 N
B6	CAP 1	100	Cap pulled out at 2 s with 100 N pull
B6	CAP 2	50	Cap pulled out at 10 s with 50 N pull
C4	CAP 1	18.00	Cap pulled out at 18 N
C4	CAP 2	115.00	Cap pulled out while ramping to 150 N
C5	CAP 1	136.80	Cap pulled out while ramping to 150 N
C5	CAP 2	154.00	Cap pulled out while ramping to 200 N
C6	CAP 1	117.70	Cap pulled out while ramping to 150 N
C6	CAP 2	95.00	Cap pulled out while ramping to 100 N







Sample	Pin Cap	End Cap Pull Force (N)	Comments	
D4	CAP 1	185.00	Cap pulled out while ramping to 200 N	
D4	CAP 2	176.00	Cap pulled out while ramping to 200 N	
D5	CAP 1	150.00	Cap pulled out at 2 s with 150 N pull	
D5	CAP 2	200	Cap pulled out at 2 s with 200 N pull	
D6	CAP 1	200	Cap pulled out at 2 s with 200 N pull	
D6	CAP 2	146	Cap pulled out while ramping to 150 N	
E4	CAP 1	66.8	Cap pulled out while ramping to 100 N	
E4	CAP 2	82.9	Cap pulled out while ramping to 100 N	
E5	CAP 1	50	Cap pulled out at 35 s with 50 N pull	
E5	CAP 2	72.2	Cap pulled out while ramping to 100 N	
E6	CAP 1	50	Cap pulled out at 6 s with 50 N pull	
E6	CAP 2	50	Cap pulled out at 7 s with 50 N pull	
F4	CAP 1	76	Cap pulled out while ramping to 100 N	
F4	CAP 2	88	Cap pulled out while ramping to 100 N	
F5	CAP 1	67.8	Cap pulled out while ramping to 100 N	
F5	CAP 2	86.6	Cap pulled out while ramping to 100 N	
F6	CAP 1	69	Cap pulled out while ramping to 100 N	
F6	CAP 2	67.2	Cap pulled out while ramping to 100 N	

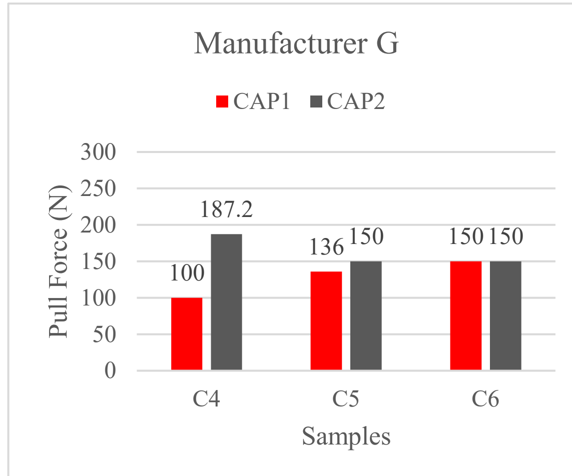
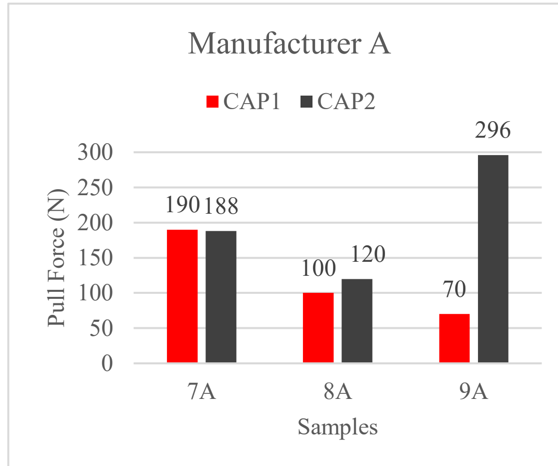
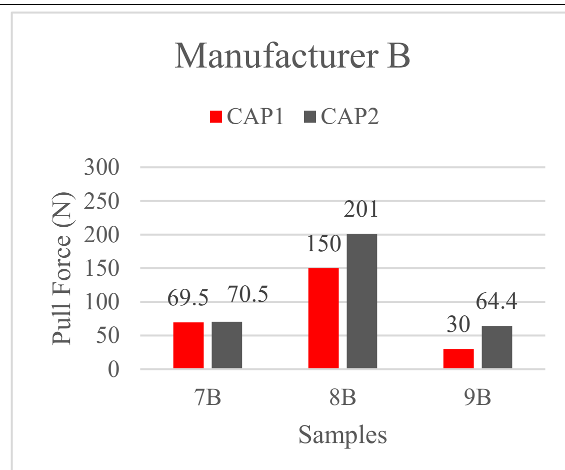
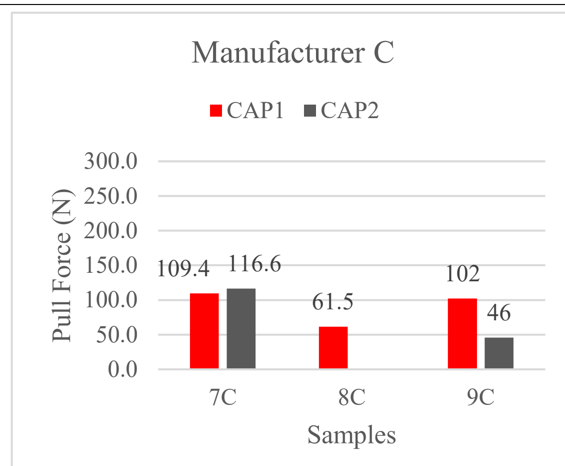
Sample	Pin Cap	End Cap Pull Force (N)	Comments	
G4	CAP 1	100	Cap pulled out at 6 s with 50 N pull	
G4	CAP 2	187.2	Cap pulled out while ramping to 200 N	
G5	CAP 1	136	Cap pulled out while ramping to 150 N	
G5	CAP 2	150	Cap pulled out at 13 s with 150 N pull	
G6	CAP 1	150	Cap pulled out at 18 s with 150 N pull	
G6	CAP 2	150	Cap pulled out at 15 s with 150 N pull	

Table B-3. Evaluation 3b Results

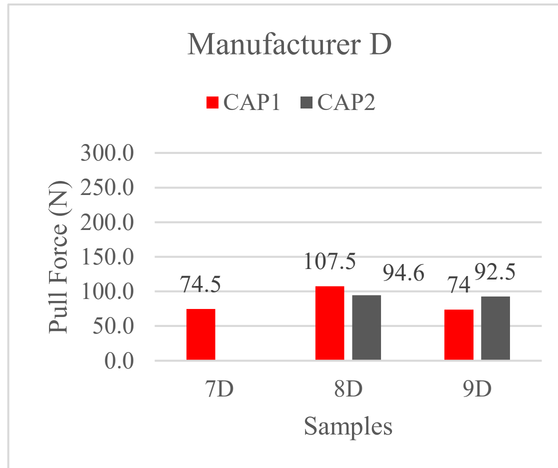
Sample	Pin Cap	End Cap Pull Force (N)	Comments
A7	CAP 1	190	Cap pulled out while ramping to 200 N
A7	CAP 2	188	Cap pulled out while ramping to 200 N
A8	CAP 1	100	Cap pulled out at 100 N
A8	CAP 2	120	Cap pulled out while ramping to 150 N
A9	CAP 1	70	Cap pulled out while ramping to 100 N
A9	CAP 2	296	Cap pulled out while ramping to 300 N
B7	CAP 1	69.5	Cap pulled out while ramping to 100 N
B7	CAP 2	70.5	Cap pulled out while ramping to 100 N
B8	CAP 1	150	Cap pulled out at 8 s with 150 N pull
B8	CAP 2	201	Cap pulled out while ramping to 250 N
B9	CAP 1	30	Cap pulled out while ramping to 50 N
B9	CAP 2	64.4	Cap pulled out while ramping to 100 N
C7	CAP 1	109.4	Cap pulled out while ramping to 150 N
C7	CAP 2	116.6	Cap pulled out while ramping to 150 N
C8	CAP 1	61.5	Cap pulled out while ramping to 100 N
C8	CAP 2	-	Data not available
C9	CAP 1	102	Cap pulled out while ramping to 100 N
C9	CAP 2	46	Cap pulled out while ramping to 50 N

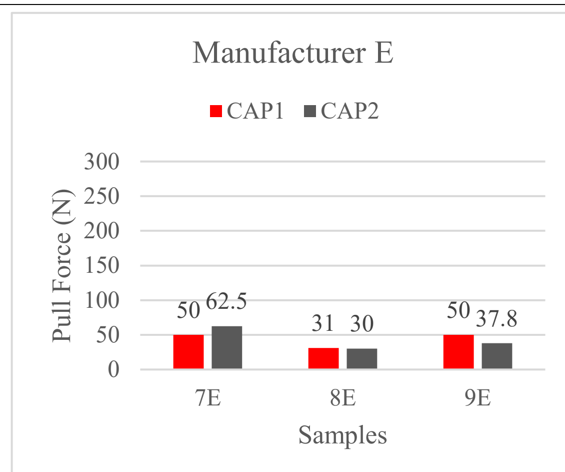


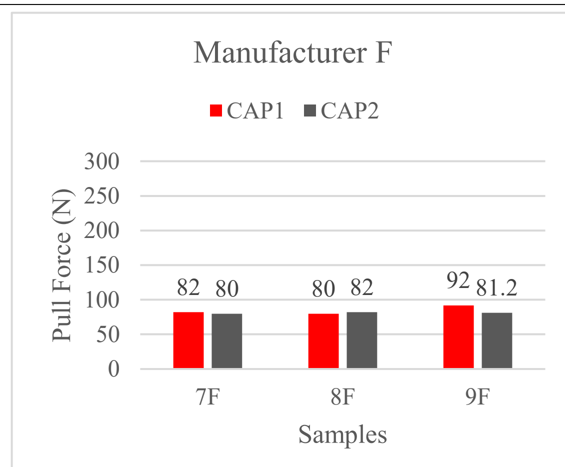




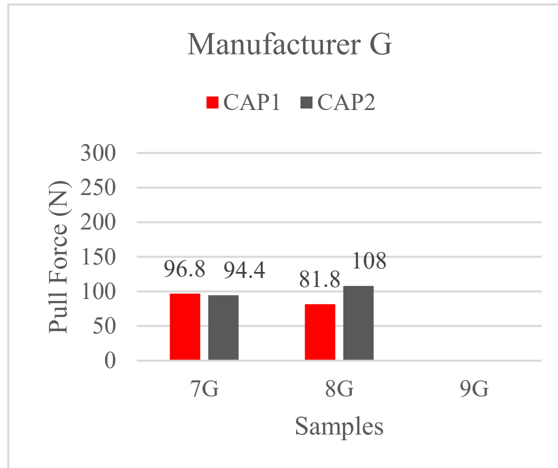
Sample	Pin Cap	End Cap Pull Force (N)	Comments
D7	CAP 1	74.5	Cap pulled out while ramping to 100 N
D7	CAP 2	-	Data not available
D8	CAP 1	107.5	Cap pulled out while ramping to 150 N
D8	CAP 2	94.6	Cap pulled out while ramping to 100 N
D9	CAP 1	74	Cap pulled out while ramping to 100 N
D9	CAP 2	92.5	Cap pulled out while ramping to 100 N
E7	CAP 1	50	Cap pulled out at 25 s with 50 N pull
E7	CAP 2	62.5	Cap pulled out while ramping to 100 N
E8	CAP 1	31	Cap pulled out while ramping to 50 N
E8	CAP 2	30	Cap pulled out while ramping to 50 N
E9	CAP 1	50	Cap pulled out at 7 s with 50 N pull
E9	CAP 2	37.8	Cap pulled out while ramping to 50 N
F7	CAP 1	82	Cap pulled out while ramping to 100 N
F7	CAP 2	80	Cap pulled out while ramping to 100 N
F8	CAP 1	80	Cap pulled out while ramping to 100 N
F8	CAP 2	82	Cap pulled out while ramping to 100 N
F9	CAP 1	92	Cap pulled out while ramping to 100 N
F9	CAP 2	81.2	Cap pulled out while ramping to 100 N







Sample	Pin Cap	End Cap Pull Force (N)	Comments	
G7	CAP 1	96.8	Cap pulled out while ramping to 100 N	
G7	CAP 2	94.4	Cap pulled out while ramping to 100 N	
G8	CAP 1	81.8	Cap pulled out while ramping to 110 N	
G8	CAP 2	108	Cap pulled out while ramping to 150 N	
G9	CAP 1	-	Data not available	
G9	CAP 2	-	Data not available	



Appendix C: Box-and-Whisker Plot

A box-and-whisker plot is used to visualize the distribution of a dataset by highlighting key statistics, such as the median, quartiles, and minimum and maximum values. The box represents the middle 50% of the data, known as the interquartile range, and a line inside the box indicates the median, or the central value of the dataset. The whiskers extend to the minimum and maximum values, providing a clear view of the data spread.

The quartiles divide a dataset into four equal parts. There are multiple methods to calculate quartiles; the most common are the inclusive and exclusive methods. The report uses the inclusive method, which treats datasets as a continuous distribution. In this approach, the first quartile (Q1) is the 25th percentile, and the third quartile (Q3) is the 75th percentile, calculated using linear interpolation, if necessary. This method ensures that the minimum and maximum values correspond to the 0th and 100th percentiles, respectively.

For example, in Evaluation 1c, Manufacturer A, the pull-force data points are: 140, 300, 87.75, 175, 90, and 194 N. Figure C-1 shows a box-and-whisker plot for the dataset.

- Minimum value = 87.75 N (tip of the lower whisker)
- Maximum value = 300 N (tip of the upper whisker)
- Median = 157.5 N (line inside the box)
- First quartile (Q1) = 89.4 N
- Third quartile (Q3) = 220.5 N
- Mean (X) = 164.46 N (shown by an "X" in the box).

The Q1 and Q3 values are not necessarily the medians of the lower or upper halves of the dataset, but they are interpolated to better represent the 25th and 75th percentiles.

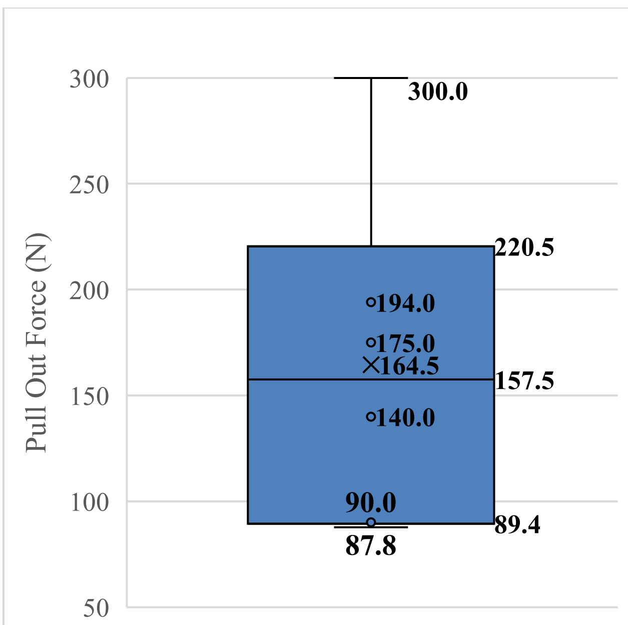


Figure C-1. Example box-and-whisker plot

About the ChargeX Consortium

The National Charging Experience Consortium (ChargeX Consortium) is a collaborative effort between Argonne National Laboratory, Idaho National Laboratory, National Laboratory of the Rockies, 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.

JANUARY 2026

DOE/GO-102026-6942

Argonne NATIONAL LABORATORY

INL Idaho National Laboratory

NATIONAL LABORATORY OF THE ROCKIES