



NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

**PERFORMANCE EVALUATION OF A MEDIUM VOLTAGE
DIRECT CURRENT SOLID-STATE CIRCUIT BREAKER
IN A HIGH-ALTITUDE WORKING ENVIRONMENT**

by

Brandon Keck

June 2023

Thesis Advisor:
Co-Advisor:

Di Zhang
Yuntao Xu

Approved for public release. Distribution is unlimited.

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			<i>Form Approved OMB No. 0704-0188</i>	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE June 2023	3. REPORT TYPE AND DATES COVERED Master's thesis	
4. TITLE AND SUBTITLE PERFORMANCE EVALUATION OF A MEDIUM VOLTAGE DIRECT CURRENT SOLID-STATE CIRCUIT BREAKER IN A HIGH-ALTITUDE WORKING ENVIRONMENT			5. FUNDING NUMBERS	
6. AUTHOR(S) Brandon Keck				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			10. SPONSORING / MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.			12b. DISTRIBUTION CODE A	
13. ABSTRACT (maximum 200 words) Medium voltage direct current (MVDC) power distribution systems are gaining importance in hybrid and all-electric aircraft, as well as in shipboard power systems. The solid-state circuit breaker (SSCB) is a key enabler for MVDC circuit protection due to its superfast and arc-less current interruption capability. Funded by the National Aeronautics and Space Administration, the Naval Postgraduate School, together with collaboration partners, developed a new 2000 V, 1200 A SSCB with a quadrupled power density and significantly advanced the state of the art of the SSCB. This thesis focuses on the evaluation of the high-altitude performance of this SSCB. A vacuum chamber with customized feedthroughs was utilized to simulate the high-altitude working environment up to 51,000 ft. Switching and steady-state tests were meticulously conducted to verify the insulation and thermal design of the SSCB prototype at high altitudes. The results show the SSCB has satisfactory performance and meets the design parameters. Challenges and anomalies encountered during the high-altitude testing were detailed and resolved. Improvements and optimizations for future SSCB design iterations are proposed.				
14. SUBJECT TERMS insulated-gate bipolar transistor, IGBT, electronic metal oxide varistor, eMOV, solid-state circuit breaker, SSCB, high altitude, medium voltage direct current, MVDC			15. NUMBER OF PAGES 129	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UU	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release. Distribution is unlimited.

**PERFORMANCE EVALUATION OF A MEDIUM VOLTAGE
DIRECT CURRENT SOLID-STATE CIRCUIT BREAKER
IN A HIGH-ALTITUDE WORKING ENVIRONMENT**

Brandon Keck
Lieutenant, United States Navy
BS, University of Washington, 2016

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

from the

**NAVAL POSTGRADUATE SCHOOL
June 2023**

Approved by: Di Zhang
Advisor

Yuntao Xu
Co-Advisor

Douglas J. Fouts
Chair, Department of Electrical and Computer Engineering

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

Medium voltage direct current (MVDC) power distribution systems are gaining importance in hybrid and all-electric aircraft, as well as in shipboard power systems. The solid-state circuit breaker (SSCB) is a key enabler for MVDC circuit protection due to its superfast and arc-less current interruption capability. Funded by the National Aeronautics and Space Administration, the Naval Postgraduate School, together with collaboration partners, developed a new 2000 V, 1200 A SSCB with a quadrupled power density and significantly advanced the state of the art of the SSCB. This thesis focuses on the evaluation of the high-altitude performance of this SSCB. A vacuum chamber with customized feedthroughs was utilized to simulate the high-altitude working environment up to 51,000 ft. Switching and steady-state tests were meticulously conducted to verify the insulation and thermal design of the SSCB prototype at high altitudes. The results show the SSCB has satisfactory performance and meets the design parameters. Challenges and anomalies encountered during the high-altitude testing were detailed and resolved. Improvements and optimizations for future SSCB design iterations are proposed.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

I.	INTRODUCTION.....	1
A.	BACKGROUND OF THE SOLID-STATE CIRCUIT BREAKER.....	2
1.	DCCB Overview and State of the Art.....	2
2.	SSCB Development at Naval Postgraduate School.....	5
B.	CHALLENGES OF HIGH-ALTITUDE OPERATION.....	9
1.	Insulation Performance.....	9
2.	Thermal Performance.....	10
C.	THESIS OUTLINE.....	11
II.	VACUUM CHAMBER, ACCESSORIES, AND SETUP FOR HIGH-ALTITUDE TESTING.....	13
A.	VACUUM CHAMBER BACKGROUND.....	13
B.	CHAMBER SELECTION.....	14
1.	Size and Shape.....	14
2.	Construction Material.....	15
C.	FEEDTHROUGH AND CONNECTOR SELECTION.....	16
1.	HV and High Current Feedthroughs for Power Cable Connections.....	16
2.	Flexible Braided Copper Connectors.....	17
3.	HV Feedthroughs for Voltage Measurements.....	18
4.	BNC Feedthroughs for Current Measurements and Control Signaling.....	19
5.	D-Sub Feedthrough for Low-Voltage Power.....	20
D.	CHAMBER CUSTOMIZATION.....	20
E.	VACUUM PUMP.....	22
F.	CHAMBER PREPARATION.....	23
G.	SSCB ASSEMBLY.....	25
H.	SSCB INSTALLATION AND INITIAL SETUP.....	28
III.	EVALUATION OF SSCB SWITCHING AND INSULATION PERFORMANCE AT HIGH ALTITUDE.....	33
A.	SWITCHING TEST SETUP AND INSTRUMENTATION.....	33
B.	PCB POTTING.....	41
1.	Gate Drive PCB and eMOV PCB Potting at NPS Using Silicone Gel.....	42

2.	Potting of Original eMOV PCB at UConn Using Epoxy Resin	44
3.	Potting of Updated eMOV PCB at UConn Using Epoxy Resin	45
4.	Potting Procedure Optimization Testing at NPS	47
C.	TEST EXECUTION, DATA ACQUISITION, AND PROCESSING.....	52
1.	Incremental Test Execution: Sea Level – 10 000 ft – 35 000 ft – 51 000 ft.....	53
2.	Current Measurement Errors While Using Multiple Rogowski Coils on the BNC Feedthrough and the Solution	56
3.	SSCB Switching Test in Chamber with Silicone-Potted eMOV PCB	59
4.	SSCB Switching Test in Chamber with Epoxy-Potted eMOV PCB	60
5.	Asymmetrical Short-Circuit Behavior and Investigation	64
D.	CONCLUSIONS ON SSCB INSULATION PERFORMANCE	71
IV.	EVALUATION OF SSCB THERMAL PERFORMANCE AT HIGH ALTITUDE.....	73
A.	THERMAL TEST SETUP AND INSTRUMENTATION.....	73
B.	TEST EXECUTION, DATA ACQUISITION AND PROCESSING.....	78
1.	Incremental Test Execution: Sea Level – 10 000 ft – 35 000 ft – 51 000 ft.....	79
2.	Instrumentation Enhancement for Busbar Temperature Measurement	86
C.	CONCLUSIONS ON SSCB THERMAL PERFORMANCE	97
V.	SUMMARY AND FUTURE WORK.....	99
A.	SUMMARY	99
B.	FUTURE WORK.....	99
	LIST OF REFERENCES	101
	INITIAL DISTRIBUTION LIST	107

LIST OF FIGURES

Figure 1.	SSCB Topology	4
Figure 2.	HCB Topology.....	4
Figure 3.	Auxiliary Switch Inserted in the MOV Branch	6
Figure 4.	eMOV-Based SSCB.....	7
Figure 5.	Breakdown Voltage of Air per Paschen's Law. Source: [26].	9
Figure 6.	Dimensions of a Single Pole of the SSCB Installed in Housing.....	15
Figure 7.	HV and HC 1-in Copper Feedthrough	17
Figure 8.	HV and HC 1-in Copper Feedthrough Milling Schematic	17
Figure 9.	Storm Power Components SC-B4F12, 12 in, 1000 A Copper Braid.....	18
Figure 10.	FA11672-02 – 5 kV, 28 A, Molybdenum Conductor HV Feedthrough. Adapted from [36].	18
Figure 11.	FP10883 – 20 kV, 30 A HV Plug and Cable. Source: [37].	19
Figure 12.	KT13025 – 500 V, 3.6 A, BNC Feedthrough. Source: [38].	19
Figure 13.	FA13288 – 500 V, 5 A, 9-Pin D-Sub Feedthrough. Source: [39].	20
Figure 14.	Mechanical Model of Chamber Feedthroughs.....	21
Figure 15.	Drilling Feedthrough Holes in Vacuum Chamber Walls.....	21
Figure 16.	Flow Capacity of KNF Laboport N820.3FTP Vacuum Pump. Source: [40].....	22
Figure 17.	Air Side of Power Feedthrough Assembly Installed in Vacuum Chamber Wall	24
Figure 18.	Vacuum Chamber Before (L) and After (R) Feedthrough Installation.....	24
Figure 19.	TG-N909 Non-Silicone Thermal Grease Applied to IGBT Baseplate Using Stencil.....	25
Figure 20.	Model of Custom ATS Cold Plate with One IGBT Installed	26

Figure 21.	MOV Assembly, Snubber Capacitor, SCR, and eMOV PCB Mounted on G-10 Plate	26
Figure 22.	SSCB prior to Busbar Installation.....	27
Figure 23.	SSCB Installed on Cold Plate	27
Figure 24.	SSCB Electrical Connections	28
Figure 25.	SSCB Housing; Top Cover Removed.....	28
Figure 26.	SSCB Installed in Housing	29
Figure 27.	Test Setup for Switching Performance Evaluation of SSCB Prototype	33
Figure 28.	Switching Test Setup	34
Figure 29.	Positive Cable from Air-Core Inductor to Power Feedthrough for Switching Test	35
Figure 30.	Vacuum-Side Power Connections for Switching Tests	35
Figure 31.	Air-Side Power Cable Setup for Short-Circuit Test	36
Figure 32.	Vacuum-Side Power Cable Setup for Short-Circuit Test	37
Figure 33.	Measurement of Power Circuit Signals	38
Figure 34.	Voltage Probe Connections for Switching Test.....	39
Figure 35.	Current Measurement of Snubber and MOV (L); MOV Only (R).....	39
Figure 36.	Screenshot of SSCB Prototype Switching Transient with $V_{dc} = 2000\text{ V}$, $T_{ON} = 25\text{ }\mu\text{S}$ and $L_{SYS} = 25\text{ }\mu\text{H}$	40
Figure 37.	SSCB Prototype Switching Transient Waveforms with $V_{dc} = 2000\text{ V}$, $T_{ON} = 25\text{ }\mu\text{S}$ and $L_{SYS} = 25\text{ }\mu\text{H}$	41
Figure 38.	Gate Drive PCB Encapsulation Areas	42
Figure 39.	Potting Areas on Top and Bottom of eMOV PCB	42
Figure 40.	eMOV PCB Potted with Dowsil 3-4155 Silicone Gel.....	43
Figure 41.	Potting of Original eMOV Triggering Board Using EpoxiCure 2	45
Figure 42.	Potting of Updated eMOV PCB Using EpoxiCure 2.....	46

Figure 43.	Test PCB in Silicone Mold with Fastener Jig.....	48
Figure 44.	Epoxy in Vacuum Chamber to Remove Air Bubbles.....	49
Figure 45.	Epoxy-Potted Test PCB Before (L) and After (R) Mold Removal	50
Figure 46.	Removing Excess Potting Material with Table Saw.....	51
Figure 47.	Finished Test PCB Potted with MAS Deep Pour Epoxy.....	52
Figure 48.	Current Signal Distortion When Using Two BNC Feedthroughs (Ch. 7 and Ch. 8).....	57
Figure 49.	Current Signals When Using One Feedthrough and One Direct Connection to Oscilloscope; No Distortion (Ch. 7 and Ch. 8)	57
Figure 50.	Current Signals When Using One Rogowski Coil via Feedthrough and One Measured Indirectly (Ch. 7 and Math 1)	58
Figure 51.	Comparison of Switching Transient Waveforms at Sea Level (L) and 51 000 ft (R) with $V_{dc} = 2000\text{ V}$, $T_{ON} = 25\text{ }\mu\text{S}$, $L_{SYS} = 25\text{ }\mu\text{H}$, Current Flow in Positive Direction	61
Figure 52.	Comparison of Switching Transient Waveforms at Sea Level (L) and 51 000 ft (R) with $V_{dc} = 2000\text{ V}$, $T_{ON} = 25\text{ }\mu\text{S}$, $L_{SYS} = 25\text{ }\mu\text{H}$, Current Flow in Negative Direction	62
Figure 53.	Desaturation Triggered Opening of SSCB; Current Flow in Positive Direction	63
Figure 54.	Desaturation Triggered Opening of SSCB; Current Flow in Negative Direction	63
Figure 55.	Short-Circuit Test Waveforms; Current Flow in Positive Direction	64
Figure 56.	Short-Circuit Test Waveforms; Current Flow in Negative Direction.....	65
Figure 57.	Short-Circuit Test Waveforms; Snubber Resistance Doubled; Current Flow in Negative Direction	66
Figure 58.	Early SSCB Layout with Narrow (L) and Wide (R) Emitter Busbar	67
Figure 59.	SSCB Prototype Layout.....	68
Figure 60.	Snubber Termination Points at Positive (L) and Negative (R) Poles	69
Figure 61.	Alternative Placement of Snubber Branch in Benchtop Unit	70

Figure 62.	Short-Circuit Test Waveforms; Current Flow in Positive Direction; Alternative Snubber Placement.....	70
Figure 63.	Short-Circuit Test Waveforms; Current Flow in Negative Direction; Alternative Snubber Placement.....	71
Figure 64.	Test Setup Schematic for Thermal Performance Evaluation of SSCB Prototype	73
Figure 65.	Thermal Performance Test Setup.....	74
Figure 66.	313 kcmil DLO Power Cables from High-Current Power Supply to Power Feedthroughs for Thermal Test	75
Figure 67.	12-in Copper Braids for HC Thermal Test	75
Figure 68.	Cooling Capacity of SMC HRS060-AN-20 Thermal Chiller. Source: [44].....	76
Figure 69.	Keysight DAQ970A Data Acquisition System. Source: [45].....	77
Figure 70.	DAQM902A 16-Channel Multiplexer (2 / 4-Wire) Module	77
Figure 71.	Thermal Test Record; Sea Level.....	81
Figure 72.	Thermal Test Record; 10 000 ft, 35 000 ft and 51 000 ft.....	81
Figure 73.	Detailed Thermal Test Data; 10 000 ft.....	82
Figure 74.	Detailed Thermal Test Data; 35 000 ft.....	83
Figure 75.	Detailed Thermal Test Data; 51 000 ft.....	84
Figure 76.	Extended Runtime Thermal Test Record; 51 000 ft	85
Figure 77.	Vishay Lug-Type Negative Temperature Coefficient (NTC) Thermistor.....	87
Figure 78.	Lug-Type NTC Thermistors Installed for Busbar Temperature Measurement.....	87
Figure 79.	Housing Cover Installed for Thermal Testing	88
Figure 80.	Thermal Test Record with Lug-Type Thermistors; Sea Level	89
Figure 81.	Thermal Test Record with Lug -Type Thermistors; 35 000 ft.....	89
Figure 82.	Thermal Test Record with Lug-Type Thermistors; 51 000 ft.....	90

Figure 83.	Extended Runtime Thermal Test Record with Lug-Type Thermistors; 51 000 ft.....	91
Figure 84.	Infineon IHM/IHV B Module Package and Internal Layout. Source: [46].....	93
Figure 85.	Copper Terminal Bonding Using Ultrasonic Welding. Source: [47].	93
Figure 86.	Extended Runtime Thermal Test Record with Lug-Type Thermistors; Busbar Bolts Torqued to 9 N·m; 51 000 ft.....	95
Figure 87.	Flat Busbar Painted Black.....	96
Figure 88.	Extended Runtime Thermal Test Record with Flat Busbar Painted Black; 51 000 ft.....	96

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

Table 1.	Comparison of Vacuum Chamber Materials. Adapted from [34].	14
Table 2.	Pressure to Altitude Conversion Table. Adapted from [41].	22
Table 3.	Feedthrough Connections for Switching Test.....	31
Table 4.	SSCB Benchtop Switching Test Results; No Housing; Silicone-Potted eMOV PCB; Current Flow in Positive Direction	55
Table 5.	SSCB Benchtop Switching Test Results; No Housing; Silicone-Potted eMOV PCB; Current Flow in Negative Direction	55
Table 6.	SSCB Benchtop Switching Test Results; with Housing; Silicone-Potted eMOV PCB; Current Flow in Positive Direction	55
Table 7.	SSCB Benchtop Switching Test Results; with Housing; Silicone-Potted eMOV PCB; Current Flow in Negative Direction	55
Table 8.	SSCB Switching Test in Chamber; Silicone-Potted eMOV PCB; Current Flow in Negative Direction	59
Table 9.	SSCB Switching Test in Chamber at 51 000 ft; Silicone-Potted eMOV PCB; Current Flow in Positive Direction	59
Table 10.	SSCB Switching Test in Chamber; Epoxy-Potted eMOV PCB; Current Flow in Positive Direction	60
Table 11.	SSCB Switching Test in Chamber; Epoxy-Potted eMOV PCB; Current Flow in Negative Direction	61
Table 12.	SSCB Switching Test in Chamber at 51 000 ft; Epoxy-Potted eMOV PCB; DC Source Voltage at 2000 V; Desaturation Protection Activated	62
Table 13.	Keysight DAQ System Channel Lineup	78
Table 14.	Voltage Drop and Dissipation Data; 10 000 ft.....	82
Table 15.	Voltage Drop and Dissipation Data; 35 000 ft.....	83
Table 16.	Voltage Drop and Dissipation Data; 51 000 ft.....	84
Table 17.	Voltage Drop and Dissipation Data, Extended Runtime; 51 000 ft.....	85

Table 18.	Detailed Thermal Data for Extended Runtime; 51 000 ft	91
Table 19.	Detailed Thermal Data for Extended Runtime; Busbar Bolts Torqued to 9 N·m; 51 000 ft.....	95
Table 20.	Detailed Thermal Data for Extended Runtime with Flat Busbar Painted Black; 51 000 ft.....	97

LIST OF ACRONYMS AND ABBREVIATIONS

ac	alternating current
AEA	all electric aircraft
ATS	Advanced Thermal Solutions
AWG	American wire gauge
BNC	Bayonet Neill–Concelman
BOD	breakover diode
CB	circuit breaker
DAQ	data acquisition
DBC	direct bond copper
dc	direct current
DLO	diesel locomotive
eMOV	electronic metal oxide varistor
EPS	electric power system
FLASH	Fast Light-Weight Altitude Ready Solid-State Circuit Breaker for Hybrid Electric Propulsion
HC	high current
HCB	hybrid circuit breaker
HED	hybrid electric drive
HV	high voltage
IGBT	insulated-gate bipolar transistor
kcmil	thousand circular mil
LC	low current
LV	low voltage
MCB	mechanical circuit breaker
MEA	more electric aircraft
MOV	metal oxide varistor
MV	medium voltage

NPS	Naval Postgraduate School
NTC	negative temperature coefficient
PCB	printed circuit board
PD	partial discharge
RoR	rate of rise
RTD	resistance temperature detector
SCR	silicon controlled rectifier
SSCB	solid-state circuit breaker
SST	Solid Sealing Technology
UConn	University of Connecticut

ACKNOWLEDGMENTS

I would like to thank my advisors for their assistance during this thesis. Dr. Di Zhang, your patience in getting me caught up on the academics behind this project was second to none. Dr. Yuntao Xu, our time spent in the lab working on this project was the highlight of my time here. I cannot thank you enough for all the time and effort you have spent helping and guiding me. I would also like to thank Mr. Bob Broadston for ensuring we always had everything we needed to keep the lab running and the project moving forward.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

In the past several decades, there has been an ever-increasing trend in the electric power industry of adopting the direct current (dc) network. There are several reasons behind this important paradigm shift. It is generally agreed that carbon dioxide emissions from the burning of fossil fuel for power generation and transportation contribute significantly to climate change. Against this backdrop, electric power generation from renewable energy sources and electrification in the ground and maritime transportation and aviation sectors have seen drastic growth and are expected to grow even faster. In the meantime, progress in power electronics, from semiconductor devices to power converters and controls, has been an enabler for these developments.

Using medium voltage (MV) dc systems as the collector grid and distribution network for electric power generated from large renewable sources, such as offshore wind farms [1] and large photovoltaic parks [2], offers many advantages over traditional alternating current (ac) systems. The technical advantages include easier and more straightforward integration, modularity and scalability, and more efficient and economical operation. High voltage (HV) dc systems are a proven technology for transmission of large amounts of power over long distances. On the consumer side, low voltage (LV), or even MV, dc residential distribution systems are expected to see significant growth [3]–[5].

In the aviation sector, the more electric aircraft (MEA) and all electric aircraft (AEA) have been proposed to reduce fuel consumption and production of greenhouse gases and to increase overall efficiency [6]–[9]. The electric power consumption ranges from hundreds of kilowatts in MEA to megawatts in AEA. Such electric power necessitates the use of higher voltage to contain the conductor weight. In the electric power system (EPS) for AEA, voltage levels in the kilovolts range are required, which is considered as MVDC and even HVDC in the aviation sector, where the voltage levels are categorized differently from the ground-based EPS.

The MVDC distribution system is also seen as an attractive candidate for next-generation shipboard power systems to accommodate such developments as the integrated power system, hybrid electric drive (HED), and all electric ship [10]–[13]. The MVDC distribution facilitates integration of the energy storage systems for high power pulse load handling, more efficient generator operation, and enhancement of power quality and availability. The HED decouples the engine or turbine speed from the propeller, allowing increased efficiency and fuel savings.

A. BACKGROUND OF THE SOLID-STATE CIRCUIT BREAKER

Protection is an important aspect in the design, implementation, and operation of dc systems. The protection hardware and controls must be able to detect the fault or overload condition and isolate the problematic portion without affecting other parts of the system. Compared with the protection in a traditional ac system, the dc system poses unique challenges. In a traditional thyristor based HVDC transmission line, the filtering requirement necessitates the installment of line reactors of large inductance, which can be significantly reduced in the more recent HVDC technology based on the voltage source converters. MVDC and LVDC systems typically have lower inductance compared with their ac counterparts. Upon a short-circuit fault, the lower inductance results in a higher rate of rise (RoR) of the fault current, but the ubiquitous power converters have limited overload capability [14], [15]. Therefore, the fault isolation device (i.e., the circuit breaker (CB)) is required to have a high response speed. On the other hand, there is no natural zero crossing of the fault current, as in the ac system. This creates difficulty in arc extinguishing in the typical mechanical CB (MCB). This, together with the relatively long operating time of typical MCBs, up to tens of milliseconds, necessitates special or new types of CBs for dc protection.

1. DCCB Overview and State of the Art

Arc extinguishing in the MCB can be enhanced by increasing the number of gaps, or by passive or active counter-current injection using a resonant circuit [16], [17]. This, however, does not improve the operating speed. Additionally, the contacts wear due to the dc arc, affecting the CB life and reliability. Therefore, high-speed DCCBs usually

incorporate power semiconductor or solid-state switches to achieve arc-less current interruption [18]–[21]. A DCCB typically consists of three branches (i.e., the load current carrying branch, the current commutation branch, and the voltage clamping and energy absorption branch). Large variations exist in the actual implementation. For example, current commutation, voltage clamping, and energy absorption might be implemented in a single physical branch. Alternatively, multiple commutation branches could be used for a multi-staged commutation.

The solid-state circuit breaker (SSCB) is solely based on power semiconductor devices, with no mechanical switch or moving parts. A typical SSCB capable of current flow and voltage blocking in both directions (i.e., four-quadrant operation) consists of two semiconductor modules connected in anti-series and a voltage clamping device, as shown in Figure 1. Each semiconductor module, such as an insulated-gate bipolar transistor (IGBT) module with antiparallel diode, is a two-quadrant solid-state switch allowing bidirectional current flow but only capable of blocking one polarity. The voltage clamping device is connected in parallel with the semiconductor modules to provide a current commutation path and voltage containment during the opening, or turn-off, of the SSCB. In high power applications, the voltage clamping device is usually a metal oxide varistor (MOV) due to its highly nonlinear voltage-current characteristics and high energy absorption capability.

Compared with the MCB, the SSCB has much higher dissipation while carrying the load current since the conduction voltage drop across the semiconductor device is significant compared to that incurred in the metal contacts of the MCB. The hybrid CB (HCB) is intended as a compromise, combining the advantages of both the MCB and the SSCB. Figure 2 shows a representative HCB configuration, where the path consisting of a mechanical switch and a low voltage power semiconductor device carries the load current, and the other paths are engaged in current commutation and energy absorption during current interruption. The low voltage device does not need to have the same voltage rating as that in the middle branch and therefore incurs a much lower conduction voltage drop. In some HCB configurations, the low voltage device is removed to further reduce the conduction dissipation, but the arc cannot be eliminated during the opening of

the mechanical switch. Due to the limited thermal handling capability of the semiconductor devices, the mechanical switch in the HCB should be of the fast-acting or high-speed type. The currently achievable operating time of high-speed mechanical switches is still in the milliseconds range, much slower than the solid-state devices.

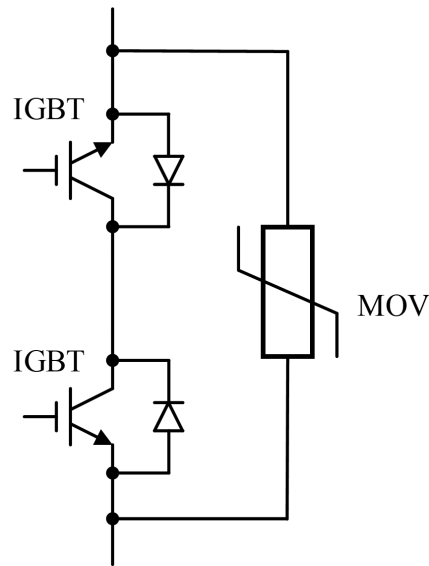


Figure 1. SSCB Topology

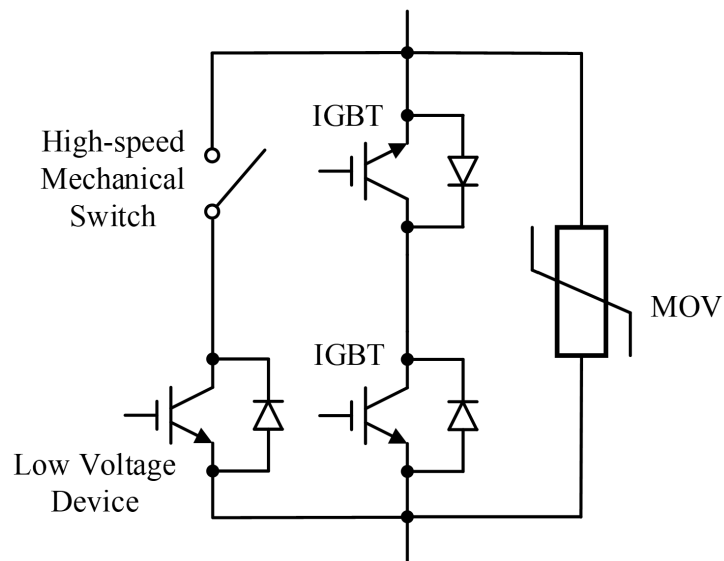


Figure 2. HCB Topology

2. SSCB Development at Naval Postgraduate School

Starting in early 2020, the Naval Postgraduate School (NPS) began a collaboration with Virginia Tech, the University of Connecticut (UConn), Clemson University, and the Naval Air Warfare Center Weapons Division to develop an MVDC SSCB intended for use in hybrid electric aircraft propulsion. This three-year, three-phase project, named Fast Light-Weight Altitude-Ready Solid-State Circuit Breaker for Hybrid Electric Propulsion (FLASH) [22], was sponsored by the National Aeronautics and Space Administration (NASA) to advance existing SSCB technologies. The major objective was to develop an altitude-ready 2000 V, 1200 A bi-directional SSCB with volumetric and gravimetric power densities significantly higher than the state of the art. This objective has been successfully accomplished with an ingenious voltage clamping circuit design and by elimination of the fault current limiting inductor usually employed in the standard MVDC SSCB.

Referring to Figure 1, despite a high pulse energy rating, the MOV has limited continuous power dissipation capability. As a result, a MOV selected based on the nominal dc system voltage can clamp voltage only at a much higher value, typically two to three times the dc system voltage. This necessitates the use of semiconductor modules with a voltage margin noticeably higher than that typically adopted in the power converter design. As a result, the efficiency of the SSCB is negatively impacted. A fundamental improvement can be made if the MOV is subject to none or only part of the dc system voltage when the SSCB is open while maintaining the same voltage clamping function as in the conventional SSCB during the turn-off transient. Such decoupling of the MOV clamping voltage and the dc system voltage can be achieved by inserting an auxiliary switch in the MOV branch, as shown in Figure 3. The auxiliary switch stays open when the SSCB is off but will close to allow current commutation to the MOV and voltage clamping.

Such an auxiliary switch can be implemented with thyristors or silicon controlled rectifiers (SCRs), as in the well-known crowbar circuit. The resulting MOV branch is termed the electronic MOV (eMOV) [23] since the auxiliary switch is implemented with

electronic components, and accordingly, an eMOV-based SSCB, as shown in Figure 4, is obtained. In this circuit, the SCRs stay open except during the IGBT turn-off transient.

Referring to Figure 4, in the electronic portion of the MOV branch are two identical SCRs connected in antiparallel. Each SCR has a breakover diode (BOD) connected between its anode and gate. A diode in series with the BOD blocks most of the negative voltage when the SCR is negatively biased. A resistor in parallel with the BOD, together with another resistor connected across the MOV, form a voltage divider when the SSCB is in the off state. The trio of a Zener diode, a capacitor, and a resistor between the gate and cathode of each SCR provides protection against parasitic triggering and gate overvoltage.

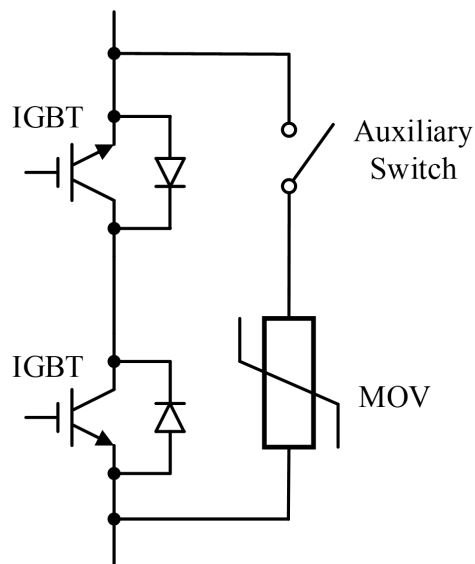


Figure 3. Auxiliary Switch Inserted in the MOV Branch

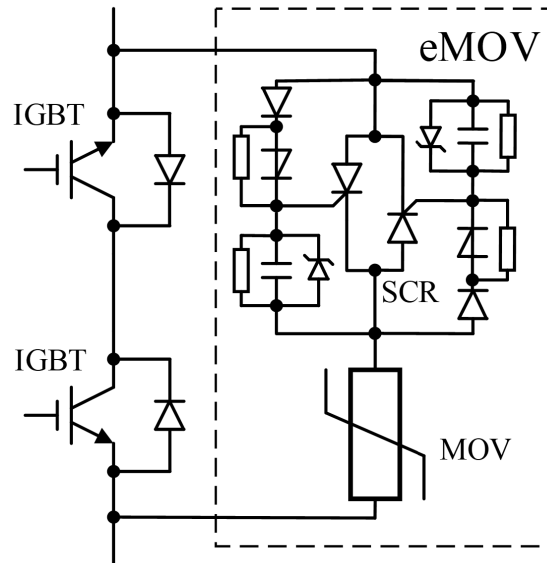


Figure 4. eMOV-Based SSCB

There are four typical operating modes in the eMOV-based SSCB:

1. When the SSCB is open (i.e., IGBTs are off), the dc source voltage is divided between the MOV and SCR per the voltage divider mentioned earlier. For example, equal voltage division is achieved if the resistance values are the same for the two resistors. As a result, only half of the dc source voltage is applied across the MOV. By comparison, all the dc source voltage is applied across the MOV in the conventional SSCB.
2. When the IGBTs are turned on, the voltage across the eMOV collapses. The MOV and SCR voltages drop at different rates determined by their parasitic capacitances, typically ending up with positive and negative polarity, respectively. Afterwards, both the MOV and SCR voltages decay to almost zero, with the decay rate determined by the parasitic capacitances and resistances in the eMOV branch.
3. When the IGBTs are turned off to open the SSCB, the MOV and SCR voltages rise at different rates determined by their parasitic capacitances. The voltage across the BOD follows that across the SCR, gradually reaching the BOD breakover voltage. Consequently, the BOD breaks over and a current pulse is generated in the SCR

gate path, turning on the SCR and allowing fast current commutation to the eMOV path. The MOV clamps the voltage across the SSCB just as in the conventional SSCB.

4. After the IGBT turn-off, the load or fault current flows through the MOV and is cleared in due course. The SCR turns off after the MOV current decays below the SCR holding current. The voltage distribution between the MOV and SCR is restored to that prior to the IGBT turn-on.

The advantage of the eMOV-based SSCB is apparent from the above description. The auxiliary switch is implemented with no mechanical moving parts or additional controls and is capable of fast response when called for. The decoupling of the dc source voltage and that across the MOV during the normal off state allows the use of IGBT modules with a voltage rating most suited for the dc system voltage, thus improving the SSCB efficiency.

The FLASH SSCB has another unique design feature aimed at weight and size reduction, which is particularly relevant for aviation applications. As discussed earlier, the system inductance in an MVDC system is typically too low to limit the fault current RoR, and an additional current limiting inductor is required for fault current containment. The current limiting inductor adds to the SSCB size, weight, and cost. The FLASH SSCB achieves an inductor-less design by reducing the IGBT on-state gate voltage and utilizing the current saturation characteristic of the IGBT module [24]. The trade-off is more dissipation during load current carrying and SSCB efficiency reduction. Detailed testing and data analysis validated that this design achieves fault current containment with an acceptable and insignificant efficiency penalty [25].

The FLASH SSCB switching transient behavior during current interruption and the thermal performance during continuous load current carrying have been thoroughly evaluated with a benchtop prototype in the lab, as detailed in [25]. Following this, a fully packaged SSCB prototype was manufactured for further evaluation, with a specific focus on its performance in a high-altitude working environment.

B. CHALLENGES OF HIGH-ALTITUDE OPERATION

The FLASH SSCB was designed for aviation applications, intended to be deployed in future MVDC systems onboard aircraft. High altitude poses unique challenges to the design of aircraft EPS and components. The design challenges fall into two categories, insulation performance and thermal management.

1. Insulation Performance

Electrical systems onboard aircraft have historically used low voltages (i.e., 28 V dc or 115/200 V ac). Such selection of voltage levels is rooted in the well-known Paschen's law, which describes the breakdown voltage between two electrodes as a function of the product of the electrode separation and the ambient gas pressure. In air, curves based on Paschen's law can be depicted as in Figure 5 [26]. It is apparent that there is no breakdown concern with voltages below 327 V, which translates to a root-mean-square voltage of 231 V in the ac system [27]. The electric power consumption and transfer in an MEA or AEA necessitates the use of higher voltage levels. The FLASH SSCB is intended for use in an MVDC EPS with a nominal dc supply voltage up to 2000 V and at altitudes up to 51 000 ft. Its insulation design and evaluation are essential.

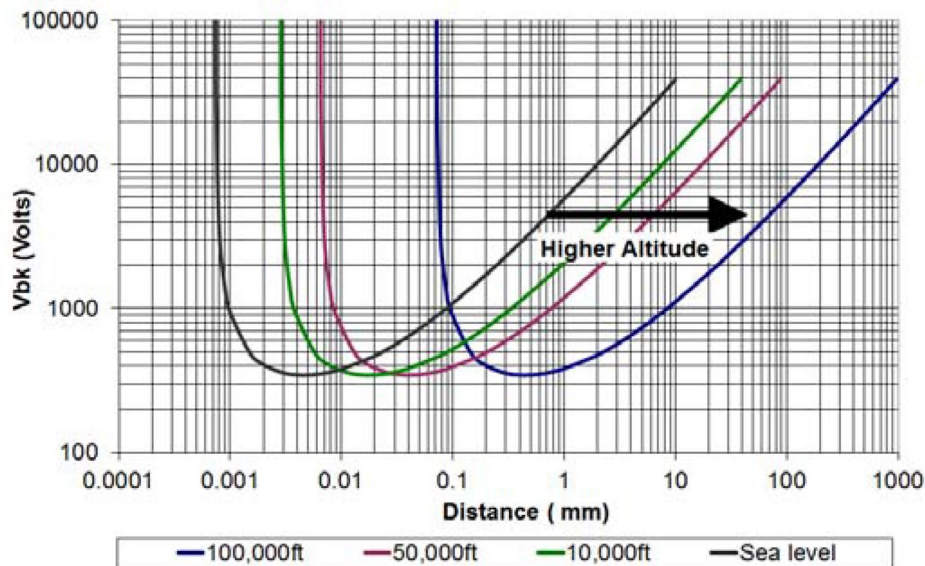


Figure 5. Breakdown Voltage of Air per Paschen's Law. Source: [26].

In the first phase of the FLASH SSCB project, a rigorous process was followed for component selection and development. The key components are those subject to high standby and/or transient voltage, including the IGBT modules, SCR module, MOV, gate drive printed circuit board (PCB), SCR trigger PCB, and copper busbars and wires. The insulation performance of some of these components (e.g., the IGBT modules) at high altitudes was verified before incorporation into the SSCB [28].

One method of eliminating the dependance between insulation performance and air pressure is to use solid insulating materials, such as silicone gel or epoxy, to pot the areas where voltage stress is expected. However, any small air pocket or void remaining in the solid potting material can actually strengthen the local electric field in the void, leading to local breakdown or partial discharge (PD).

In the final phase of this project, it was a critical step to evaluate the insulation performance of the fully packaged SSCB prototype in the high-altitude environment. The standard PD test for component screening is not directly applicable to this evaluation. Instead, switching tests were conducted in the whole range of altitudes up to 51 000 ft in a simulated environment to identify any indicators of deteriorating insulation performance.

2. Thermal Performance

The high-altitude working environment brings thermal challenges to the aircraft EPS and its components due to reduced air pressure and air density. The convective heat transfer is negatively affected the most [29], [30], while radiative heat transfer could become relevant [31], [32]. For this reason, together with the fact that the dissipation incurred in the SSCB is relatively high compared with that in an MCB, active liquid cooling was selected for the FLASH SSCB to remove the heat generated by the semiconductor power devices in the IGBT modules. However, there are parts in the SSCB, especially the heavy copper busbars, that have an ambiguous thermal interface to the environment, warranting a thorough evaluation of the SSCB thermal behavior in the high-altitude operating condition. This was another focus of this thesis. The thermal test

in the simulated high-altitude environment allowed validation of the SSCB thermal design, extraction of the operating efficiency, and a detailed loss breakdown.

C. THESIS OUTLINE

This thesis focused on the third phase of the FLASH SSCB development, which entailed a full functional test of the developed 2 kV, 1.2 kA SSCB prototype, both at sea level and in a simulated high-altitude (up to 51 000 ft) environment, against the design specifications. The fully tested SSCB prototype will be incorporated in the hybrid electric propulsion EPS for evaluation in the NASA Electric Aircraft Testbed.

Chapter 2 discusses the use of a vacuum chamber for simulating the high-altitude environment where the SSCB prototype is to operate. The chamber sizing and selection is covered, along with discussions on the plumbing and the customized feedthrough arrangement for passing power, signals, coolant, and instrumentation through the chamber walls. The potting of PCBs and the mechanical assembly aspects of the SSCB prototype are detailed.

Chapter 3 focuses on the SSCB switching performance test in the vacuum chamber. The switching test setup, instrumentation, and results are presented. Challenges encountered, anomalies uncovered, and solutions devised are detailed.

Chapter 4 centers on the SSCB thermal performance at high altitudes. The thermal test setup, instrumentation, and results are presented. The interesting results related to the copper busbars are explained. Detailed loss breakdown and SSCB prototype efficiency data are presented.

Finally, Chapter 5 summarizes the high-altitude testing results for the SSCB prototype and suggests future research activities to further improve the SSCB performance.

THIS PAGE INTENTIONALLY LEFT BLANK

II. VACUUM CHAMBER, ACCESSORIES, AND SETUP FOR HIGH-ALTITUDE TESTING

A. VACUUM CHAMBER BACKGROUND

A vacuum chamber is any rigid enclosure capable of having the air inside of it removed to reduce the pressure inside, thus creating a vacuum. Vacuum chambers have a variety of uses, including research, manufacturing, and even home use. They can be used for atmospheric simulations, degassing, leak testing, drying, inert gas storage, or any number of other applications that require an object to be at a pressure lower than atmospheric pressure. They can be made from any material capable of handling the pressure changes seen in the chamber. Common vacuum chamber construction materials include acrylic, stainless steel, aluminum, or even glass. They can come in a variety of different shapes, such as box, cylinder, sphere, or bell jar, and in sizes ranging from a volume as small as one cubic centimeter up to the largest chamber in the world, which is 100 ft in diameter and 122 ft tall [33]. Vacuum chambers also need at least one feedthrough or penetration to allow for connecting the vacuum pump and pressure release valve.

The final design of a chamber is highly dependent on its intended application. A small, box-shaped vacuum chamber might work well if the chamber is going to be used for small-scale research on the vacuum encapsulation of printed circuit boards (PCBs). On the other hand, if the chamber is going to be used to test the effects of space on a ballistic missile, then a much larger, cylindrical chamber is likely going to be a better choice. Some materials are better suited to one application versus another. Table 1 gives a quick comparison of a few common chamber construction materials used in smaller box-shaped vacuum chambers. Most chambers will also have additional feedthroughs for sensors, communication, power, etc. While the application will dictate the number and type of feedthroughs needed, the selected construction material will determine the ease of feedthrough installation.

Table 1. Comparison of Vacuum Chamber Materials. Adapted from [34].

Material	Advantages	Disadvantages
Acrylic	• Transparent • Ideal for degassing, vacuum encapsulation, and general-purpose vacuum experiments • Least expensive option • Lightest option	• Hygroscopic • Can be damaged by isopropyl alcohol and many other cleaners • More prone to cracking which could result in leaking
Aluminum	• Better chemical resistance • Minimizes moisture within chamber • Easier to machine and modify for feedthroughs	• Typically, only one small window, if any, to see inside • More expensive than acrylic • Heaviest option
Stainless Steel	• Easiest to clean • Chemical and heat resistant, better suited for wider range of operations • Very durable	• Most expensive option • Typically, only one small window, if any, to see inside • Heavier than acrylic • Limited sizes available

B. CHAMBER SELECTION

1. Size and Shape

The purpose of the vacuum chamber in this project was to simulate the effects of decreased pressure at high altitude on the solid-state circuit breaker (SSCB). The first step in determining which chamber to use was to determine the size and shape needed. To do this, the mechanical model of the SSCB was analyzed. Note that while the final design of the SSCB consists of two poles, only a single pole is used for discussion in this thesis. Using a single pole significantly simplifies mounting and testing within the vacuum chamber. At the same time, using a single pole also represents the worst-case scenario where the fault is isolated across a single pole, and that pole must handle the entire fault load instead of sharing it across two poles. Once the dimensions of the SSCB and housing, seen in Figure 6, were analyzed, space for the coolant plumbing was added to the length, space for power connections was added to the width, and room for various sensor and control feedthroughs was added to the height. Additional space was allowed all around for placing meters, tucking away excess cabling, and working room. Based on

these estimates, it was determined that a standard box-shaped chamber approximately 20 in long, 20 in wide, and 20 in high would be the best choice. The next step was to determine the best construction material.

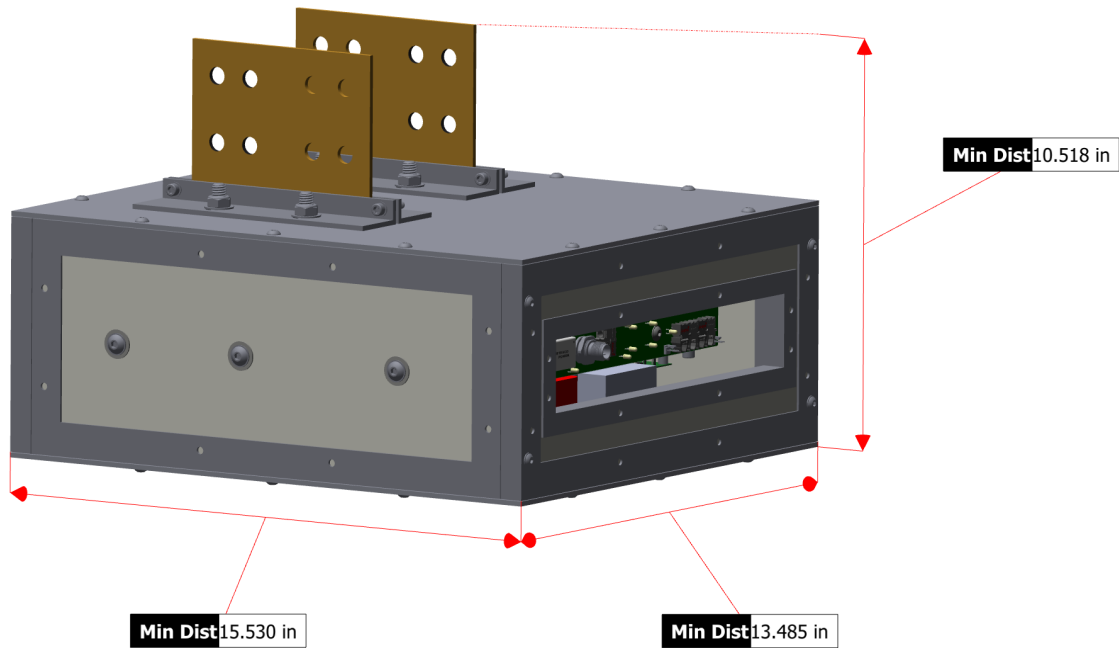


Figure 6. Dimensions of a Single Pole of the SSCB Installed in Housing

2. Construction Material

The primary concerns when selecting the construction material were SSCB visibility and chamber availability, with cost being a contributing factor. Of the three materials compared in Table 1, acrylic is the only one that is transparent on all sides. It is also readily available and the least expensive option. The hygroscopic nature of acrylic is easily mitigated by drawing a vacuum in the chamber a couple times before use to draw out any moisture that the acrylic may have absorbed. Weight was also not a substantial concern, as all variations in the 20-in $\times$ 20-in $\times$ 20-in size were heavy enough to warrant at least two people to move it, so the chamber was going to be placed on a cart for maneuvering around the lab regardless of the material chosen. Therefore, an acrylic chamber from Terra Universal (P/N: 5235-62) was chosen. The acrylic used in this model

is 1.5-in thick, making the exterior dimensions of the finished chamber, exclusive of any feedthrough or attachment, 23 in × 23 in × 23 in. The shipping weight of the chamber was approximately 220 lb. The next step was to determine which feedthroughs would be needed.

C. FEEDTHROUGH AND CONNECTOR SELECTION

Multiple feedthroughs were needed for measuring the voltage and current at various locations and for providing control signals and LV power to the various PCBs on the SSCB. These feedthroughs needed to be reliable, readily available, and hermetically sealed for use in a vacuum chamber. Solid Sealing Technology (SST) components met these requirements and were chosen for the control and measurement feedthroughs. Additional feedthroughs included copper rods for supplying the power and grounding the housing, and stainless-steel tubing for the coolant. To ensure these feedthroughs were both secure and airtight, Swagelok tube fittings were chosen. Swagelok tube fittings use a unique two-ferrule design in which the front ferrule creates a seal while the back ferrule grips the tube [35].

1. HV and High Current Feedthroughs for Power Cable Connections

HV and high current (HC) from the power supplies needed to be passed through the chamber walls to the SSCB for testing. To do this, four feedthroughs were needed, two each in the left and right walls of the chamber. To handle the HC that would be used during the thermal testing, 1-in diameter copper rods were used as the conductors. Our cooperative research team at UConn machined the ends of the rods, as seen in Figure 7, to accept the required connectors. For the air-side end of the rods, two flat faces were milled and then two holes were drilled through to accommodate two two-hole power cable lugs per feedthrough, if needed, for a total of eight possible connections. On the vacuum-side end of the rods, only one flat face was milled. Two holes were then drilled and tapped, and stainless-steel threaded inserts were installed to accommodate a single two-hole connection from the copper rod to an emitter busbar. See Figure 8 for the machining details.



Figure 7. HV and HC 1-in Copper Feedthrough

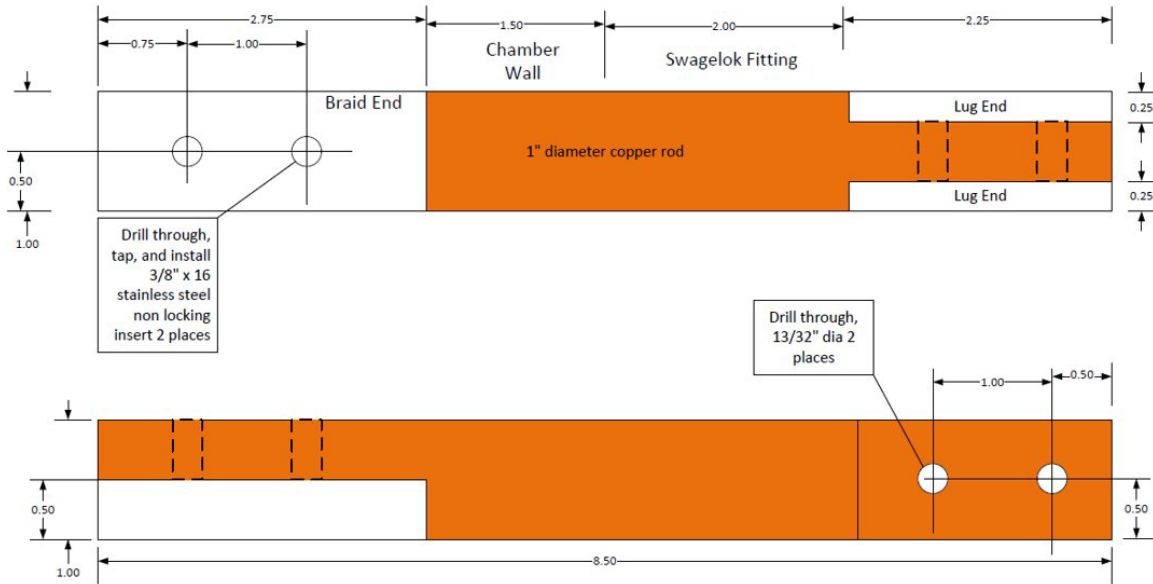


Figure 8. HV and HC 1-in Copper Feedthrough Milling Schematic

2. Flexible Braided Copper Connectors

Once the copper rods carried the power through the chamber walls, the power still had to go from the copper rod to the emitter busbars. For the HV switching test, 6 AWG Diesel Locomotive (DLO) cable was used for the connection. For the thermal testing though, a heavier conductor was needed to carry the continuous HC. One option that would have been capable of carrying the needed current was the same 313 kcmil DLO cable with two-hole lugs that was used to connect the HC power supply to the air side of the 1-in copper feedthroughs. However, due to the short bend radius that would have been needed to make the connection while keeping the chamber size to a minimum, 313 kcmil DLO cable would have placed too much pressure on the emitter busbars and

risked damaging the IGBTs. Instead, flexible braided copper connectors were chosen due to their flexibility. The selected 12-in copper braids from Storm Power Components (P/N: SC-B4F12), seen in Figure 9, are rated for 1000 A.



Figure 9. Storm Power Components SC-B4F12, 12 in, 1000 A Copper Braid

3. HV Feedthroughs for Voltage Measurements

Tektronix voltage probes (P/N: THDP0200) were used to measure the voltage across various components in the SSCB. To connect the probes through the chamber wall to the SSCB, two HV feedthroughs (SST P/N: FA11672-02), seen in Figure 10, were installed in the chamber wall. Each feedthrough has four molybdenum conductors and is rated for 5 kV and 28 A [36].

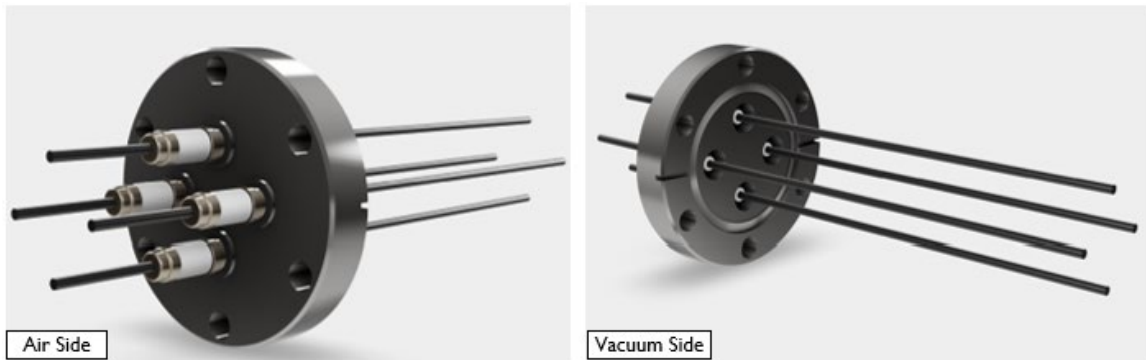


Figure 10. FA11672-02 – 5 kV, 28 A, Molybdenum Conductor HV Feedthrough. Adapted from [36].

The voltage probes would be connected to the air side of the conductors. For the vacuum side, HV plugs and cables (SST P/N: FP10883), seen in Figure 11 and rated at 20 kV and 30 A [37], were needed to connect from the HV feedthrough contacts to the various components of interest.

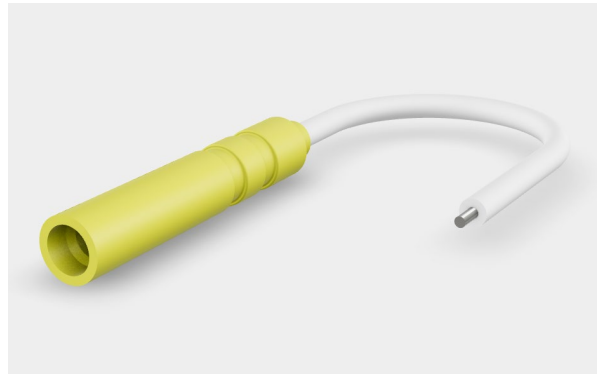


Figure 11. FP10883 – 20 kV, 30 A HV Plug and Cable. Source: [37].

4. BNC Feedthroughs for Current Measurements and Control Signaling

A Bayonet Neill–Concelman (BNC) connector feedthrough (SST P/N: KT13025), seen in Figure 12, was needed to carry the control signal from the function generator to the electrical-to-fiber conversion board and to carry the signal from the two Rogowski current probes (PEM P/N: CWT30). This feedthrough has a grounded shield with four double-ended BNC connectors and is rated for 500 V and 3.6 A [38].

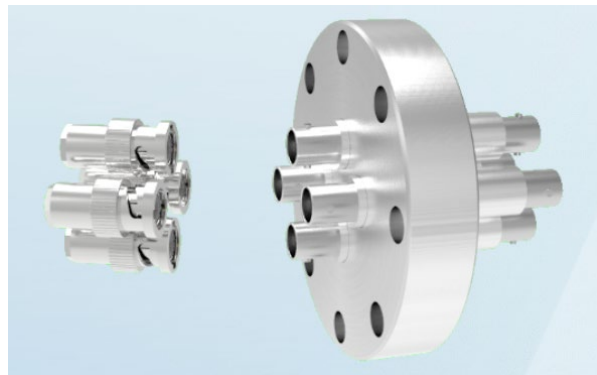


Figure 12. KT13025 – 500 V, 3.6 A, BNC Feedthrough. Source: [38].

5. D-Sub Feedthrough for Low-Voltage Power

One final feedthrough was needed to provide low-voltage power to the various PCBs. This was accomplished using a 9-pin D-Sub feedthrough (SST P/N: FA13288) with gold-plated stainless-steel conductors, as seen in Figure 13. It is rated for 500 V and 5 A [39].



Figure 13. FA13288 – 500 V, 5 A, 9-Pin D-Sub Feedthrough. Source: [39].

D. CHAMBER CUSTOMIZATION

The selected vacuum chamber from Terra Universal comes equipped with two metering valves and a vacuum gauge preinstalled on the chamber lid. Any customization for selected feedthroughs needs to be specially ordered or performed by the customer. After the specific feedthroughs were determined, the mechanical drawings were updated to reflect the feedthrough selections and their locations, as seen in Figure 14. The locations for the coolant-tube feedthroughs were the most critical. The coolant tubes were straight, stainless-steel tubes that fed through the chamber wall and connected into the tube fittings installed on the cold plate of the SSCB. The height from the floor of the chamber and the spacing between the inlet and outlet tubes had to be precise, as the tubing and tube fittings offer very little room for error when connecting. Once connected, the coolant tubes fix the location of the SSCB within the chamber and therefore form the basis for the location of all other feedthroughs. The feedthrough locations for the copper

power rods were determined based on the location of the emitter busbars and the bend dimensions of the copper braids. The chamber and all feedthroughs were then ordered by research partners at UConn. They drilled all the feedthrough holes, as seen in Figure 15, and fit tested all the feedthroughs before shipping everything to us here at NPS for final assembly and testing.

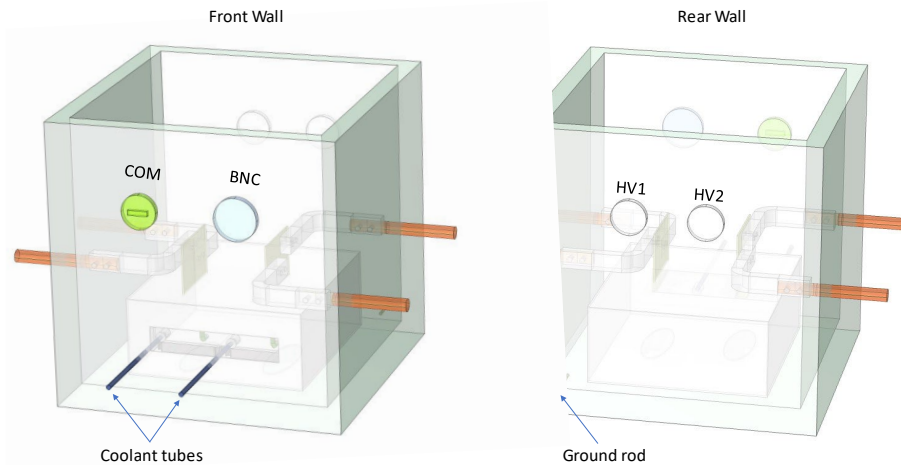


Figure 14. Mechanical Model of Chamber Feedthroughs

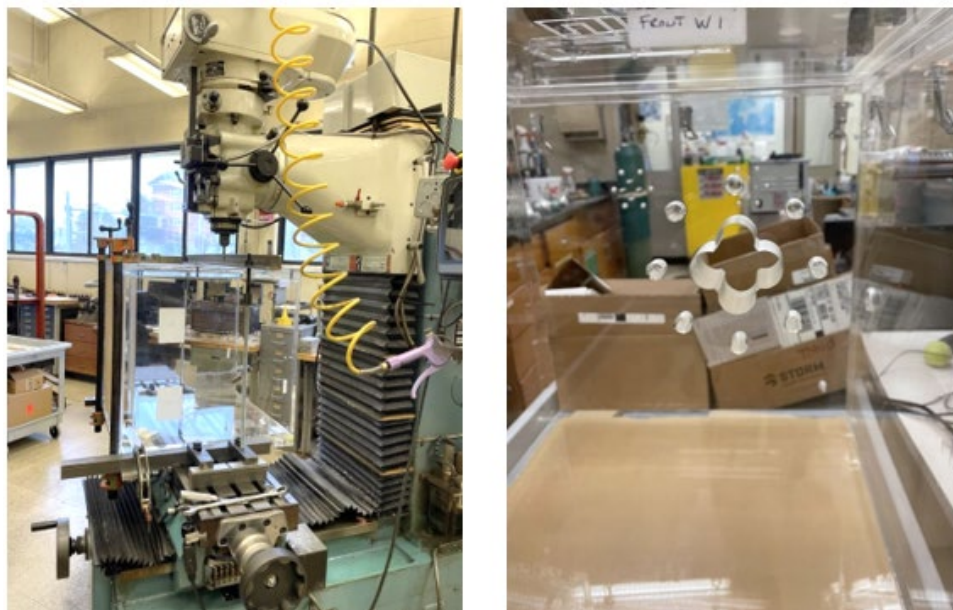


Figure 15. Drilling Feedthrough Holes in Vacuum Chamber Walls

E. VACUUM PUMP

In addition to the chamber itself, a vacuum pump was needed to create the vacuum in the chamber for the high-altitude testing. The pump needed to be able to achieve a vacuum equivalent to at least 51 000 ft, as seen in Table 2. Additionally, due to the large volume of the chamber, the pump needed to have a relatively high flow rate. The vacuum pump chosen for this chamber was a KNF Laboport diaphragm vacuum pump (P/N: UN820.3FTP), which is capable of pulling a 29.68 inHg vacuum [40], equivalent to approximately 135 000 ft. As shown in Figure 16, the pump has a peak flow capacity, which decreases with decreasing pressure, of 20 l/min at sea level.

Table 2. Pressure to Altitude Conversion Table. Adapted from [41].

Altitude (ft)	Vacuum (inHg)
Sea Level	0
10 000	9.34
35 000	22.86
51 000	26.64

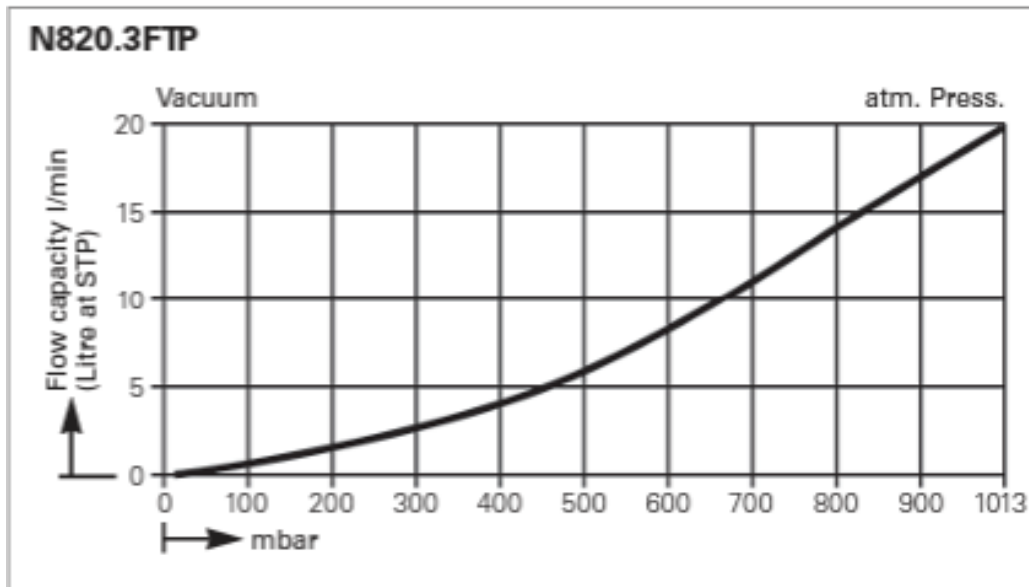


Figure 16. Flow Capacity of KNF Laboport N820.3FTP Vacuum Pump.

Source: [40].

F. CHAMBER PREPARATION

After the drilled vacuum chamber, the pump, and all the components were received, a custom cart was built to hold everything. The HV, BNC, and D-sub feedthroughs were installed into the pre-drilled holes using the supplied fasteners. These feedthroughs were equipped with either a rubber O-ring or a rubber gasket to create an airtight seal. Next, Swagelok bored-through tube fittings (P/N: SS-1610-1-16BT) were installed into the four power feedthrough locations. The threads of the tube fittings were wrapped in thread sealant tape prior to installation to ensure an airtight seal. The 1-in copper rods were then inserted through the tube fittings and tightened down. Figure 17 shows an example of an installed rod and tube-fitting assembly. To provide a ground for the SSCB and housing, a 1/4-in diameter copper rod and a tube fitting (Swagelok P/N: SS-400-1-4BT) were installed through the rear wall in the same manner as the 1-in rods. For the coolant feedthroughs, two 3/8-in diameter stainless steel rods and tube fittings (Swagelok P/N: SS-600-1-6BT) were installed through the front wall. Because one of the disadvantages for acrylic was its tendency to crack, special care was taken when installing the fasteners and tube fittings to tighten them just enough to create a seal. The vacuum pump was then connected to one of the chamber valves with a silicone hose and the chamber was pumped down to a 27 inHg vacuum and held overnight to check for any signs of leaking and to draw out any moisture that may have been trapped in the acrylic. Figure 18 shows the chamber as received from UConn, and then after all feedthroughs were installed and the chamber was ready to receive the SSCB for testing.



Figure 17. Air Side of Power Feedthrough Assembly Installed in Vacuum Chamber Wall

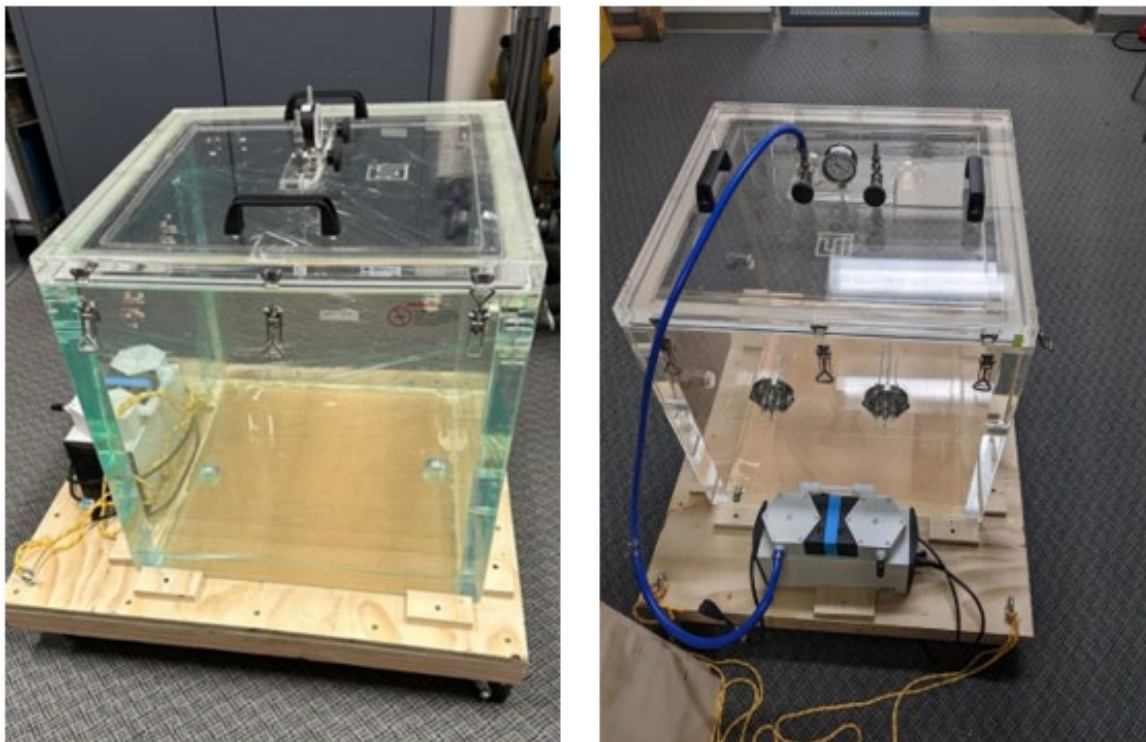


Figure 18. Vacuum Chamber Before (L) and After (R) Feedthrough Installation

G. SSCB ASSEMBLY

The cold plate provides the mechanical backbone for this SSCB. Designed and built by Advanced Thermal Solutions, Inc. (ATS), the custom cold plate consists of four off-the-shelf cold plates (P/N: ATS-CP-1001-DIY), which were used by [25] in the component testing phase of this project, mounted in a custom aluminum carrier. The cold plate is designed to carry both poles of the SSCB. The first step in assembling the SSCB was to install the IGBTs onto the cold plate. The two IGBTs were mounted in an ECCE configuration with their emitter power terminals toward the edges of the cold plate and their collector power terminals toward the center of the cold plate. Prior to mounting, thermal grease (T-Global Technology P/N: TG-N909) was applied to the baseplate of each IGBT, as seen in Figure 19, using a specialized stencil designed for that IGBT layout. After application of thermal grease, the IGBTs were fastened to the cold plate. The fasteners were tightened in the pattern specified by the IGBT manufacturer. They were also torqued in two stages according to the manufacturer specifications. The first stage consisted of a light torque followed by a period of rest to allow the thermal grease to flow evenly. The fasteners were then torqued to their final specification. Figure 20 shows a model of the cold plate with one IGBT installed.

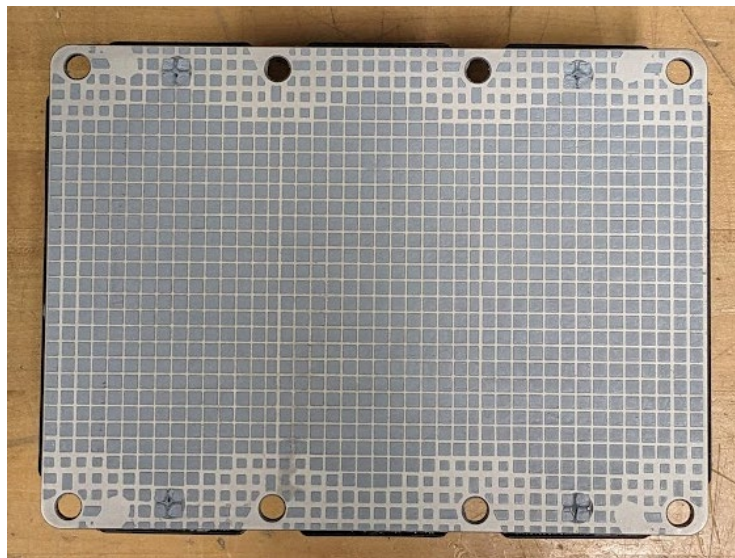


Figure 19. TG-N909 Non-Silicone Thermal Grease Applied to IGBT Baseplate Using Stencil

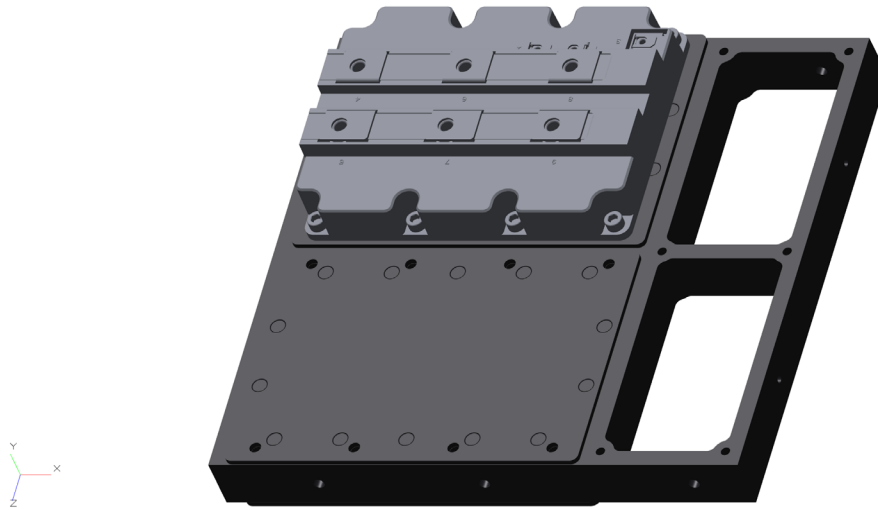


Figure 20. Model of Custom ATS Cold Plate with One IGBT Installed

After the IGBTs were installed, the next step was to mount the gate drive PCBs onto the IGBTs. Since the gate drive PCBs had some through-hole components, copper spacers were used to provide relief when attaching the board to the Kelvin terminals of the IGBTs. Nylon screws were used to support the opposite end of the board. Next, the MOV assembly, SCR, snubber capacitor, and the eMOV PCB were all mounted onto a G-10 plate, as seen in Figure 21, which was then attached to the frame of the cold plate. The control interface PCB was then mounted to the back edge of the cold plate, opposite the coolant ports, with nylon standoffs providing the necessary spacing and support for the board. Figure 22 shows the SSCB assembled to this point.

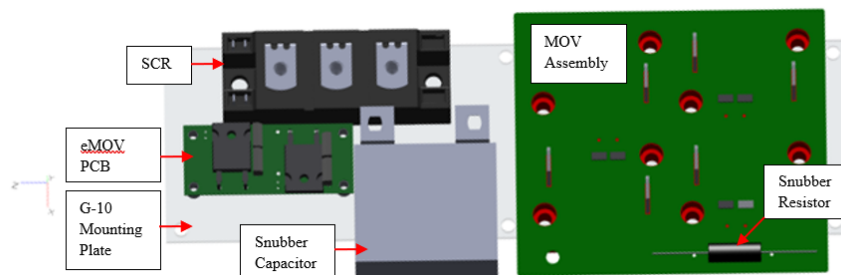


Figure 21. MOV Assembly, Snubber Capacitor, SCR, and eMOV PCB Mounted on G-10 Plate

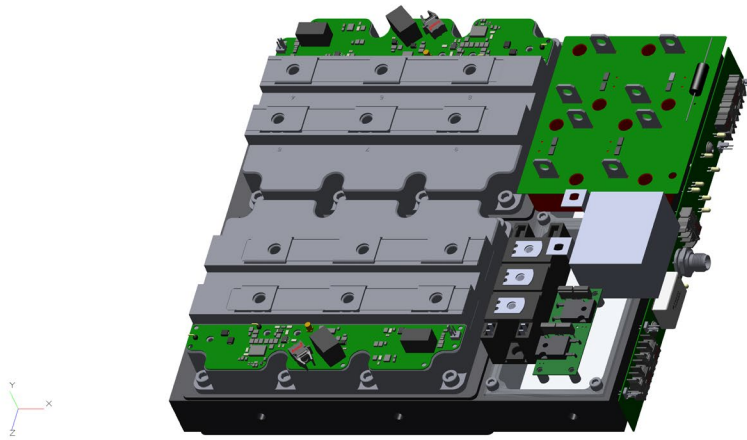


Figure 22. SSCB prior to Busbar Installation

The last components to install were the custom copper busbars. A flat busbar was used to connect the collector power terminals of both IGBTs. For the emitter power terminals, vertical busbars were needed to be able to connect the power cables. The fasteners for the busbars were torqued according to the IGBT manufacturer specifications. Custom thin copper bars were then made to connect the emitter to the SCR and to jump the common SCR terminals. Figure 23 shows the SSCB with the busbars installed. Next, the components were wired together, as seen in Figure 24. A switching test was then performed to ensure proper functionality.

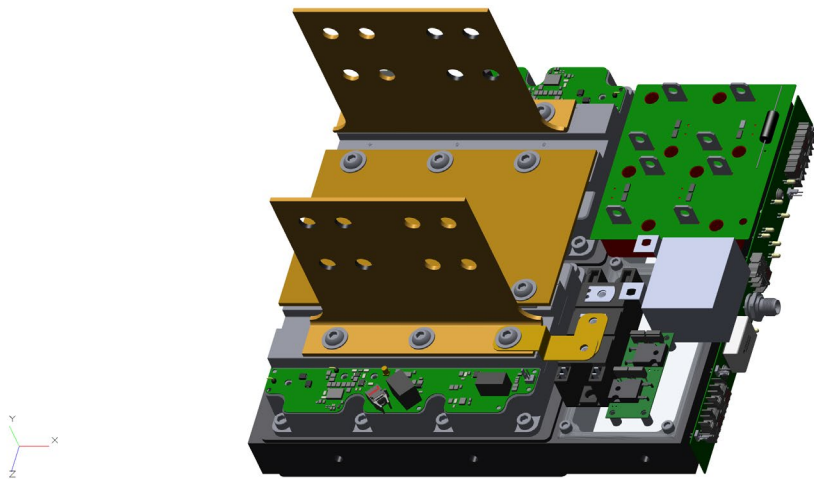


Figure 23. SSCB Installed on Cold Plate

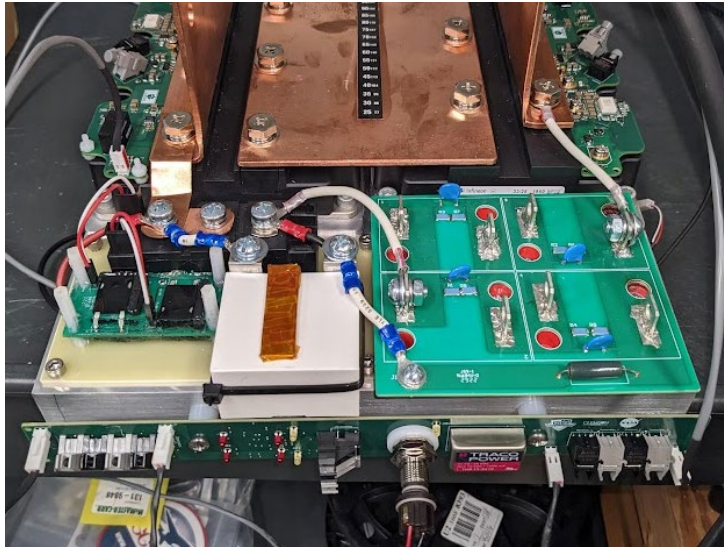


Figure 24. SSCB Electrical Connections

H. SSCB INSTALLATION AND INITIAL SETUP

A custom housing was designed to hold the SSCB. The housing consists of four walls constructed from lightweight aluminum honeycomb sheets with an aluminum frame, and then a top and bottom cover made of G-10. The walls were first assembled into a box and then the bottom cover was installed, as seen in Figure 25.

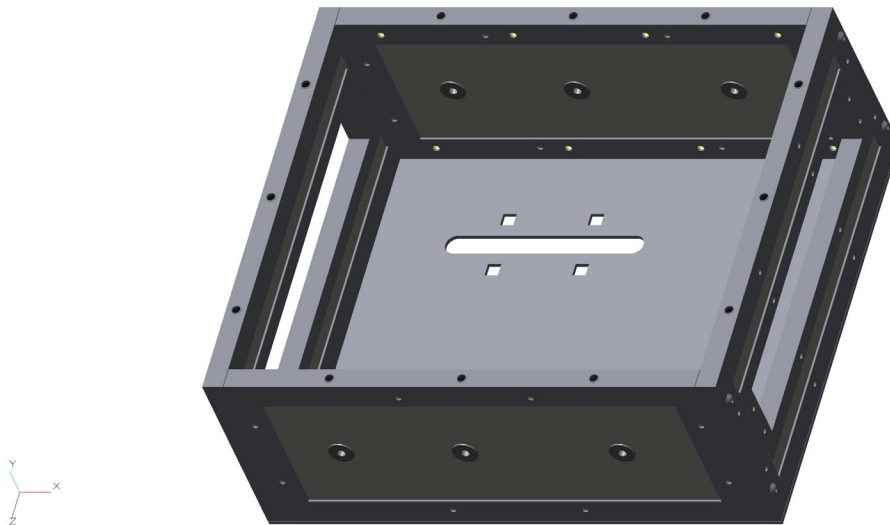


Figure 25. SSCB Housing; Top Cover Removed

The SSCB was then lowered into the housing and secured in place using six bolts, three on each long side. These bolts were passed through the honeycomb walls, through nylon spacers, and then screwed into the edges of the cold plate. This technique required two people and it was somewhat difficult to get everything properly aligned. In future iterations, a better sequence would be to install one of the sides to the cold plate, stand it up on that side and then install the other side, install the front and back sides, and finish with the covers. During the assembly process, the fasteners were not fully tightened until all of them were installed and everything was properly aligned. Figure 26 shows the SSCB installed in the housing. The top cover was left off during most of the testing to allow for visual monitoring for any flashover or tracking.

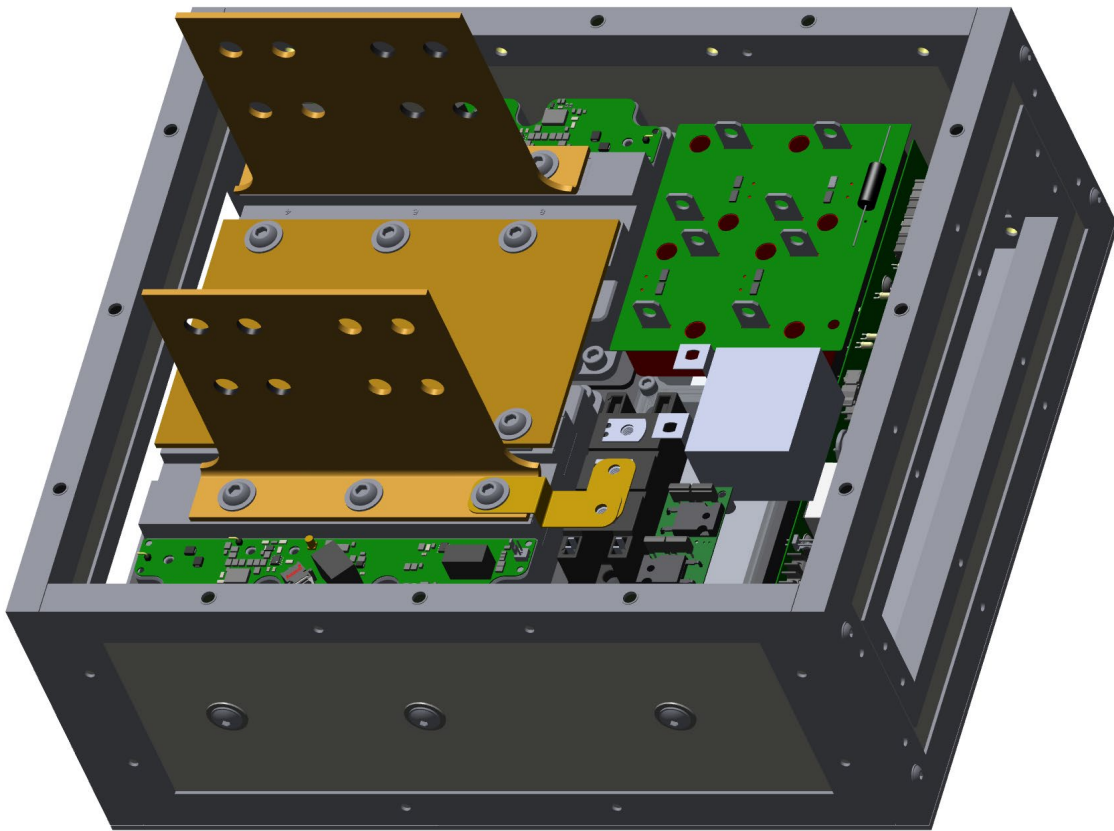


Figure 26. SSCB Installed in Housing

The last step was to install the voltage sensor wires that would later be connected to the HV feedthroughs once the SSCB was placed in the chamber. Four pairs of sensor wires were bolted in across the MOV, SCR, and each IGBT. After the SSCB was fully assembled in the housing, a switching test was performed to ensure proper functionality. The SSCB was then placed into the vacuum chamber.

Power cables were made from 6 AWG DLO cable and installed from the copper feedthroughs to the emitter busbars, and then the voltage sensor cables were attached to the HV feedthroughs. The electrical-to-fiber conversion board was secured to the chamber floor with double-sided tape. The coaxial cable carrying the gating signal was connected from the feedthrough to the conversion board, and then a fiber-optic cable was connected from the conversion board to the control interface board. The control board takes that input signal and distributes it via fiber-optic cable to each of the gate drive boards. The conversion board was connected to a 5 V power supply via the D-sub feedthrough and the control board was connected to a 28 V supply. The control board then provided 12 V power to each of the gate drive boards. The connector for the 28 V power to the control board had to be fed through the opening in the back panel of the housing and attached to the control board. This proved to be a very difficult connection to make with the given working room. When the SSCB needed to be removed from the chamber for later changes, this connection was removed last, after the housing was removed from the chamber. It was then reattached prior to placing the housing back into the chamber. Two other coaxial cables were connected from the feedthrough to current probes, which were using Rogowski coils to measure the current through the snubber and the MOV. The final connection was a ground clamp connected from the cold plate to the ground rod feedthrough. Since active cooling was not needed for the switching tests, the coolant tubes were not installed. The stainless-steel rods remained in their place to maintain the airtight seal. The air side of the ground rod was then connected to the grounded conduit in the lab to complete the setup. Table 3 summarizes the feedthrough connections.

Table 3. Feedthrough Connections for Switching Test

Feedthrough	Connected To	Purpose
High Voltage	IGBT 1	IGBT/Diode Voltage
High Voltage	IGBT 2	IGBT/Diode Voltage
High Voltage	SCR	SCR Voltage
High Voltage	MOV	MOV Voltage
BNC	Current Probe	MOV Current
BNC	Current Probe	Sum of Snubber and MOV Current
BNC	Signal Conversion Board	Gate Signal
BNC	Not Connected	Spare
9-pin D-Sub	Control Interface Board	28 V Power
9-pin D-Sub	Signal Conversion Board	5 V Power
9-pin D-Sub	Not Connected	Spare

THIS PAGE INTENTIONALLY LEFT BLANK

III. EVALUATION OF SSCB SWITCHING AND INSULATION PERFORMANCE AT HIGH ALTITUDE

A. SWITCHING TEST SETUP AND INSTRUMENTATION

The switching test aims to evaluate the SSCB transient behavior during current interruption in the whole range of operating altitudes up to 51 000 ft. The focus is on the insulation performance. Figure 27 depicts the switching test setup schematic, and Figure 28 presents a photograph showing the actual hardware, with annotations.

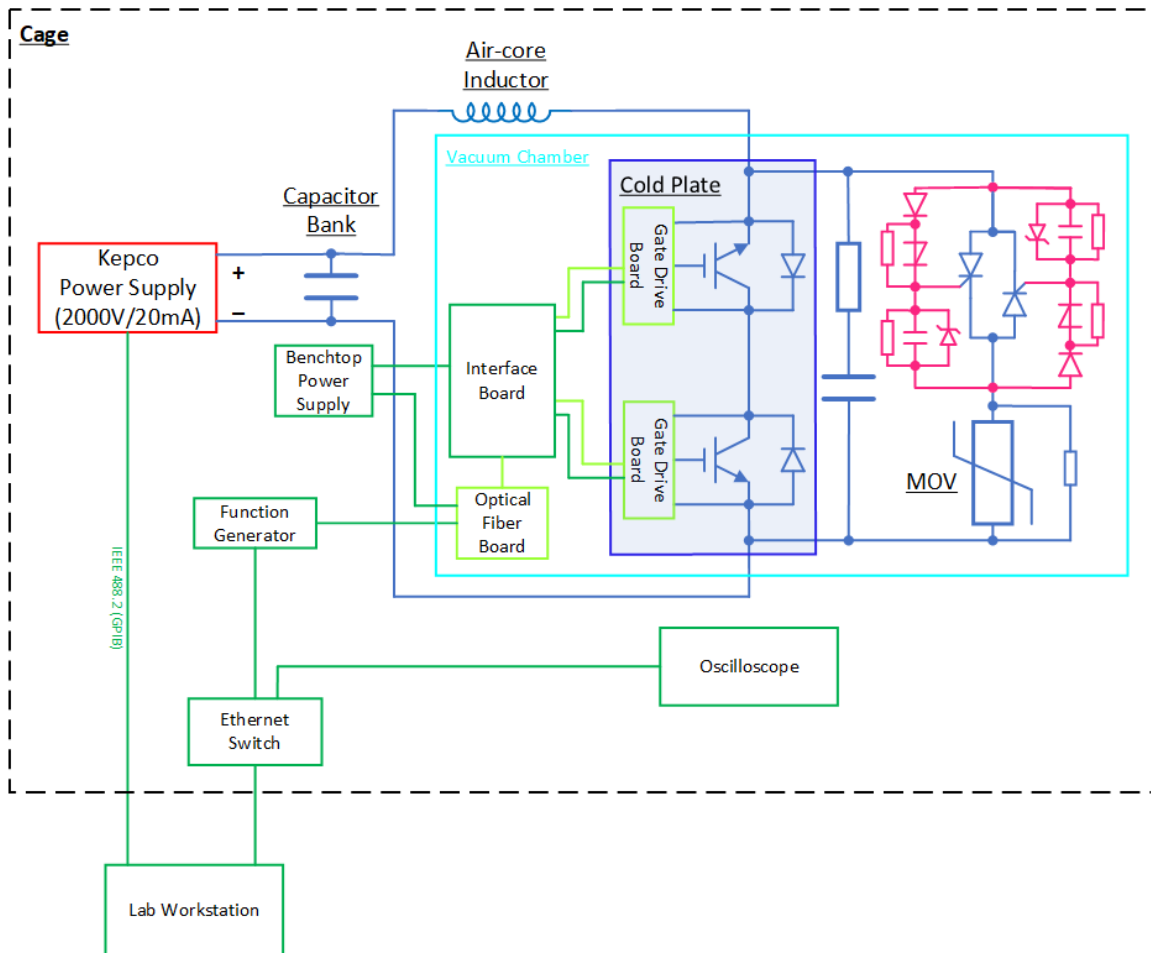


Figure 27. Test Setup for Switching Performance Evaluation of SSCB Prototype

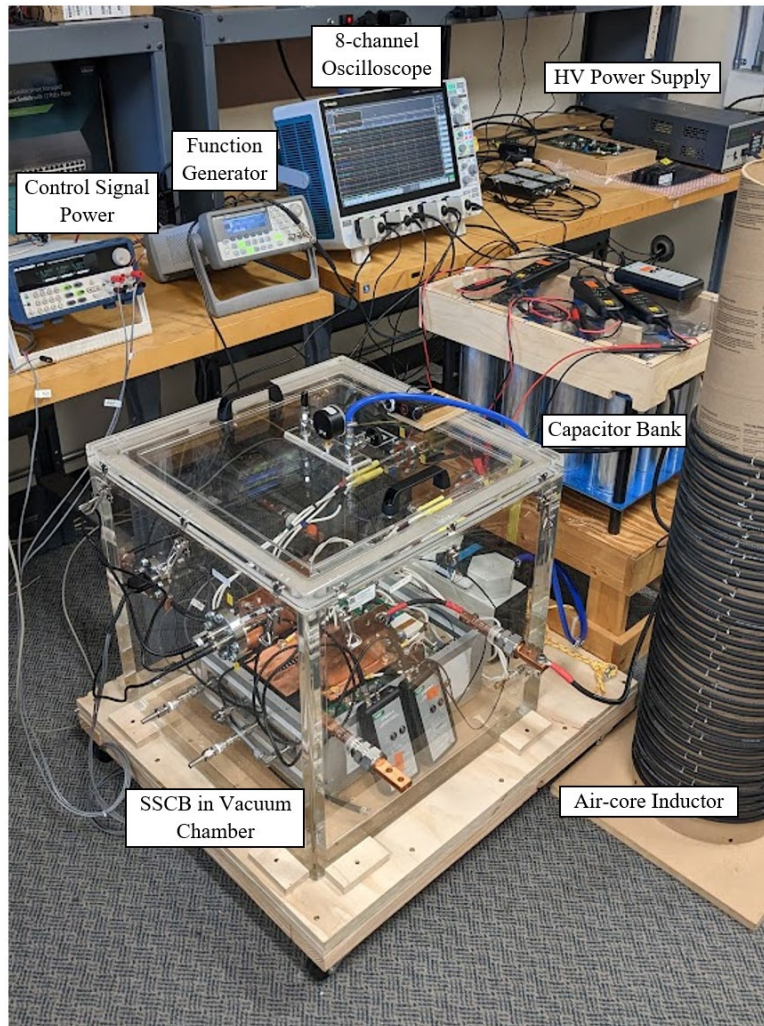


Figure 28. Switching Test Setup

The test setup consisted of the SSCB prototype installed in the vacuum chamber, a capacitor bank simulating a rigid dc bus in a dc system, and an air-core inductor with taps to simulate different system or load inductances. A low current (LC) (20 mA maximum) HV (2000 V maximum) dc power supply was selected to provide up to 2000 V charging to the capacitor bank. The capacitor bank would be charged to the desired voltage prior to the SSCB switching test, and any energy lost during the switching test would be replenished afterward. Connections between the capacitor bank, air-core inductor and SSCB prototype were made using 6 AWG DLO cable, which is rated at 2000 V. Figure 29 and Figure 30 provide details on the power cabling.



Figure 29. Positive Cable from Air-Core Inductor to Power Feedthrough for Switching Test

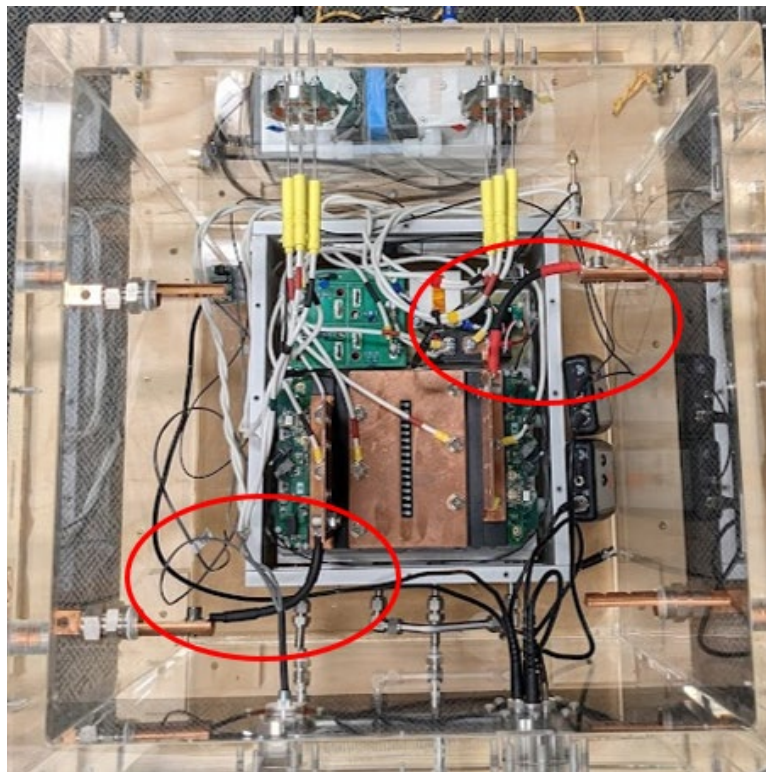


Figure 30. Vacuum-Side Power Connections for Switching Tests

The setup for the short-circuit test was similar, except the air-core inductor was removed and the positive and negative power cables on the air side were both connected directly to the capacitor bank, as seen in Figure 31. The cables were twisted together and connected to the feedthroughs on the same side of the chamber to minimize the loop inductance. The vacuum-side cables were also adjusted, as seen in Figure 32, to accommodate this. It is noted, however, that the loop could not be made as tight as when the SSCB was tested on the benchtop, due to the fact the chamber and feedthroughs were in the way.

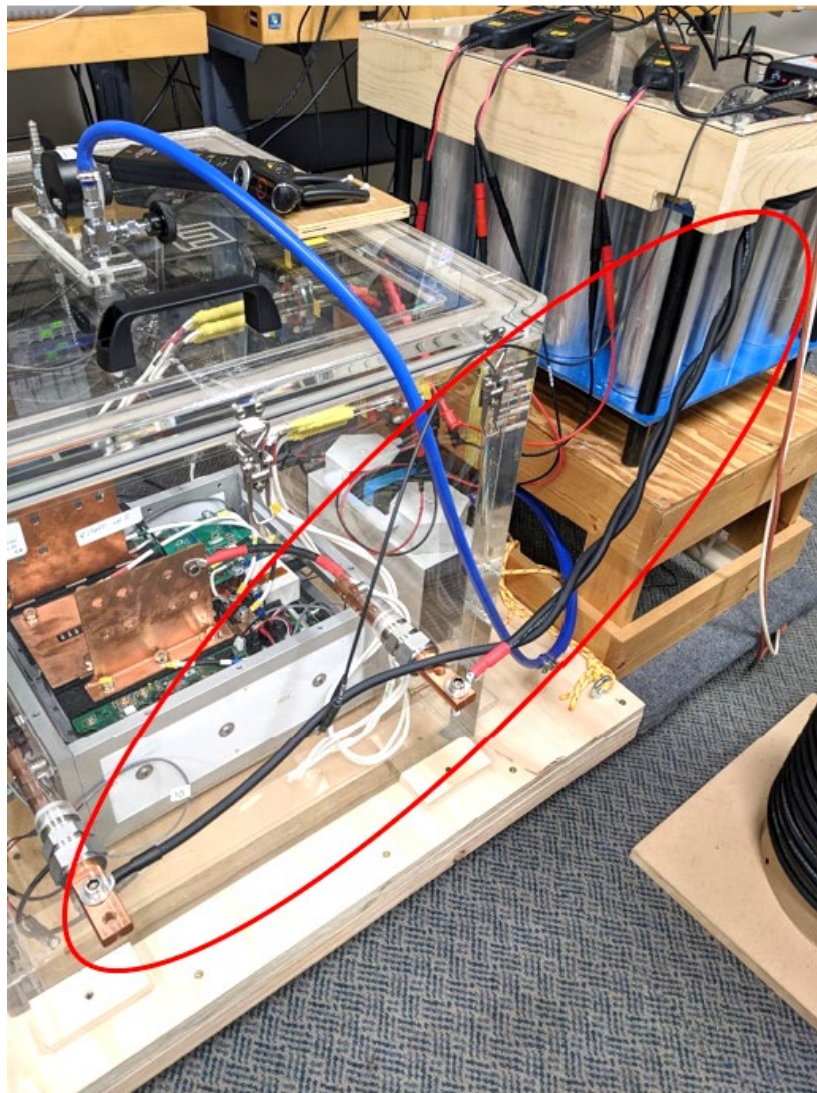


Figure 31. Air-Side Power Cable Setup for Short-Circuit Test

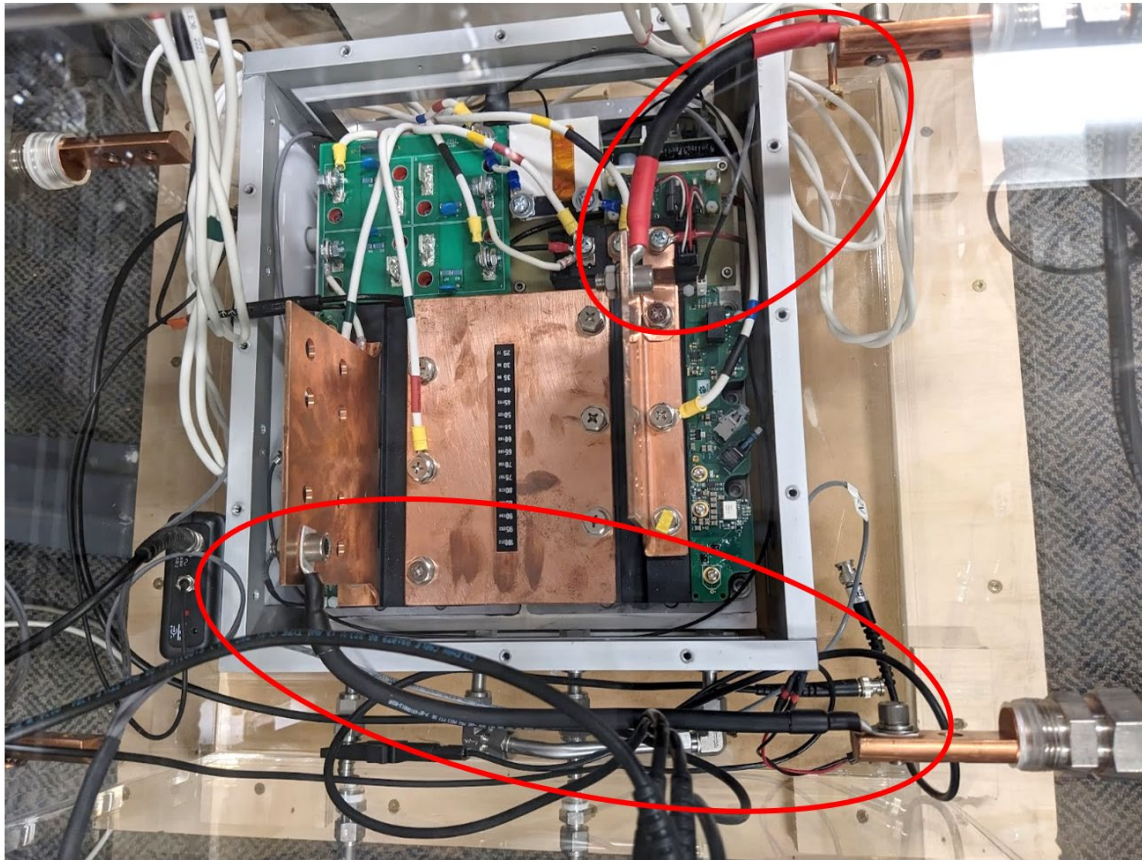


Figure 32. Vacuum-Side Power Cable Setup for Short-Circuit Test

A benchtop dc power supply (BK Precision P/N: 9130B) provided the control power. The 28 V control power was wired to an interface board inside the SSCB prototype via the 9-pin D-sub feedthrough installed in the vacuum chamber wall. The interface board accepted the 28 V input and generated all the other control voltages required for SSCB operation. A function generator (Agilent P/N: 33220A) was used to issue the gating command pulse. This electrical signal was sent via the coaxial feedthrough to the electrical-to-fiber conversion board, which converted it to a fiber-optic signal. It then sent the fiber-optic signal to the interface board, where it was further fanned out to the two gate drive boards.

A key aspect of the switching test is the measurement of transient voltage and current signals of interest. Figure 33 shows the SSCB test circuit schematic and the variables measured. Upon receiving the gating command pulse, the SSCB current starts

to ramp up, with the ramping rate determined by the system inductance. At the end of the gating pulse, upon the detection of overcurrent, the SSCB initiates current interruption. The voltage and current waveforms during this transient allow detailed evaluation of the SSCB switching performance and detection of any anomaly due to changes in the operating environment. A special note should be made here regarding the sensing of the snubber current, labeled as CT2 in Figure 33. When the SSCB was installed in the vacuum chamber, the current probes, CT2 and CT3, also had to be placed inside the chamber. The BNC feedthrough installed in the vacuum chamber wall can accommodate up to four channels. However, these BNC channels share a common ground and are not floating from each other. This turned out to cause signal distortion, as detailed in III.C.2. To resolve this problem, the snubber resistor was used as an unintended shunt, and the voltage across it was measured and then used to derive the snubber current.

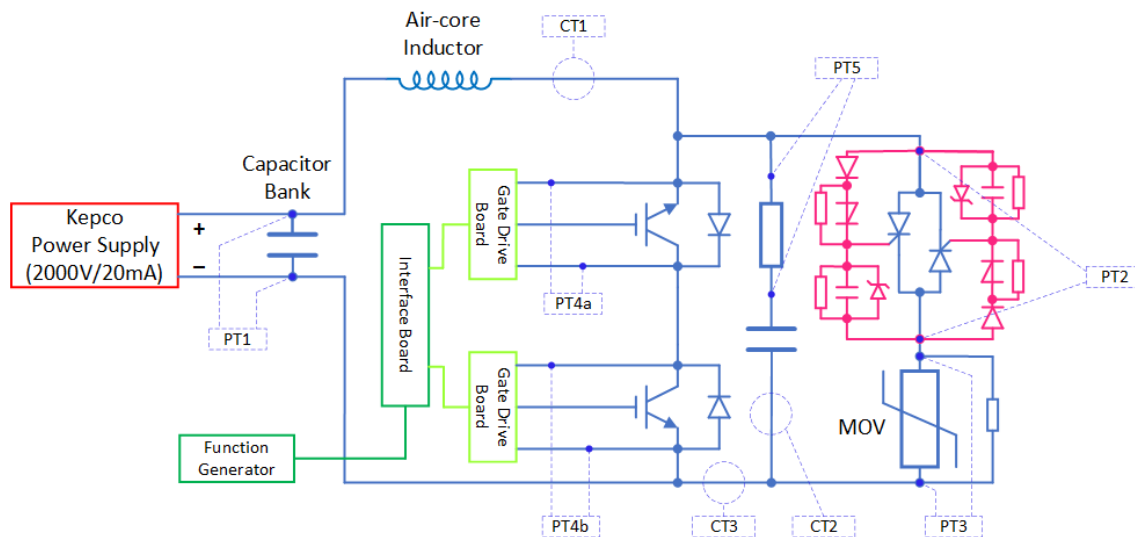


Figure 33. Measurement of Power Circuit Signals

The actual measurement arrangements are shown in Figure 34 and Figure 35. The HV test leads were bolted to points of interest in the SSCB power circuit and plugged on the other end to the vacuum side pins of the HV feedthrough. Differential voltage probes were used to measure these voltages at the air side of the HV feedthrough. An 8-channel

oscilloscope (Tektronix P/N: MSO58), the voltage probes, and the current probes constituted the required instrumentation for SSCB switching performance evaluation.

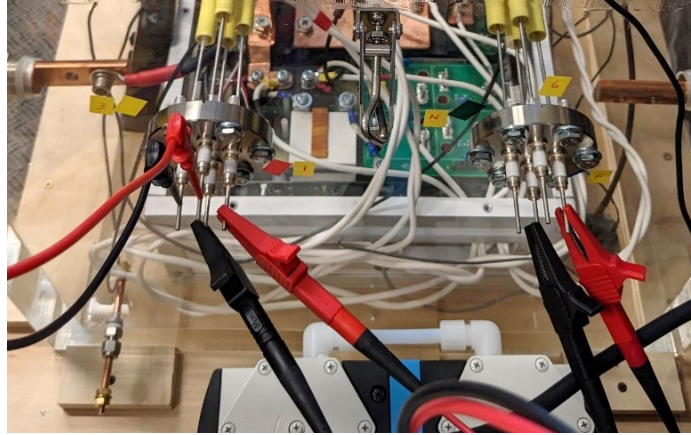


Figure 34. Voltage Probe Connections for Switching Test

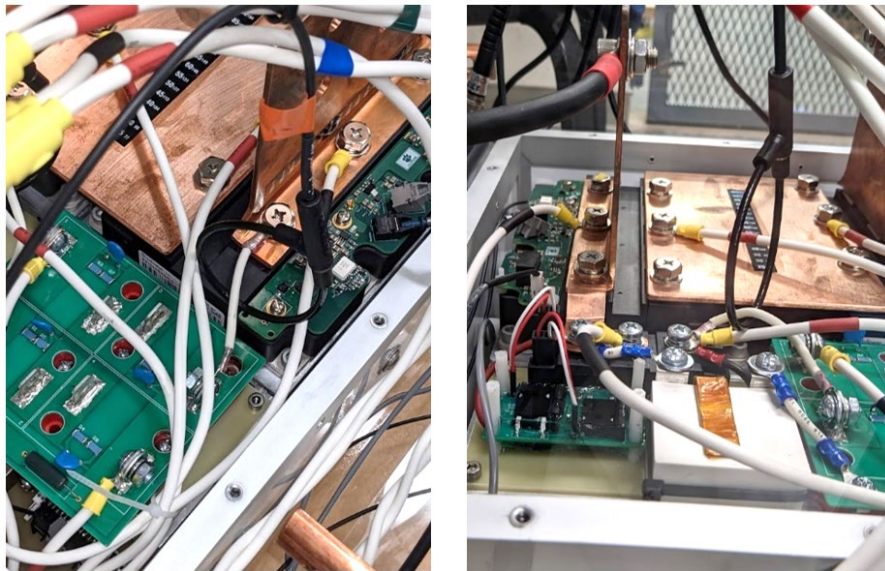


Figure 35. Current Measurement of Snubber and MOV (L); MOV Only (R)

Figure 36 shows an example screenshot of the SSCB prototype switching transient waveforms with the instrumentation detailed above. Figure 37 presents the corresponding plots generated using Matlab with the data record.

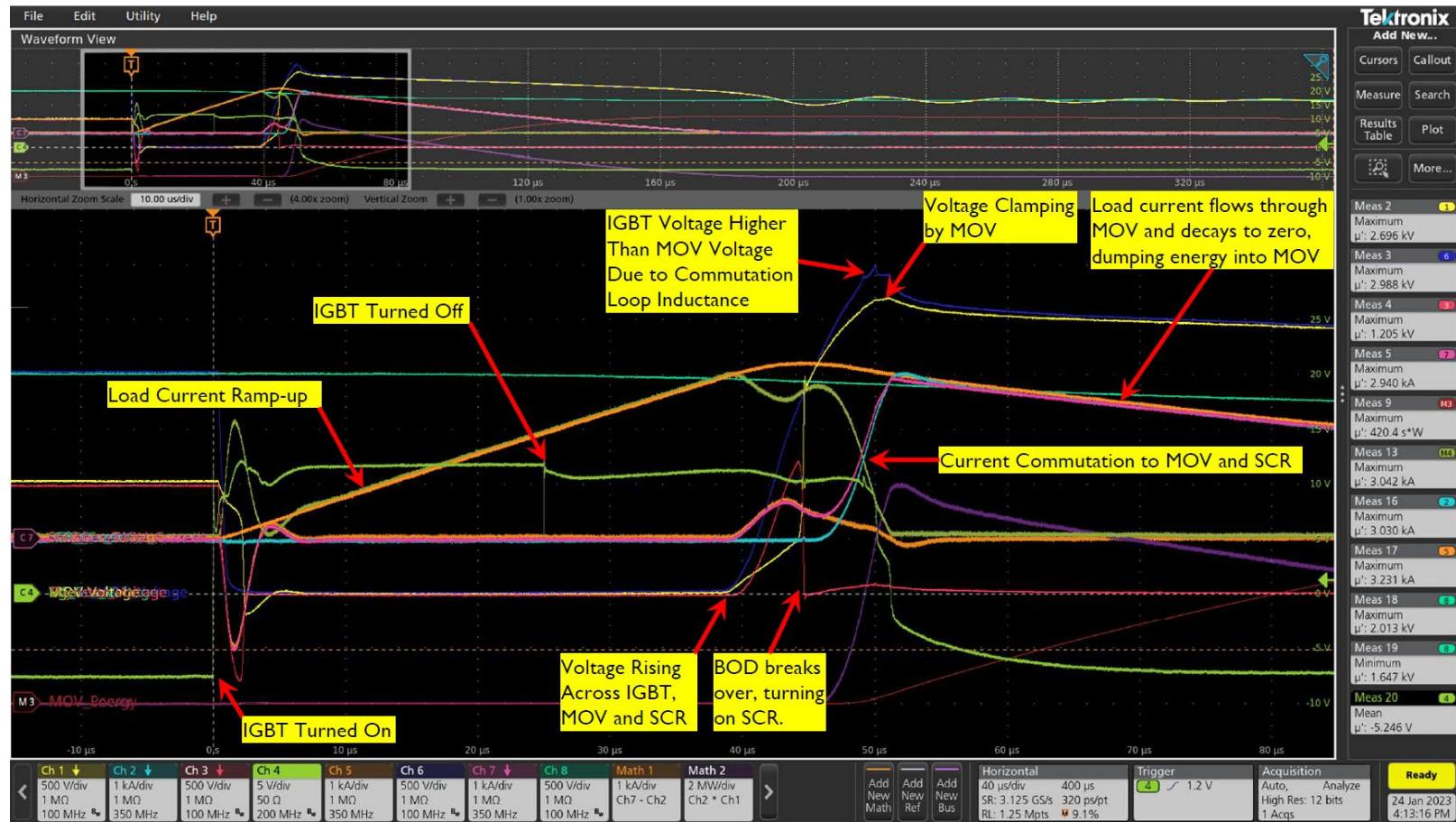


Figure 36. Screenshot of SSCB Prototype Switching Transient with $V_{dc} = 2000 \text{ V}$, $T_{ON} = 25 \mu\text{s}$ and $L_{SYS} = 25 \mu\text{H}$

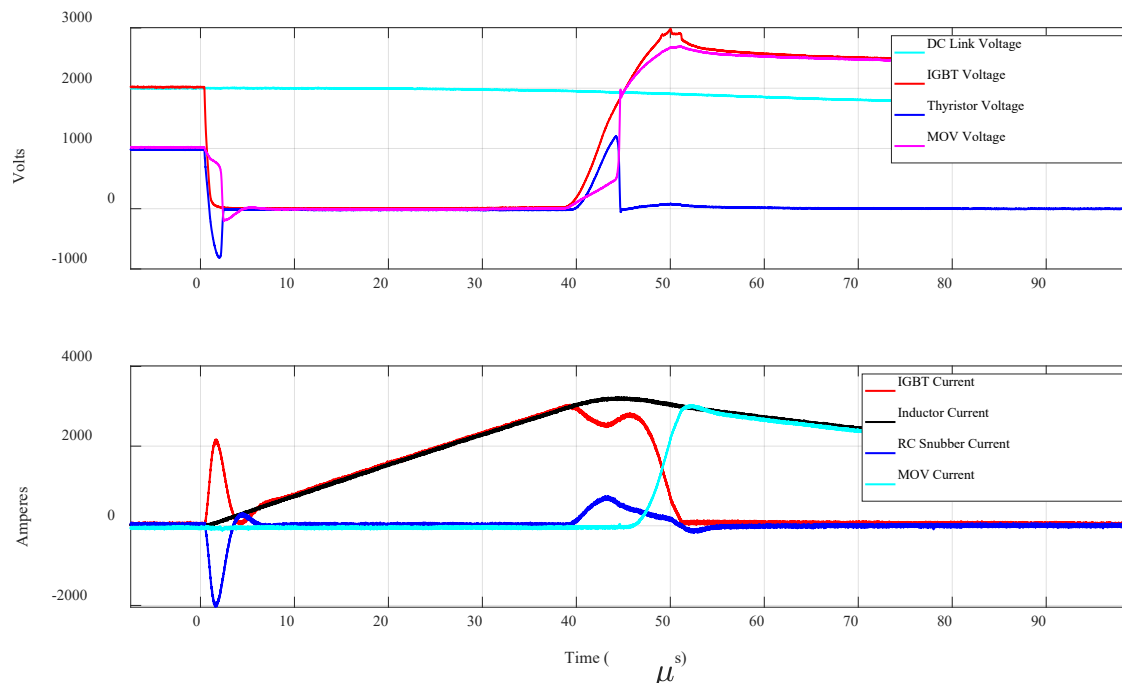


Figure 37. SSCB Prototype Switching Transient Waveforms with $V_{dc} = 2000$ V, $T_{ON} = 25$ μ S and $L_{SYS} = 25$ μ H

B. PCB POTTING

One of the primary concerns when testing at high altitude (low pressure) compared to sea level is the increased risk of flashover and tracking. To prevent these at high altitude without increasing the physical size of a PCB or the spacing between components, a potting material must be applied to areas that experience HV across conductive pads or pins with small separation distance. Silicone gel and epoxy resin potting compounds were used for this project.

The PCBs of concern for this SSCB were the gate drive boards and the eMOV triggering board. The components of concern on the gate drive boards were the silicon-carbide (SiC) diodes and the isolated power supply, as seen in Figure 38. Therefore, these components were encapsulated rather than potting the entire board. The components of concern on the eMOV triggering board were the BODs, the reverse blocking diodes, and the 6 M Ω resistors. These components take up a significant portion of the PCB, as seen in

Figure 39, and therefore the entire board was potted instead of trying to encapsulate the individual components.

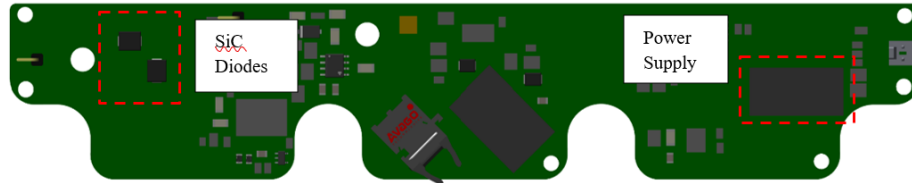


Figure 38. Gate Drive PCB Encapsulation Areas

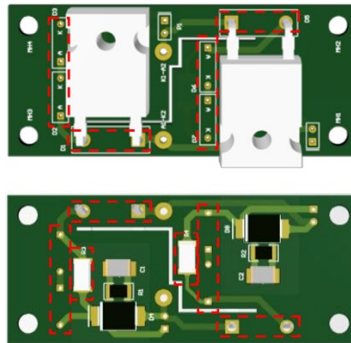


Figure 39. Potting Areas on Top and Bottom of eMOV PCB

1. Gate Drive PCB and eMOV PCB Potting at NPS Using Silicone Gel

Dow Dowsil 3-4155 high-voltage dielectric gel was used for the encapsulation of the gate drive board components. This transparent green gel is a two-part, high-viscosity silicone gel with a 1:1 mix ratio [42]. A static mixing nozzle was attached to the two-part gel cartridge, which was then loaded into a dual component caulk gun for dispensing. Prior to application, the boards were scrubbed with 99% isopropyl alcohol to remove any residues and allowed to dry. The holes for the IGBT drain connections were covered with electrical tape. A few milliliters of the gel were dispensed through the mixing tube and discarded. This was to ensure the gel coming out was fully mixed. The gel was then applied to the SiC diodes and the base of the isolated power supply on the gate drive boards. The diodes are surface-mounted devices and only required encapsulation on the

top side of the boards. The power supply is a through-hole component and required encapsulation on both sides of the boards.

Two potting methods were tested for the eMOV PCB. The first method involved using the same Dowsil 3-4155 gel that was used for the gate drive board encapsulation. The same board cleaning and gel preparation steps were taken. Nylon standoffs were installed to facilitate mounting the PCB to the G-10 mounting plate. A small enclosure was built around the board and the slit in the middle of the board was covered with electrical tape to contain the gel. A blank female 2-pin connector was placed on each male 2-pin connection to protect the pins from being covered by the gel. The bottom side of the board was potted first and allowed to cure. Once the gel was cured, the tape covering the slit was removed and the top side of the board was potted. The enclosure was removed after the gel had fully cured. Figure 40 shows the top side of the finished product. This method of potting did produce some visible air bubbles, particularly along the slit in the board and under the terminals of the diodes, which were difficult to remove without a small vacuum chamber. A toothpick was used to move the bubbles away from any area of concern, but due to the viscosity of the gel and the quick cure time, they were not able to be completely removed. These bubbles would become very apparent during testing at high altitude, but they did not affect the insulation performance.

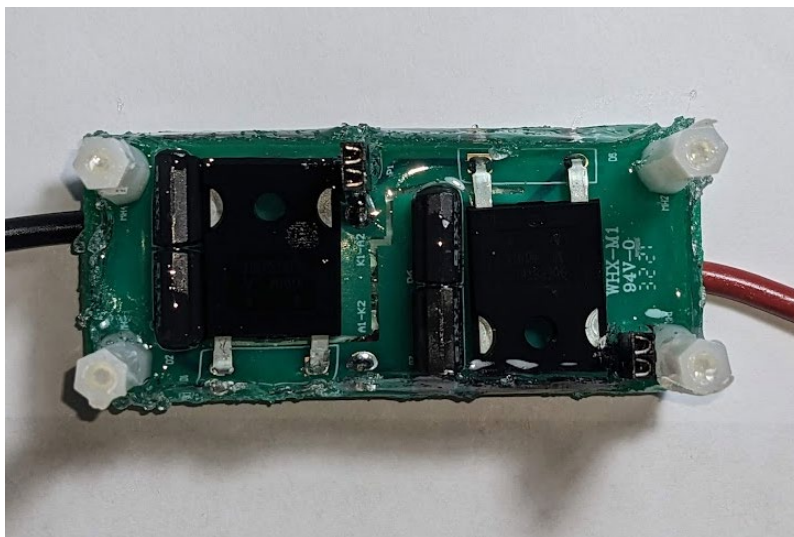


Figure 40. eMOV PCB Potted with Dowsil 3-4155 Silicone Gel

2. Potting of Original eMOV PCB at UConn Using Epoxy Resin

The second potting method for the eMOV PCB was performed by UConn using Buehler EpoxiCure 2 two-part epoxy resin. EpoxiCure 2 is a low viscosity, clear, general-purpose epoxy mixed at a 4:1 volumetric ratio of resin to hardener [43]. It cures in 6 h at room temperature with a peak exotherm of 104 °F. Again, nylon standoffs were installed prior to potting. In this case, the 2-pin connectors were removed, and the wires were soldered on instead. The board was placed into a tin mold that had been sprayed with Sprayon MR311 dry film release agent. The power wires on the bottom of the board were passed through a hole in the bottom of the tin, which was then sealed to prevent the epoxy from leaking out. The resin and hardener were measured by volume and then mixed in a cup. The cup was then placed in a Thermo Scientific Vacutherm, a vacuum heating and drying oven, under vacuum for five minutes to remove air bubbles. The epoxy was then poured into the mold and placed under vacuum for an additional five minutes to remove any air bubbles that formed during the pouring. The epoxy was left to cure under a vent hood overnight. After the epoxy was cured, it was removed from the mold and the excess material was removed using a band saw. Figure 41 shows the eMOV board in the mold and then after the excess had been removed. This method of potting was able to remove any air bubbles that would have been visible from the top and bottom, but the rough edges prevented visual inspection from all angles. The epoxy also cracked at one of the standoffs. This crack did not affect the insulation performance and the board was still able to be used.

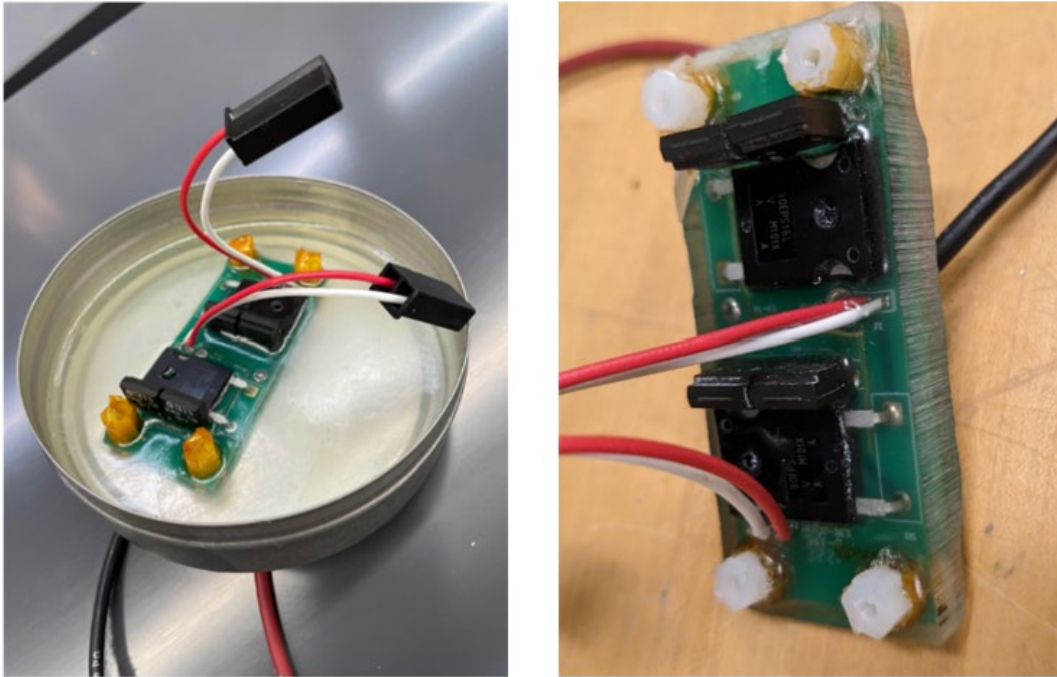


Figure 41. Potting of Original eMOV Triggering Board Using EpoxiCure 2

3. Potting of Updated eMOV PCB at UConn Using Epoxy Resin

Over the course of this research, some minor updates were made to the eMOV PCB. This updated PCB was not used for testing during this thesis, however, lessons learned from the potting process are worth discussing. Changes that would affect potting were the removal of the slit and moving all wires to a centralized location on the bottom of the board. Once the new board was assembled, it was sent to UConn for potting. The same epoxy and procedure from III.B.2 were used, with the following exception. Since all the wires were on the bottom of this board, it was placed into the tin with the top facing down, and therefore the hole in the bottom of the tin was not needed. In the previous iteration, the epoxy was poured to a depth of approximately 1/2 in, just enough to cover the terminals of the reverse blocking diodes on the top of the board. In this iteration however, the depth of the pour was approximately 3/4 in, just enough to cover the surface-mounted components. This depth differential was due to the height of the vertical breakover diodes, which were now on the bottom of the pour and had to be completely covered.

The results of this potting iteration can be seen in Figure 42. Multiple large cracks can be seen across both the bottom and top sides of the board. In contrast to the previous iteration where the crack occurred at an edge during the removal of excess potting, the cracks in this iteration were observed forming during the curing process. It is suspected that this was due to the thickness of the pour. Epoxy cures exothermically. Higher volumes and greater thicknesses create more heat, and if poured too thick can overheat and cause the epoxy to cure too quickly. The faster curing may cause fast or uneven shrinkage which causes the cracking. Other possible reasons include an improper mix ratio or incomplete mixing. Both situations could cause the same result. Further research was conducted to resolve the cracking issue and improve the visibility of the components to monitor for air bubbles prior to testing and flashover during testing.

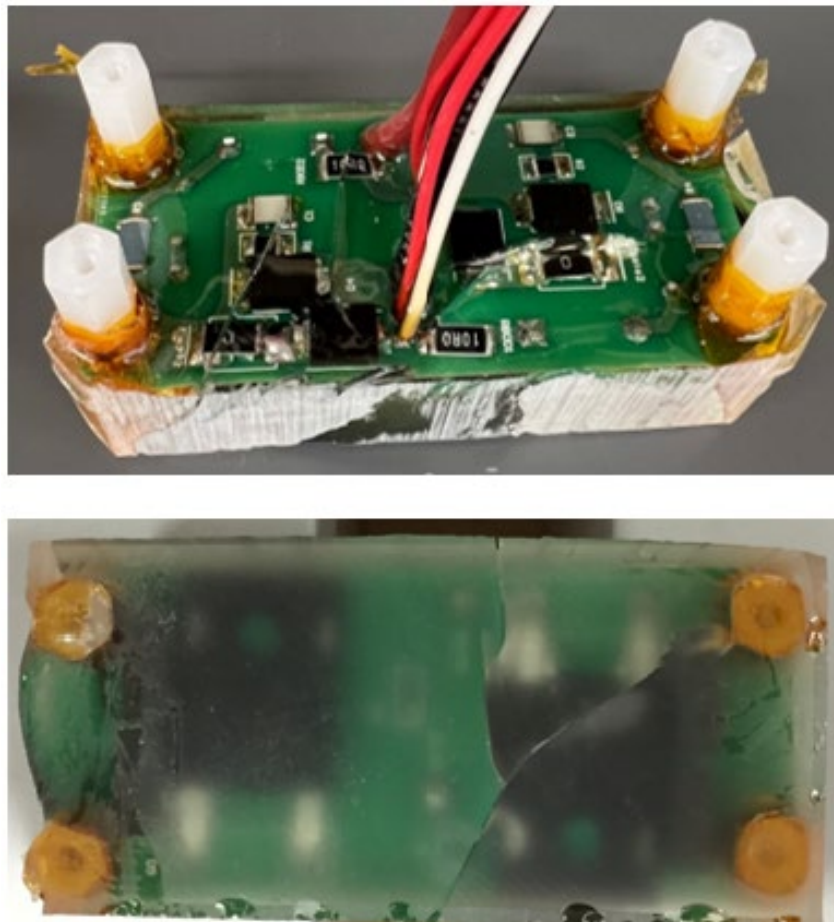


Figure 42. Potting of Updated eMOV PCB Using EpoxiCure 2

4. Potting Procedure Optimization Testing at NPS

The first step in improving the potting outcome was to select an epoxy that is specifically designed to handle thicker pours. Most epoxies can only be poured in thin layers, typically 1/8-in to 1/4-in thick, to prevent overheating. If a thicker pour is needed with these epoxies, it must be done in layers, with each subsequent layer being poured after the previous layer has become tacky, but not fully cured. This process can be time consuming and introduces more opportunities for error. Instead, MAS Deep Pour epoxy was selected for testing to see if it could achieve better results. Deep Pour is a two-part epoxy resin with a 3:1 volumetric mixing ratio, but it is specifically designed for pours from 1/2-in to 1-in thick. It has a low exotherm allowing it to cure slowly and avoid the cracking seen in the EpoxiCure 2 casting. The cure time for Deep Pour is approximately 36 h, compared to 6 h for EpoxiCure 2. To further minimize the exotherm, a rectangular mold approximately the size of the board was chosen, which serves to minimize the volume of epoxy being mixed. The mold was made of flexible silicone to minimize, compared to a rigid mold, any potential bending stress that may cause cracking when removing the cast from the mold. Once the materials were chosen, the procedure was refined.

All previous potting iterations had involved installing nylon standoffs on the board and potting them in the board. The standoffs were needed to provide a way to attach the potted board to the G-10 mounting plate. While this method was sufficient, it was not ideal. The sharp corners on the standoffs create stress points that could potentially cause the epoxy to crack over many thermal cycles. The first alternative method tested was to insert the threads of fasteners into the mold in the locations of the mounting holes. A jig was made to hold the fasteners in place during the pouring and curing process. The threads were coated with a silicone spray to aid release after the epoxy had cured. The PCB was placed into the mold and then the fastener jig was secured in place, as seen in Figure 43. The next step was to prepare the epoxy.

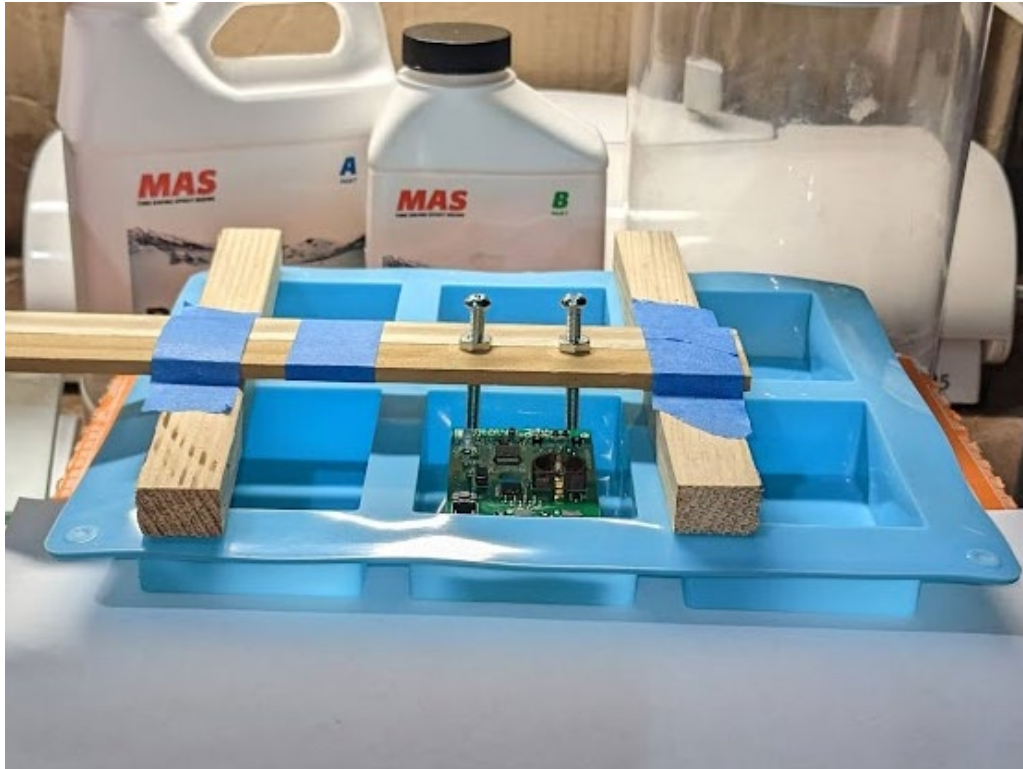


Figure 43. Test PCB in Silicone Mold with Fastener Jig

One important factor when pouring epoxy is the ambient temperature. An 18 °F increase in epoxy temperature cuts its curing time approximately in half. This is why controlling the exotherm is critical, and it starts with the room temperature. A work location was chosen where the temperature would always remain between 68–70 °F. Next, to eliminate the inaccuracies involved with volumetric measurements, the epoxy was mixed by weight. In the case of Deep Pour, that ratio is 100 parts resin to 28 parts hardener by weight. Again, to minimize the exotherm, only the amount needed to fill the mold was mixed. In this case, it was 80 g of resin and 22.4 g of hardener. To minimize the possibility of incomplete mixing, a specific mixing procedure was followed. The hardener was poured into the resin and mixed for two minutes, being sure to scrape the sides and bottom of the mixing cup, using a gentle stirring action to minimize the introduction of air bubbles. The epoxy was then transferred to another clean cup and mixed for an additional two minutes before being placed under vacuum, as seen in Figure 44, for 10 minutes to remove any air bubbles.



Figure 44. Epoxy in Vacuum Chamber to Remove Air Bubbles

The epoxy was poured slowly into the mold from approximately 12 in above the mold, which creates a very thin stream of epoxy that helps minimize the introduction of air bubbles. After the epoxy was poured into the mold, quick passes with a propane torch were made over the epoxy to help release any remaining air bubbles. While not available for this test, placing the mold back into a vacuum chamber or pressure chamber after pouring the epoxy would be ideal to remove any remaining bubbles. The epoxy was left to cure for 48 h before removing the fasteners, which came out without causing any damage. The mold was then removed, again without causing damage. Figure 45 shows the potted PCB before and after removal from the mold.



Figure 45. Epoxy-Potted Test PCB Before (L) and After (R) Mold Removal

The next step was to remove the excess material. Per the manufacturer recommendations, the epoxy was allowed to cure for five days prior to any machining work. A table saw fitted with a fine-toothed blade was used to remove the excess material, instead of a bandsaw like the previous procedure. To ensure a straight and precise cut, a crosscut sled was used on the saw. The potted board was wrapped in masking tape and the sled was fitted with a zero-clearance plate to eliminate any tear out that the saw might normally cause. Using the table saw created a cleaner, straighter, and more accurate cut compared to the cuts made on the bandsaw. Since the space tolerances around the triggering board when mounted on the SSCB are small, the table saw should be the preferred cutting method if available. Figure 46 shows the setup prior to cutting.



Figure 46. Removing Excess Potting Material with Table Saw

After all excess material was removed, a second method for providing a mounting location was tested. In this case, a drill press was used to drill holes through the board in the locations of the mounting holes. The holes were then tapped to provide threads that can be used for mounting. This method created the cleanest and most accurate mounting holes, all without having extra pieces in the potting that could potentially cause cracking. It was also the easiest to perform. For these reasons, drilling and tapping the mounting holes should strongly be considered for future iterations.

The last issue to overcome was the visibility issue. To remedy this, the edges of the cast were sanded. Being sure to use proper personal protective equipment and working in a properly ventilated area, the edges were sanded with progressively finer-grit sandpaper, starting with 120-grit and finishing with 400-grit. This removed the surface

scratches left by the saw blade, but the edges were still cloudy and difficult to see through. The edges were then buffed with automotive cutting compound, followed by automotive polish, to restore the smooth, glass-like finish. Figure 47 shows the finished product.

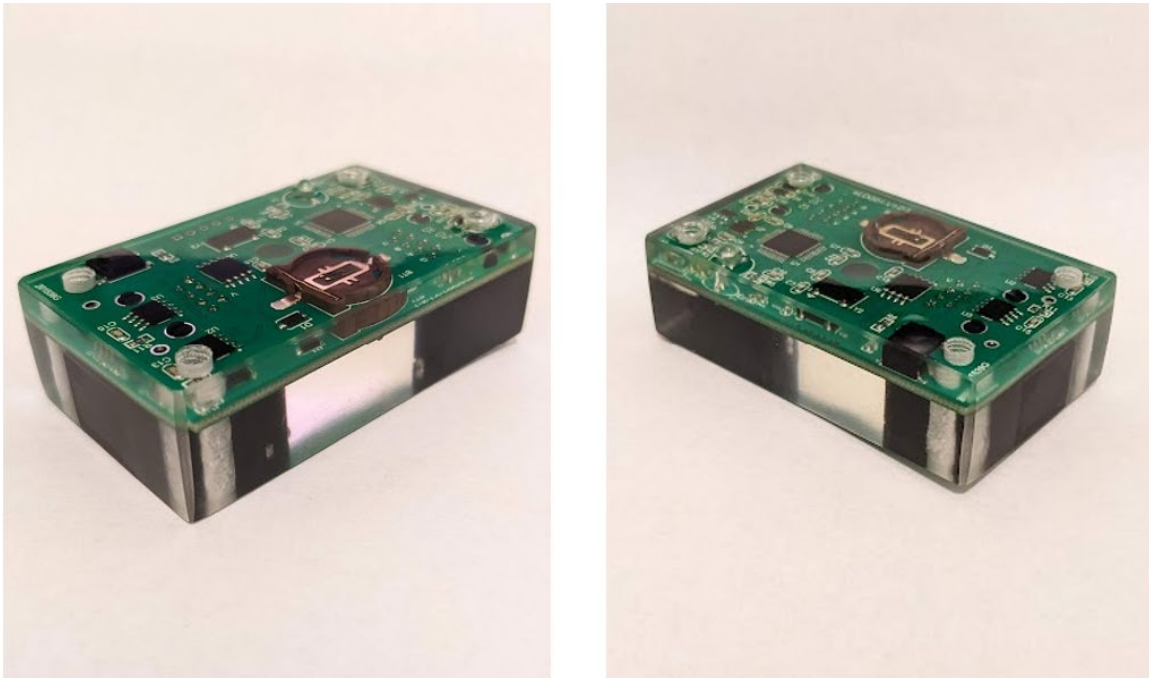


Figure 47. Finished Test PCB Potted with MAS Deep Pour Epoxy

C. TEST EXECUTION, DATA ACQUISITION, AND PROCESSING

The switching test was conducted with the SSCB prototype installed in the vacuum chamber and the instrumentation set up as detailed in III.A. It began with testing at the sea level condition, followed by testing at incrementally decreasing pressures corresponding to altitudes of interest. The top cover of the SSCB housing was left off allowing the SSCB circuit components to remain visible. One webcam was focused on the vacuum gauge to monitor the pressure, and another webcam was focused on the SSCB circuit allowing real time condition monitoring and recording. Any flashover would be noticed and recorded. The feed from the webcams was also saved for post-testing review.

The switching test was conducted for current interruption in both directions. An air-core inductance of 25 μH was selected for most of the switching test. The peak voltage incurred across the IGBT during SSCB turnoff is mainly determined by the current commutated to the MOV branch. With all other conditions identical, a higher system inductance would result in a lower rate of current rise and tighter control of the load or fault current. The commutated current, and therefore the MOV clamping voltage, would be lower. On the other hand, higher current is usually the result of lower system inductance (e.g., during the short circuit). In such a turnoff scenario with low inductance and HC, the energy dissipation in the IGBT itself and the snubber helps to significantly reduce the current commutated to the MOV branch. As a result, the worst case IGBT peak voltage or MOV energy dissipation usually does not occur during the short circuit. The selected system inductance of 25 μH therefore is representative of a most challenging, if not the worst, case as far as voltage and insulation stresses are concerned.

1. Incremental Test Execution: Sea Level – 10 000 ft – 35 000 ft – 51 000 ft

The switching test was conducted by reducing the pressure inside the vacuum chamber in steps, with each step simulating an altitude of interest. At each simulated altitude, the capacitor bank voltage was incrementally increased from 500 V to 2000 V. At each voltage step, the SSCB was commanded to conduct for 25 μs before opening, though due to the delay in the turnoff process, the actual on-time of the IGBT was longer than 25 μs . At the test point of 2000 V, the current interrupted was more than 3000 A. The IGBT overcurrent protection was not triggered during this test sequence. At the end of the 51 000 ft test sequence, the SSCB on-time was increased to create the IGBT desaturation condition. In this case, the gate drive board initiated the overcurrent protection to turn off the IGBT before the end of the on-time, resulting in the most challenging switching condition.

As described in III.B, the IGBT gate drive PCB was partially potted with the silicone gel covering the isolated power supply pins and the SiC diodes in the desaturation detection path, while the eMOV PCB for SCR triggering was fully potted.

Both versions of the potted eMOV PCB were installed, one by one, in the SSCB to undergo the high-altitude switching test.

The silicone-potted eMOV PCB from NPS was tested first. It was installed in the SSCB and then tested on the benchtop setup first before installing the SSCB into the housing and testing again. Finally, the SSCB prototype was installed into the vacuum chamber for the high-altitude switching test.

Table 4 through Table 7 summarize the benchtop test results of the SSCB before and after it was installed in the enclosure housing. The SSCB switching performance was as expected. No flashover was noticed. The detailed circuit variables showed very limited variance during the switching under various conditions. The variation of the sensed voltages was usually less than that of the sensed current. This is because the Rogowski coils used for current measurement have a lower accuracy, and their sensing results are affected by the coil positioning, orientation, etc. It was also noticed that the positive and negative current interruptions demonstrated minor differences. These differences arise from the fact that the components and current paths participating in the switching and current commutation are not exactly the same in both directions.

Table 4. SSCB Benchtop Switching Test Results; No Housing; Silicone-Potted eMOV PCB; Current Flow in Positive Direction

DC Source Voltage (V)	System Peak Current (A)	IGBT Peak Current (A)	IGBT Peak Voltage (V)	BOD Trigger Voltage (V)
500	916	880	2378	1217
800	1403	1337	2617	1210
1200	2052	1944	2763	1205
1600	2848	2501	2848	1204
2000	3294	3067	2925	1206

Table 5. SSCB Benchtop Switching Test Results; No Housing; Silicone-Potted eMOV PCB; Current Flow in Negative Direction

DC Source Voltage (V)	System Peak Current (A)	IGBT Peak Current (A)	IGBT Peak Voltage (V)	BOD Trigger Voltage (V)
500	887	870	2385	1217
800	1372	1327	2625	1208
1200	2019	1916	2781	1189
1600	2625	2477	2889	1203
2000	3232	3020	2981	1204

Table 6. SSCB Benchtop Switching Test Results; with Housing; Silicone-Potted eMOV PCB; Current Flow in Positive Direction

DC Source Voltage (V)	System Peak Current (A)	IGBT Peak Current (A)	IGBT Peak Voltage (V)	BOD Trigger Voltage (V)
500	888	844	2378	1218
800	1367	1283	2619	1207
1200	2004	1880	2765	1208
1600	2623	2423	2853	1203
2000	3230	2973	2930	1208

Table 7. SSCB Benchtop Switching Test Results; with Housing; Silicone-Potted eMOV PCB; Current Flow in Negative Direction

DC Source Voltage (V)	System Peak Current (A)	IGBT Peak Current (A)	IGBT Peak Voltage (V)	BOD Trigger Voltage (V)
500	882	897	2378	1215
800	1368	1329	2627	1205
1200	1998	1904	2788	1185
1600	2615	2488	2896	1208
2000	3231	3042	2988	1205

After the benchtop test, the SSCB prototype was installed in the vacuum chamber, and the switching test was conducted. The issues encountered and solutions devised, findings, and test results are presented in the following sections.

2. Current Measurement Errors While Using Multiple Rogowski Coils on the BNC Feedthrough and the Solution

Initially, the plan for measuring the current inside the chamber was to maintain the same arrangement as in the benchtop test. Two Rogowski coils were used inside the chamber to measure the snubber current and the sum of the snubber and MOV currents. A third Rogowski coil was used outside the chamber to measure the load current. From these current measurements, all the currents of interest could be calculated. The Rogowski coils provide a voltage output to a BNC connector, which was then connected to the BNC feedthrough allowing the signal to reach the oscilloscope.

Waveforms captured on the oscilloscope indicated that the current waveforms measured by the two Rogowski coils inside the chamber were distorted and showing significant offset. This distortion can be seen in Figure 48. The current measurements from the Rogowski coils are Ch. 7 (magenta) and Ch. 8 (light blue). Ch. 7 corresponds to the combined current flowing through the MOV and snubber branches, while Ch. 8 corresponds to the snubber current. When the IGBT is in the normal conduction state, both currents should stay at zero. However, significant drift can be seen in these two traces in Figure 48. This distortion disappeared when the two Rogowski coil outputs were connected directly to the oscilloscope, or when one was connected to the feedthrough and the other was connected directly to the oscilloscope, as seen in Figure 49. It was concluded that it was the BNC feedthrough that caused this distortion. The feedthrough accommodates four BNC connections and has a grounded shield. The cables connected to the feedthrough therefore do not have their outer shells isolated from one another. The oscilloscope channel inputs share the same common as well. As a result, ground loops can form and cause the signal distortion seen.

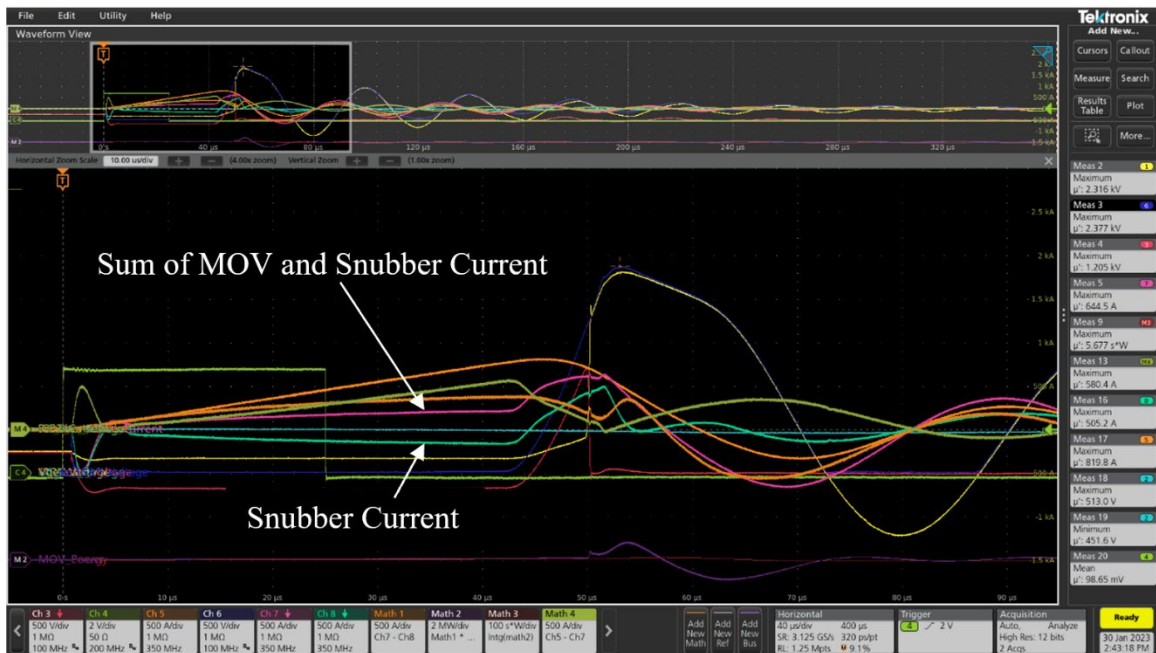


Figure 48. Current Signal Distortion When Using Two BNC Feedthroughs (Ch. 7 and Ch. 8)

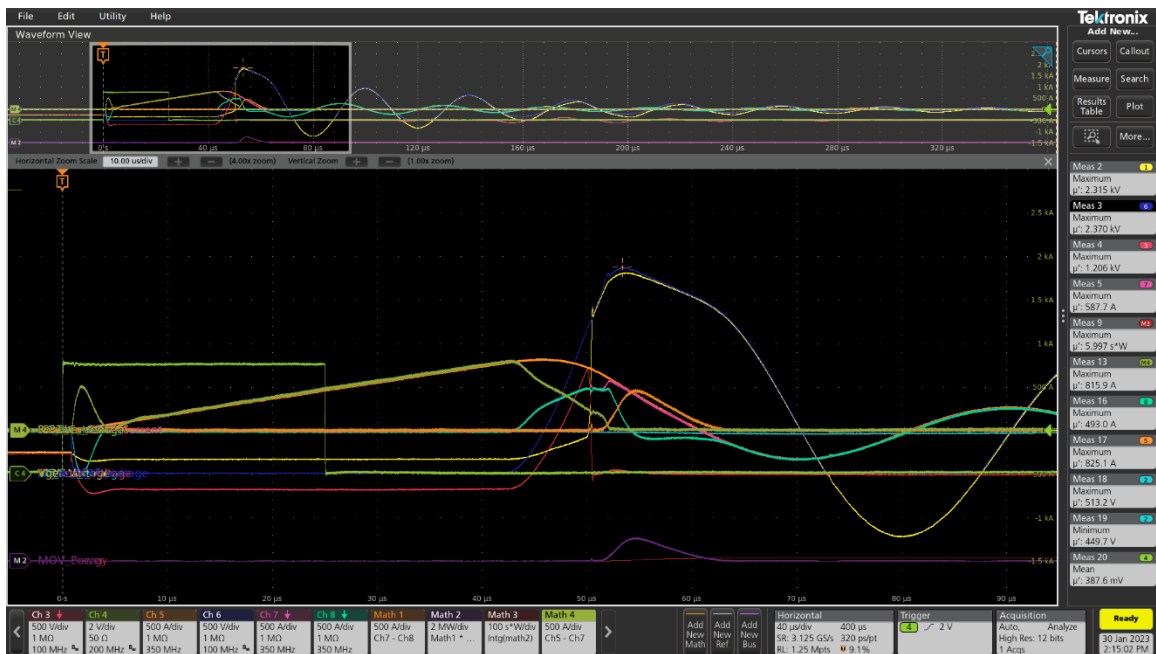


Figure 49. Current Signals When Using One Feedthrough and One Direct Connection to Oscilloscope; No Distortion (Ch. 7 and Ch. 8)

To solve this problem, one Rogowski coil was used in the chamber to measure the sum of the snubber and MOV current, and the snubber current was measured by using the snubber resistor as an unintended current shunt. The voltage across it was measured and passed to the oscilloscope via the HV feedthrough. This voltage measurement (Ch.8) was then converted to a current signal (Math 1) in the oscilloscope using its built-in math functionality. This arrangement solved the signal distortion problem, as illustrated by Figure 50, and allowed for full instrumentation.

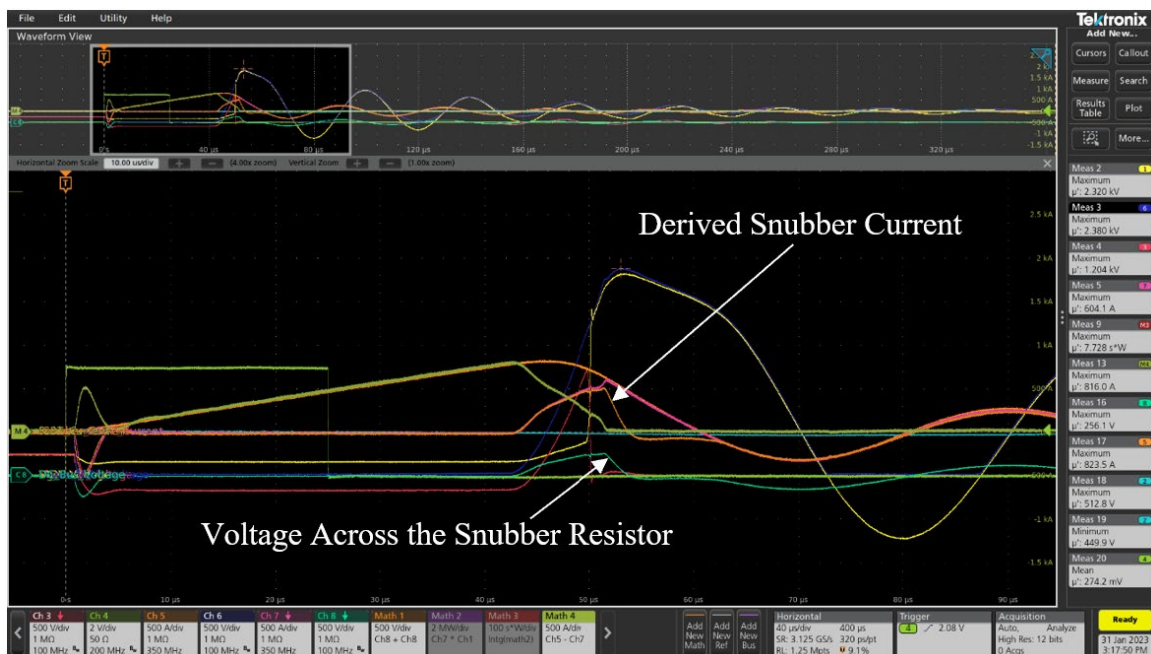


Figure 50. Current Signals When Using One Rogowski Coil via Feedthrough and One Measured Indirectly (Ch. 7 and Math 1)

3. SSCB Switching Test in Chamber with Silicone-Potted eMOV PCB

The switching test results from the silicone-potted eMOV PCB are summarized in Table 8 and Table 9. The test with the load current flowing in the negative direction was more exhaustive, while only the 51 000 ft case was tested with the current flowing in the positive direction. These results indicate that the SSCB switching performance did not change with altitude. The real time monitoring via the webcam confirmed that no flashover occurred during the test sequence.

Table 8. SSCB Switching Test in Chamber; Silicone-Potted eMOV PCB;
Current Flow in Negative Direction

DC Source Voltage (V)	Altitude	System Peak Current (A)	IGBT Peak Current (A)	IGBT Peak Voltage (V)	BOD Trigger Voltage (V)
800	Sea Level	1302	1261	2612	1201
	10 000 ft	1308	1264	2623	1208
	35 000 ft	1304	1265	2630	1205
	51 000 ft	1304	1268	2636	1208
1200	Sea Level	1930	1847	2771	1183
	10 000 ft	1929	1856	2775	1187
	35 000 ft	1932	1855	2782	1183
	51 000 ft	1922	1844	2784	1192
1600	Sea Level	2553	2454	2880	1205
	10 000 ft	2560	2469	2879	1204
	35 000 ft	2569	2460	2888	1206
	51 000 ft	2574	2469	2885	1202
2000	Sea Level	3156	3025	2967	1204
	10 000 ft	3167	3012	2969	1204
	35 000 ft	3162	3016	2971	1204
	51 000 ft	3167	3036	2977	1208

Table 9. SSCB Switching Test in Chamber at 51 000 ft; Silicone-Potted eMOV PCB; Current Flow in Positive Direction

DC Source Voltage (V)	System Peak Current (A)	IGBT Peak Current (A)	IGBT Peak Voltage (V)	BOD Trigger Voltage (V)
800	1286	1221	2597	1216
1200	1897	1789	2730	1221
1600	2495	2342	2822	1219
2000	3104	2887	2893	1221

4. SSCB Switching Test in Chamber with Epoxy-Potted eMOV PCB

The switching test results from the epoxy-potted eMOV PCB are summarized in Table 10 and Table 11. Exhaustive tests with the load current flowing in both directions were conducted. These results indicate that the SSCB switching performance did not change with altitude. There was no flashover observed. Figure 51 and Figure 52 provide side-by-side comparisons of the voltage and current waveforms with $V_{dc} = 2000$ V, $T_{ON} = 25$ μ S, $L_{SYS} = 25$ μ H, and current flowing in the positive and negative direction, respectively, to further confirm that the switching transient essentially stayed the same.

Table 10. SSCB Switching Test in Chamber; Epoxy-Potted eMOV PCB;
Current Flow in Positive Direction

DC Source Voltage (V)	Altitude	System Peak Current (A)	IGBT Peak Current (A)	IGBT Peak Voltage (V)	BOD Trigger Voltage (V)
800	Sea Level	1297	1240	2593	1210
	10 000 ft	1296	1235	2595	1212
	35 000 ft	1295	1233	2597	1216
	51 000 ft	1295	1238	2599	1211
1200	Sea Level	1915	1820	2733	1209
	10 000 ft	1916	1812	2734	1213
	35 000 ft	1913	1805	2734	1214
	51 000 ft	1912	1819	2738	1209
1600	Sea Level	2514	2367	2823	1208
	10 000 ft	2548	2397	2823	1214
	35 000 ft	2545	2381	2827	1208
	51 000 ft	2545	2387	2826	1212
2000	Sea Level	3136	2914	2902	1210
	10 000 ft	3120	2913	2902	1216
	35 000 ft	3133	2934	2906	1214
	51 000 ft	3138	2907	2902	1212

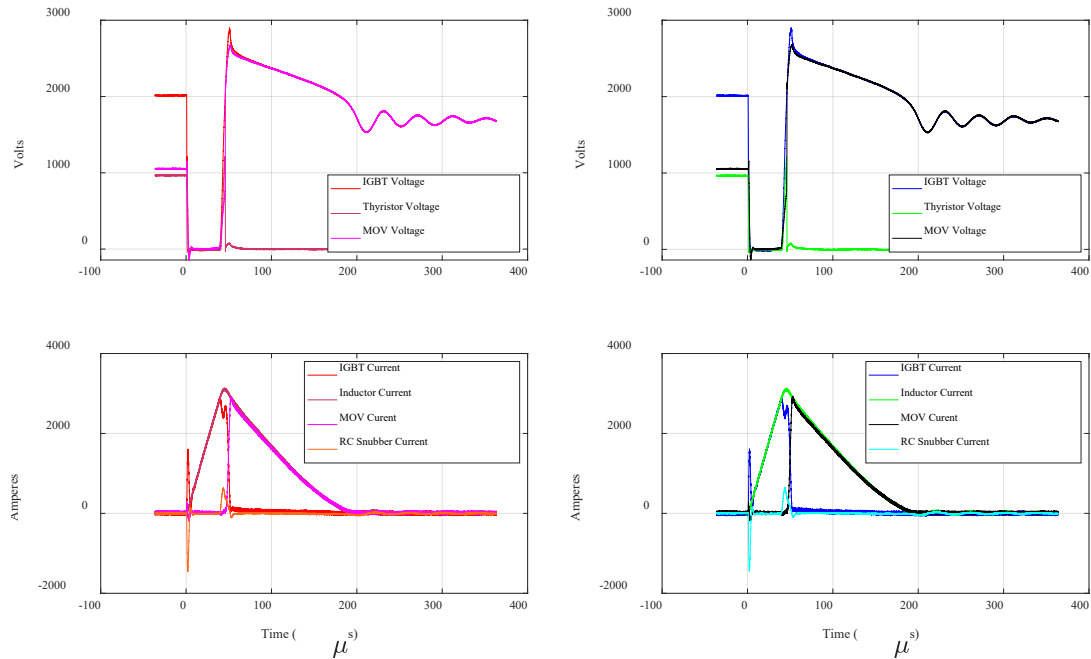


Figure 51. Comparison of Switching Transient Waveforms at Sea Level (L) and 51 000 ft (R) with $V_{dc} = 2000$ V, $T_{ON} = 25$ μ S, $L_{SYS} = 25$ μ H, Current Flow in Positive Direction

Table 11. SSCB Switching Test in Chamber; Epoxy-Potted eMOV PCB; Current Flow in Negative Direction

DC Source Voltage (V)	Altitude	System Peak Current (A)	IGBT Peak Current (A)	IGBT Peak Voltage (V)	BOD Trigger Voltage (V)
800	Sea Level	1279	1257	2602	1196
	10 000 ft	1286	1249	2611	1198
	35 000 ft	1286	1248	2614	1201
	51 000 ft	1282	1245	2616	1200
1200	Sea Level	1897	1831	2757	1198
	10 000 ft	1903	1828	2768	1196
	35 000 ft	1902	1818	2760	1195
	51 000 ft	1898	1814	2771	1198
1600	Sea Level	2533	2456	2861	1187
	10 000 ft	2535	2437	2878	1193
	35 000 ft	2531	2424	2872	1194
	51 000 ft	2529	2402	2875	1196
2000	Sea Level	3124	2985	2955	1192
	10 000 ft	3114	2970	2962	1191
	35 000 ft	3122	2976	2965	1194
	51 000 ft	3116	2990	2961	1191

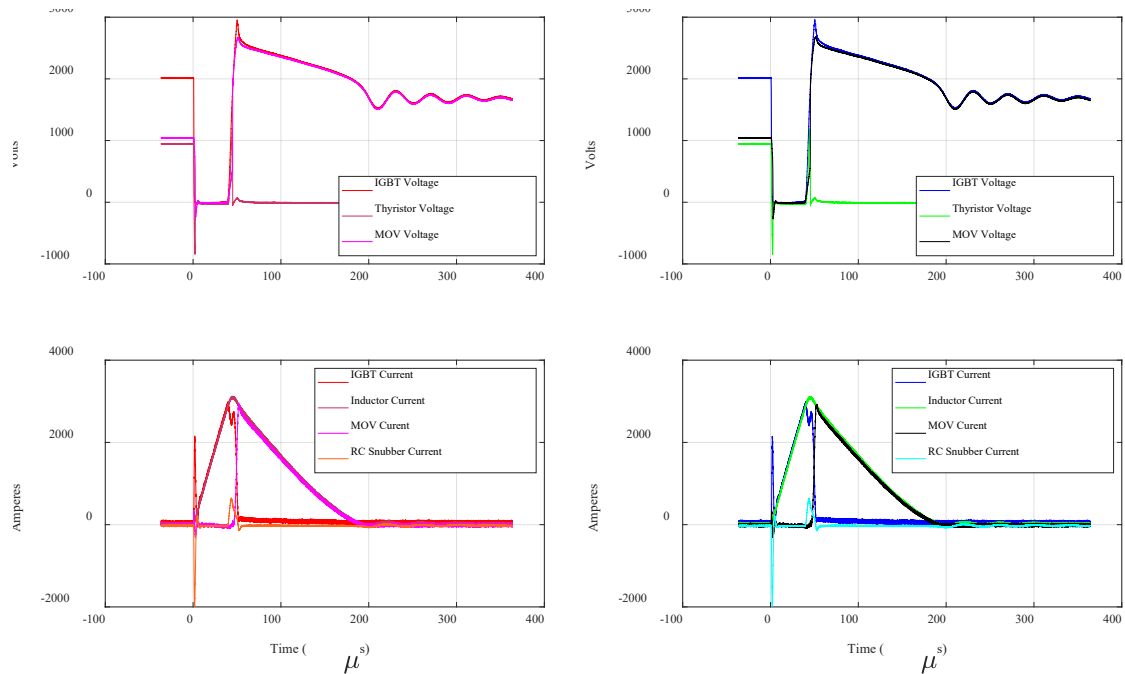


Figure 52. Comparison of Switching Transient Waveforms at Sea Level (L) and 51 000 ft (R) with $V_{dc} = 2000$ V, $T_{ON} = 25$ μ S, $L_{SYS} = 25$ μ H, Current Flow in Negative Direction

At the end of the 51 000 ft test sequence, with the dc source voltage at 2000 V, the IGBT on-time was increased to 62.5 μ S to initiate the overcurrent protection feature of the gate drive board. This test point represents the most stressful operating condition for the SSCB among the possible test scenarios. Table 12 summarizes the key circuit variables, and Figure 53 and Figure 54 show the switching transient waveforms generated from the oscilloscope captured data.

Table 12. SSCB Switching Test in Chamber at 51 000 ft; Epoxy-Potted eMOV PCB; DC Source Voltage at 2000 V; Desaturation Protection Activated

Current Flow Direction	System Peak Current (A)	IGBT Peak Current (A)	IGBT Peak Voltage (V)	BOD Trigger Voltage (V)
Positive	4117	3953	2984	1221
Negative	4116	4026	3071	1201

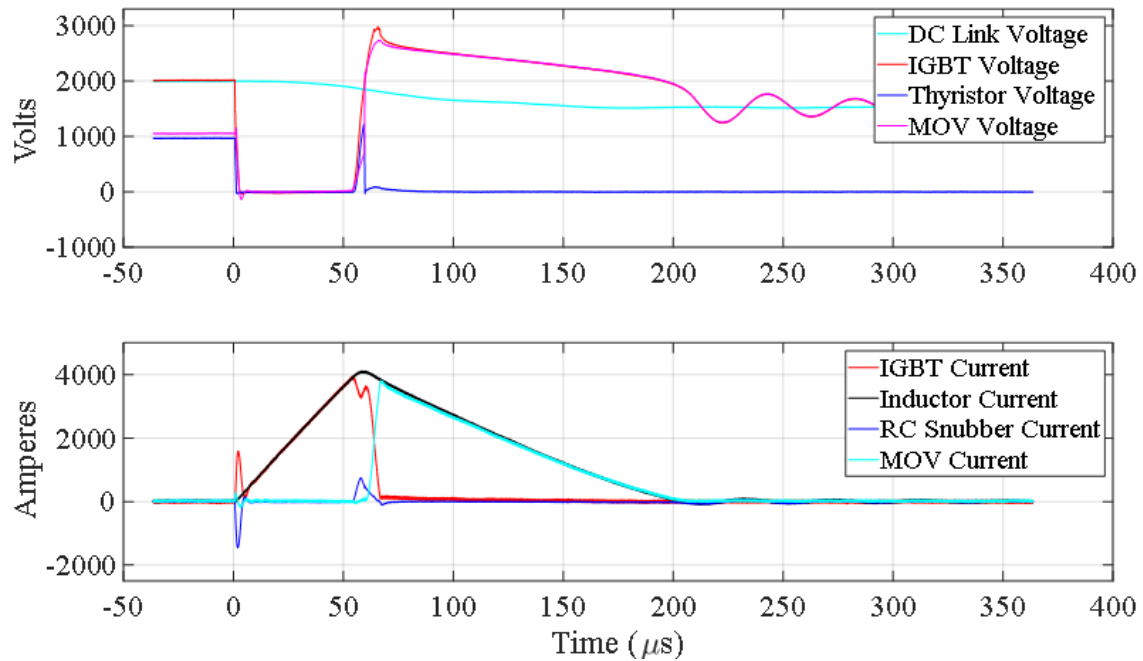


Figure 53. Desaturation Triggered Opening of SSCB; Current Flow in Positive Direction

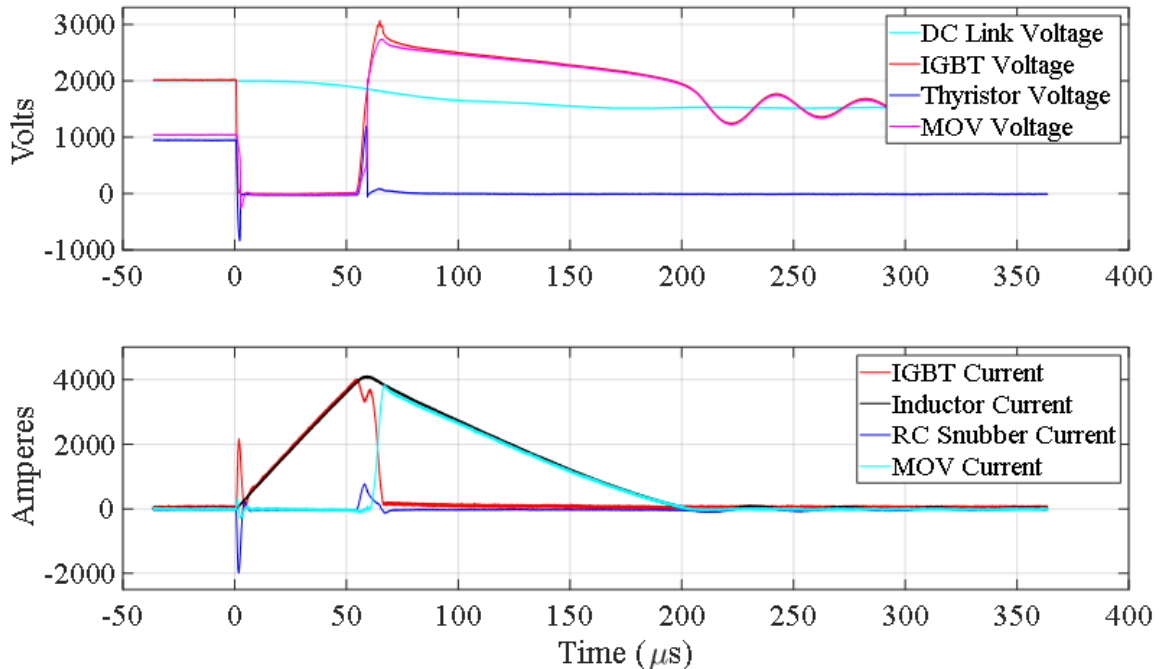


Figure 54. Desaturation Triggered Opening of SSCB; Current Flow in Negative Direction

5. Asymmetrical Short-Circuit Behavior and Investigation

In addition to the test configuration where a 25 μH air-core inductor was used, a short-circuit test was also conducted with the SSCB installed in the vacuum chamber. The configuration is shown in Figure 31 and Figure 32. The test was carried out first with the current flow in the positive direction, as was usually done during the benchtop test. The SSCB behavior was as expected and showed no noticeable difference in IGBT voltage and current waveforms from those observed during the benchtop test. Figure 55 shows the waveforms for this test case.

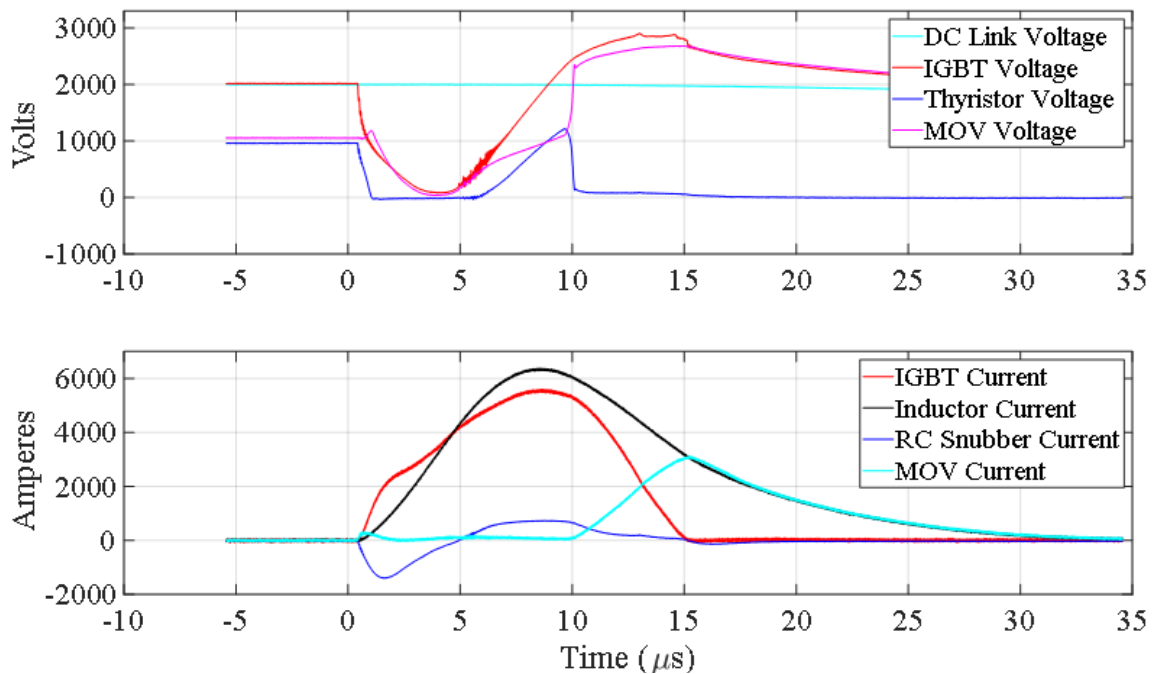


Figure 55. Short-Circuit Test Waveforms; Current Flow in Positive Direction

However, when the short-circuit test was conducted with the current flowing in the negative direction, an unexpected current pattern appeared. As shown in Figure 56, the IGBT current and voltage demonstrated growing oscillatory behavior. Such oscillation could cause various negative effects, including electromagnetic interference and worsening voltage spiking. Various methods were tried to suppress the oscillation. The only method that marginally solved the problem without making major changes to

the circuit was to increase the snubber resistance. Figure 57 shows the waveforms with the snubber resistance doubled. It was important to find the root cause of this oscillation problem and asymmetric short-circuit behavior. Due to the difficulty of circuit debugging with the SSCB fully packaged and installed inside the vacuum chamber, a benchtop unit was used to investigate this anomaly.

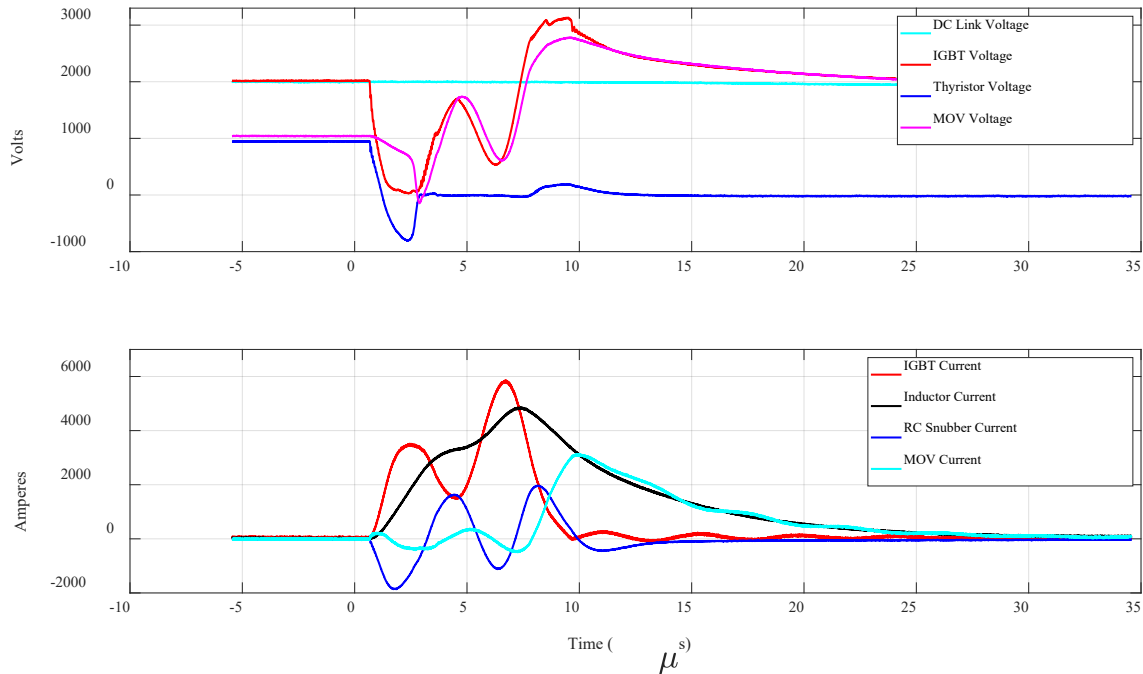


Figure 56. Short-Circuit Test Waveforms; Current Flow in Negative Direction

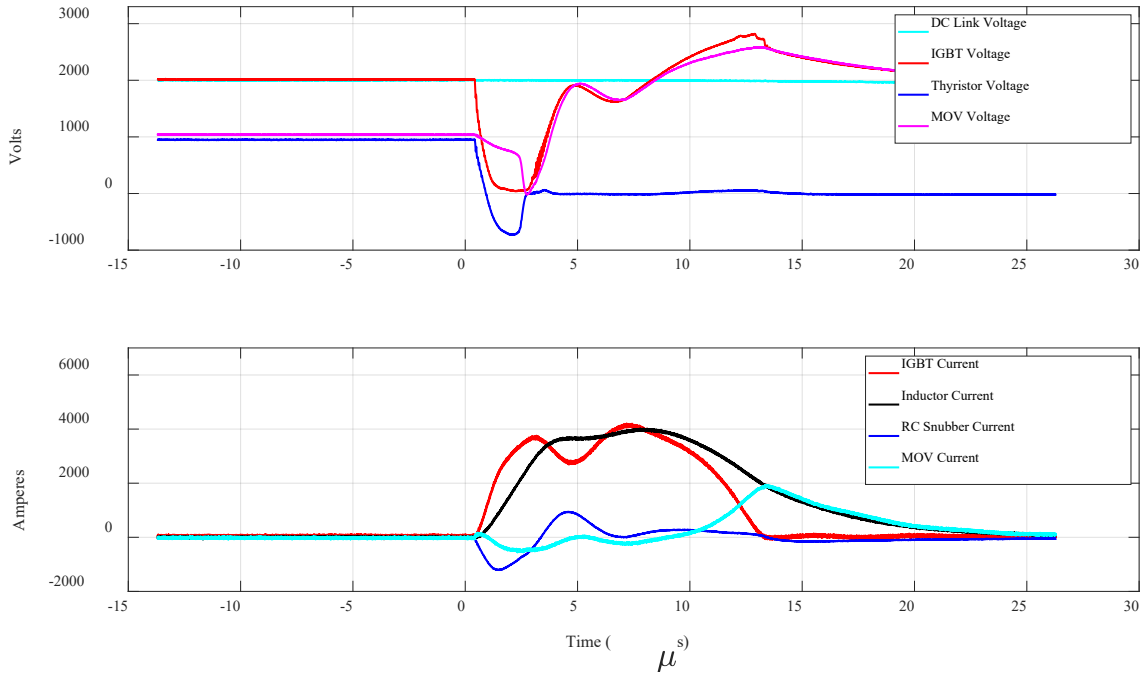


Figure 57. Short-Circuit Test Waveforms; Snubber Resistance Doubled;
Current Flow in Negative Direction

The asymmetric short-circuit behavior was observed with the benchtop unit as well. It was apparent that this anomaly was inherent to the current SSCB design. Since the SSCB behaved as expected while the short-circuit current flowed in the positive direction, there was no reason to doubt that the root cause lay in the SSCB working principle. The asymmetric or inconsistent short-circuit behavior was a reminder that in the early development stage of the SSCB, it was noticed that the emitter busbar shape had a significant effect on the short-circuit current profile [25]. When a narrow copper strip was used as the IGBT emitter busbar, the short-circuit current varied significantly, up to a factor of two, with the power termination point at the copper strip. In contrast, if a wide busbar with power cable termination points sufficiently far away from the IGBT emitter power terminals was used, the variation of short-circuit current with respect to the power cable termination point was limited, in the range of $\pm 5\%$. Figure 58 shows this early SSCB layout with the narrow and wide busbars. The root cause was identified as the interaction between the IGBT gate drive loop and current flow in the busbar, especially when di/dt , the rate of current change, was high, such as during a short circuit. When

the narrow copper strip was used, the short-circuit current distribution changed significantly depending on the termination point. Referring to the narrow busbar layout in Figure 58, the three power terminals are labeled as #1, #2, and #3, with #3 being the closest to the IGBT gate loop and #1 the furthest. When the power cable is terminated at #3, all the short-circuit current is concentrated around the gate loop and exits at #3. When the power cable is terminated at #1, the least amount of current flows in the area around the gate loop and the current flow in the copper strip is in the opposite direction as compared to the case where #3 is used. Therefore, the effect on the gate loop is not only opposite, but also differs in quantity. Such dependence of the interaction on the power cable termination point diminishes when the wide busbar is used since the current would mostly spread out when it reaches the IGBT emitter power terminals.

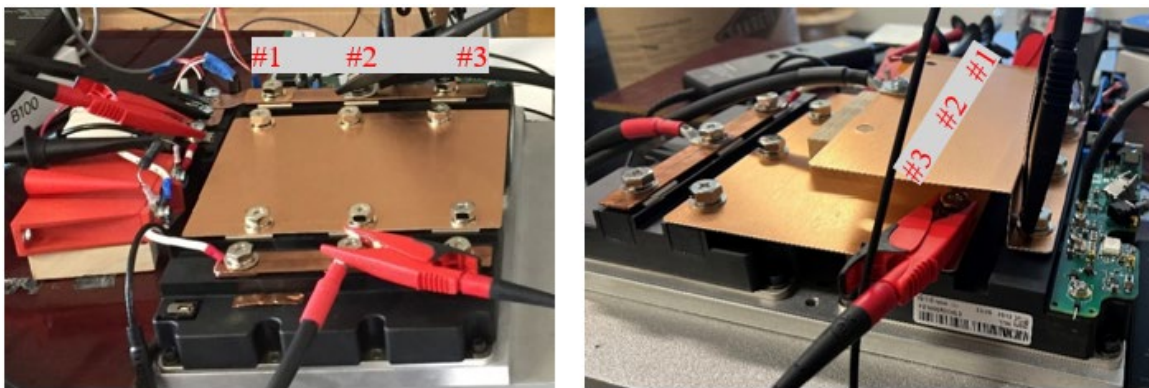


Figure 58. Early SSCB Layout with Narrow (L) and Wide (R) Emitter Busbar

In the case of the current SSCB prototype, as shown in Figure 59, the snubber capacitor discharges through the snubber resistor and the IGBT when it is turned on. This discharge current has a high di/dt , and therefore has the potential to strongly affect the gate loop. Figure 60 zooms in on the snubber termination points at the positive and negative poles of the SSCB. At the positive pole, the snubber termination point is the furthest from the Kelvin terminals, while at the negative pole, the snubber termination point is the closest. It is apparent that for the negative pole, the snubber discharge current concentrates near the IGBT gate loop terminals and exits there. In comparison, for the

positive pole, the snubber discharge current concentrates on the opposite end of the gate loop terminals, and its effect on the gate loop is opposite in polarity and much less severe in magnitude. Comparing the waveforms in Figure 55 and Figure 56, the short-circuit current shows much higher di/dt upon SSCB turn-on when current flows in the negative direction, due to its strengthening effect on the gate voltage. This effect, together with the short-circuit condition, results in the sustained oscillation involving the snubber branch, the IGBT, and the dc source (i.e., the capacitor bank). Such oscillation cannot develop when there is sufficient system inductance between the SSCB and the dc source, since the system inductance will inhibit the source current feeding the energy needed for sustaining the oscillation. It will therefore decay very quickly when the energy stored in the snubber capacitor is dissipated.

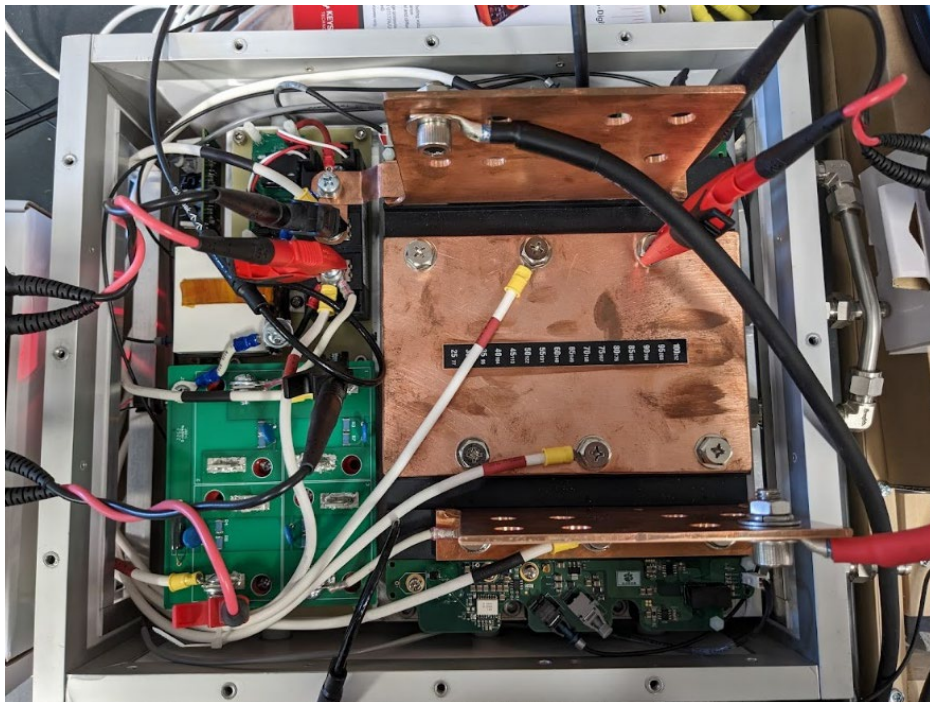


Figure 59. SSCB Prototype Layout

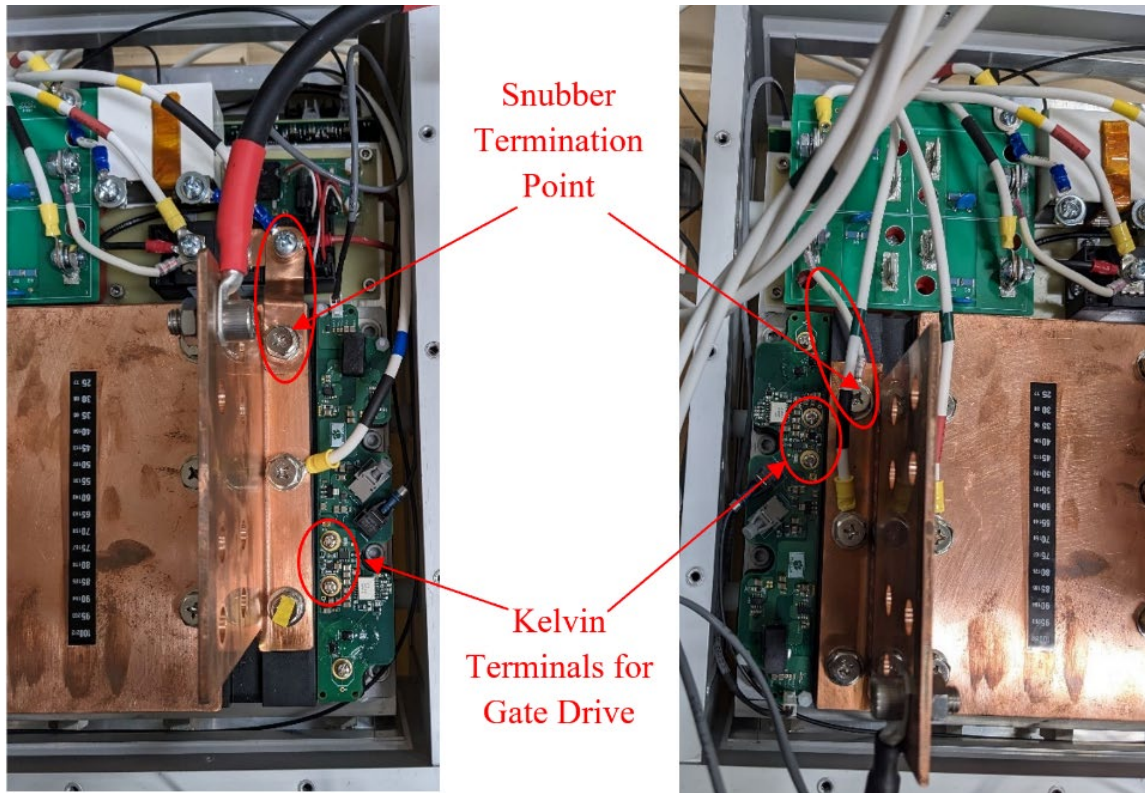


Figure 60. Snubber Termination Points at Positive (L) and Negative (R) Poles

One apparent solution is to optimize the SSCB packaging such that the snubber branch terminates at the opposite end of the IGBT gate terminals for both the negative pole as well as the positive pole. Figure 61 shows such an arrangement. The snubber branch is placed diagonally instead of on one side of the SSCB. This placement allows the snubber termination at both poles to be the same (i.e., at the opposite end of the IGBT gate terminals). Short-circuit testing was conducted to evaluate the effectiveness of this layout change. Figure 62 and Figure 63 present the test results. The voltage and current waveforms show similar profiles in both the positive and negative current flow cases, and the asymmetric short-circuit behavior and anomaly observed in the SSCB prototype were eliminated.

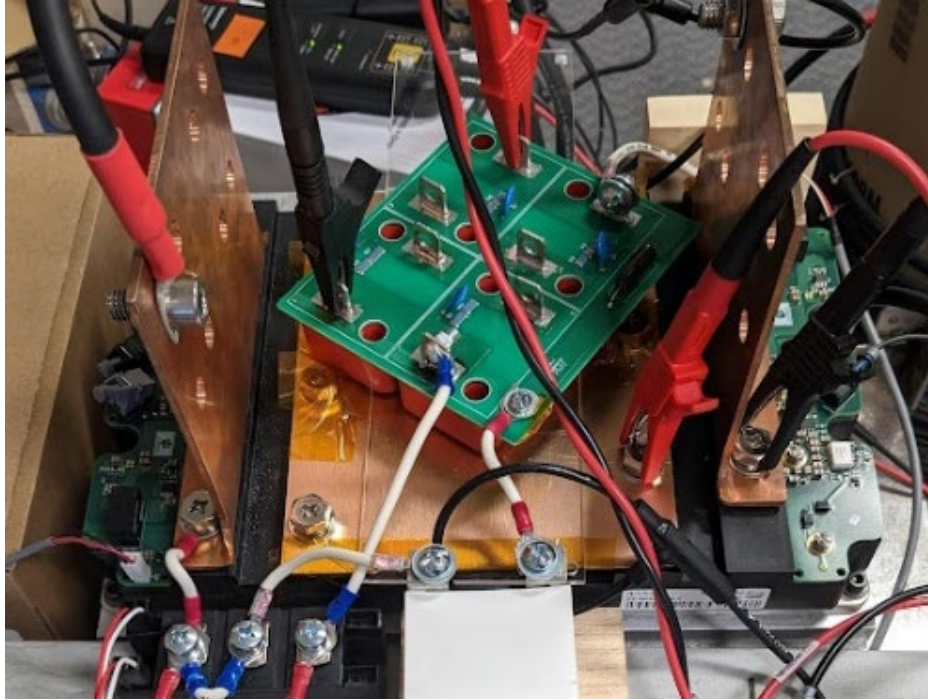


Figure 61. Alternative Placement of Snubber Branch in Benchtop Unit

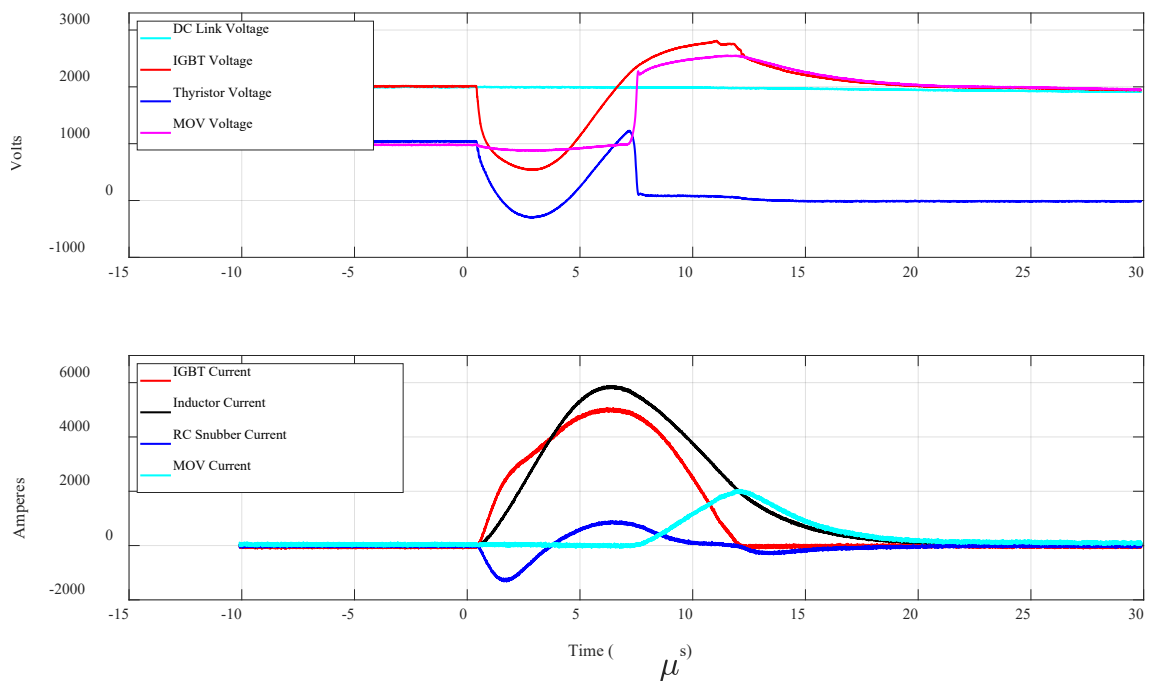


Figure 62. Short-Circuit Test Waveforms; Current Flow in Positive Direction; Alternative Snubber Placement

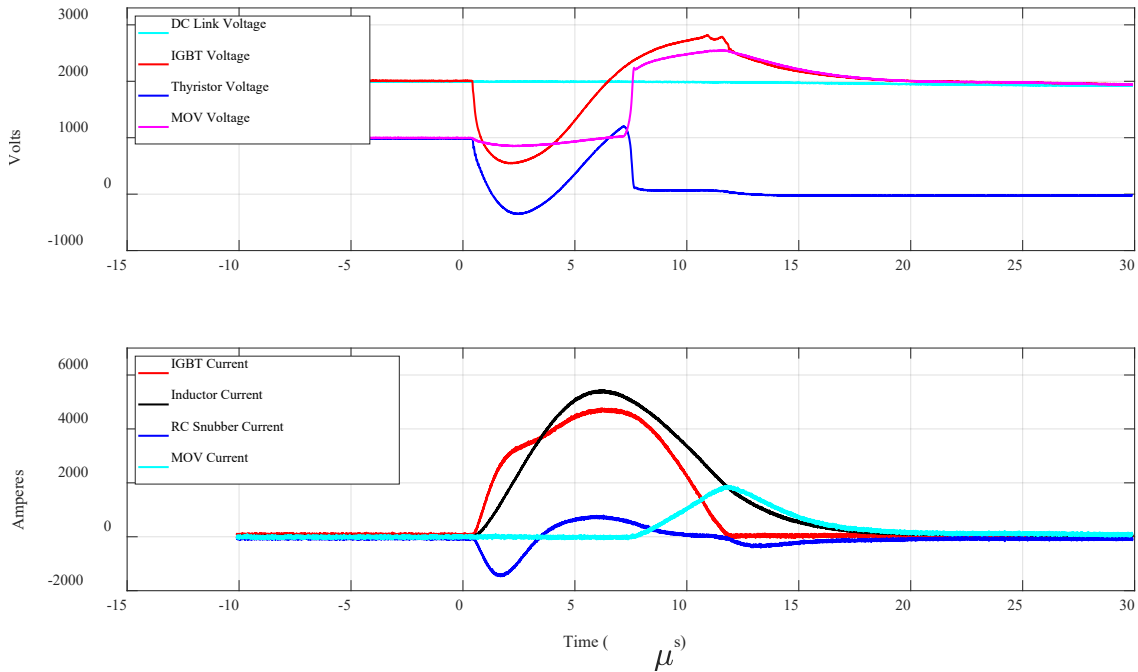


Figure 63. Short-Circuit Test Waveforms; Current Flow in Negative Direction; Alternative Snubber Placement

Although it is straightforward to try various component placements on a benchtop unit, it is not trivial to incorporate such changes into the SSCB prototype. It can be incorporated in the next iteration of the SSCB design, but it will not be pursued further in this thesis. It should be emphasized that the abnormal short-circuit behavior observed in the SSCB prototype does not affect the purpose of the switching test (i.e., to evaluate its insulation performance at high altitudes), since the voltage stresses experienced by the components and insulation materials in the default testing configuration with a system inductance of 25 μH are higher than those in the short-circuit case.

D. CONCLUSIONS ON SSCB INSULATION PERFORMANCE

This chapter focused on the switching test of the SSCB prototype in high-altitude conditions to evaluate its insulation performance. The switching test setup and instrumentation were described. The potting of the gate drive PCB for driving the IGBT module and of the eMOV PCB for triggering the SCR was covered in detail. The switching test execution was presented with comprehensive test data.

The silicone gel is appropriate for the partial potting of the gate drive PCB. However, it is not preferred for the eMOV PCB. The silicone gel is difficult to work with when doing full-board potting, and it remains tacky after curing making the board difficult to handle, thus the epoxy is better suited.

The switching test meticulously conducted incrementally from sea level to the target altitude of 51 000 ft confirms that the SSCB prototype has satisfactory insulation performance in high-altitude operating conditions. No deterioration in electrical performance was noticed. No flashover was captured during the real-time monitoring with the webcam.

Abnormal voltage and current profiles were noticed during the short-circuit test in the negative current flow direction. The root cause of this anomaly was identified, and a solution was devised and verified in the benchtop unit. Design optimization can be incorporated in the next SSCB iteration.

IV. EVALUATION OF SSCB THERMAL PERFORMANCE AT HIGH ALTITUDE

A. THERMAL TEST SETUP AND INSTRUMENTATION

The SSCB should have acceptable thermal behavior while carrying the load current continuously during steady state operations. The thermal dissipation inside the SSCB arises mainly from conduction voltage drops incurred in the semiconductor devices (i.e., the freewheeling diode and the IGBT in the anti-series IGBT modules). There is also dissipation in the copper busbars outside as well as inside the IGBT modules. The dissipation results in a temperature rise and impacts the operating efficiency. For the SSCB prototype, the thermal performance must be thoroughly evaluated. The operating efficiency of the SSCB prototype needs to be evaluated against the design specification. The thermal test setup schematic is shown in Figure 64, followed by a photograph of the lab setup in Figure 65 with the key components labeled.

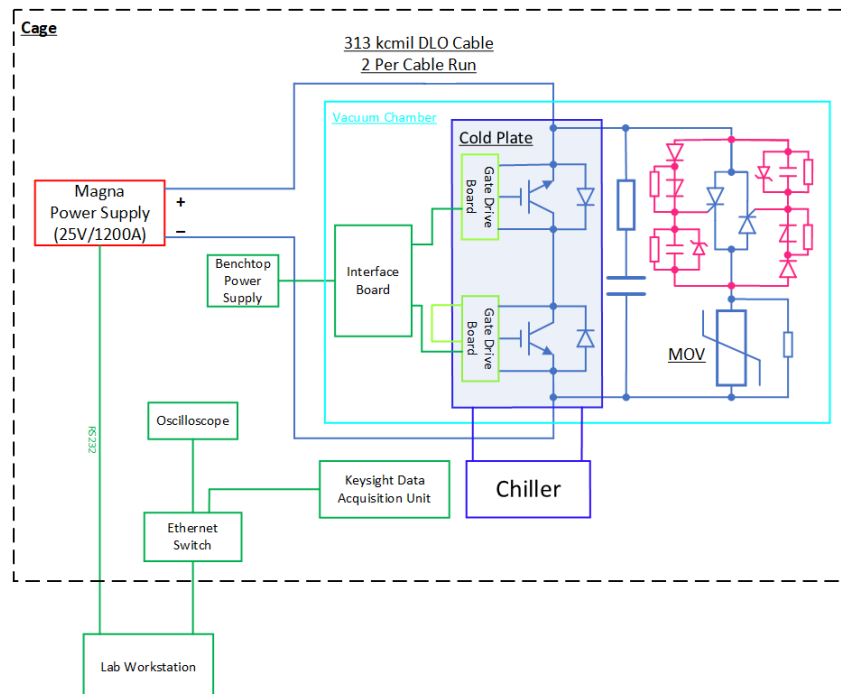


Figure 64. Test Setup Schematic for Thermal Performance Evaluation of SSCB Prototype

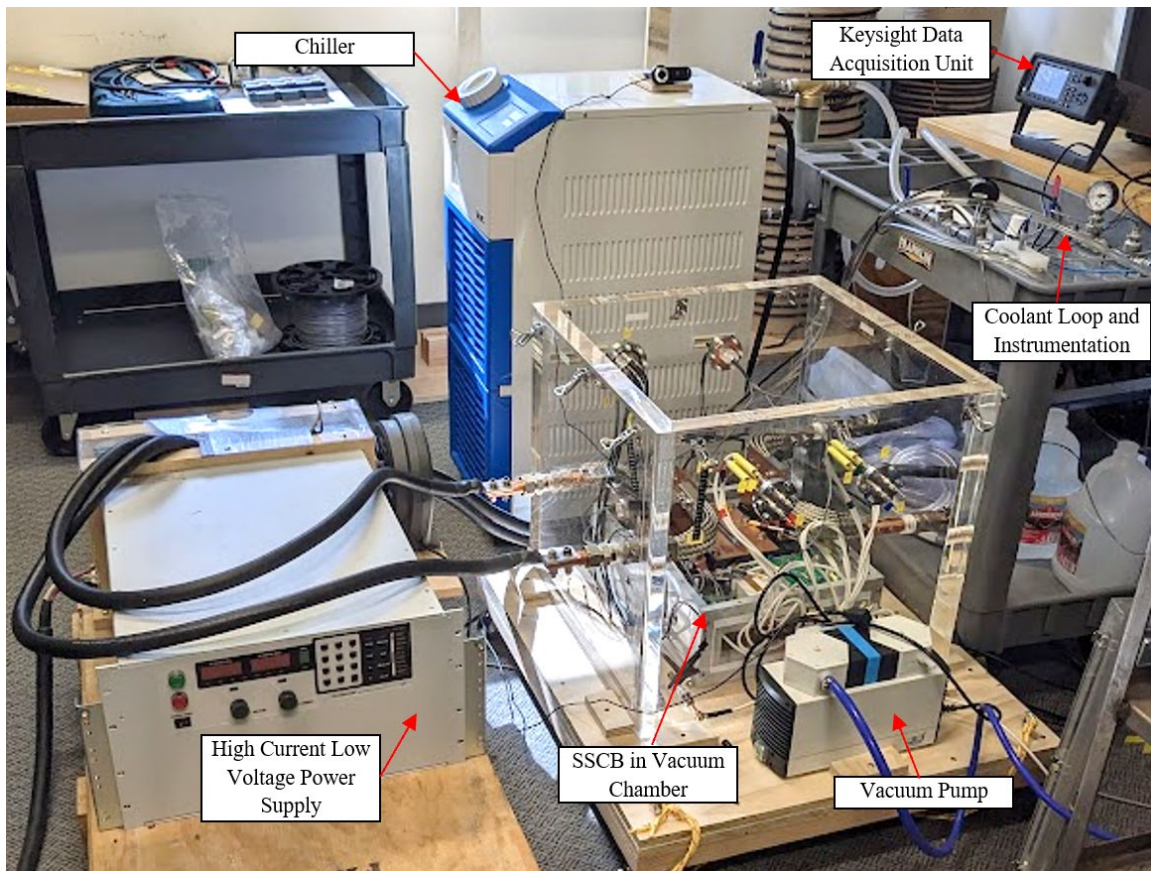


Figure 65. Thermal Performance Test Setup

Similar to the switching test setup, the SSCB prototype was installed inside the vacuum chamber with the air pressure controlled at specific values to simulate the high-altitude operating conditions. However, the coolant tubes were now installed through the feedthroughs and connected to the cold plate on the vacuum side and to the supply and return tubing on the air side. Instead of the HV, LC power supply, an LV, HC power supply was used to supply a continuous current flow of up to 1200 A through the SSCB prototype. To allow such a steady state current flow, two DLO cables with a wire gauge of 313 kcmil were used in each cable run, as shown in Figure 66, for connection between the power supply output terminals and the HC feedthroughs in the vacuum chamber. Inside the vacuum chamber, the 6 AWG DLO power cables were replaced with the copper braids, as seen in Figure 67.

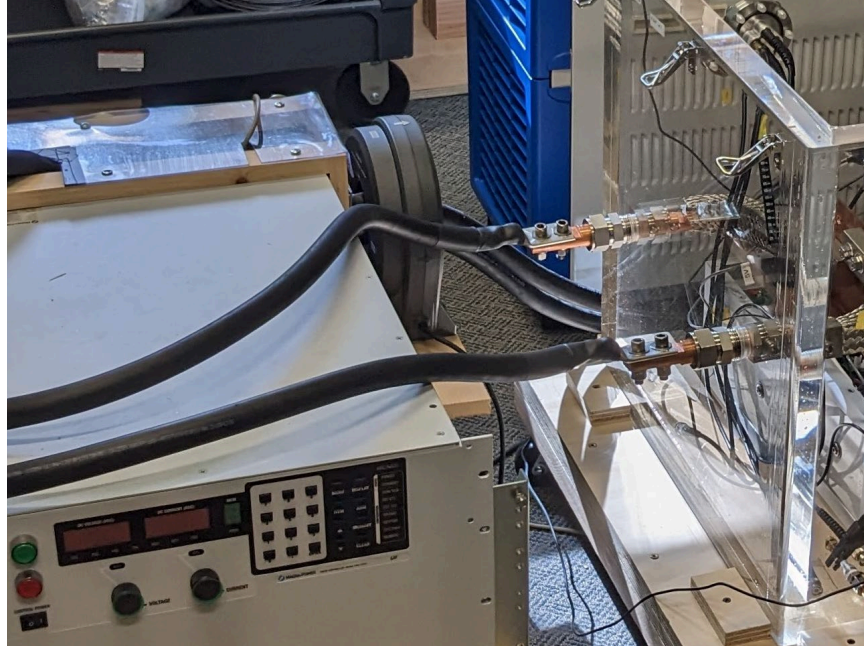


Figure 66. 313 kcmil DLO Power Cables from High-Current Power Supply to Power Feedthroughs for Thermal Test

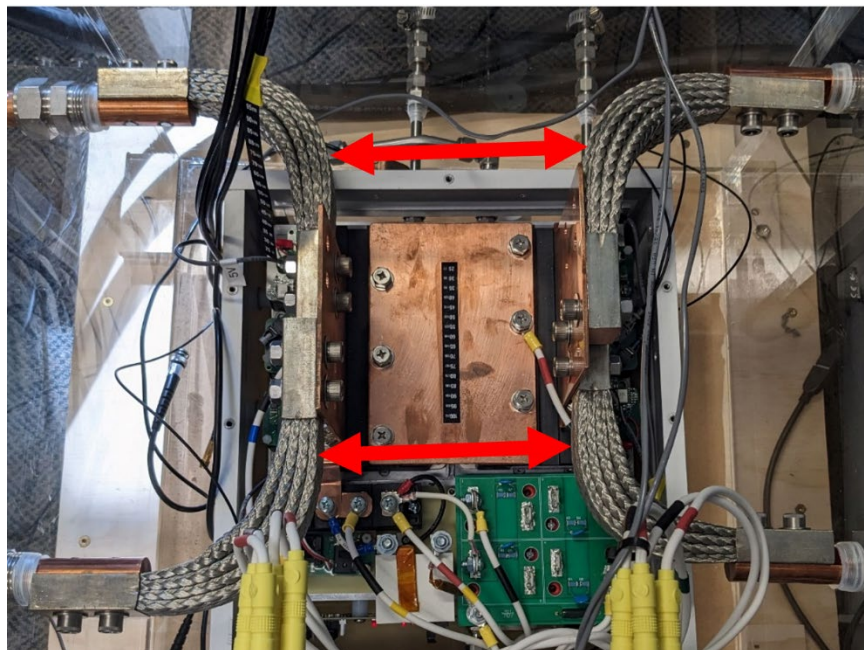


Figure 67. 12-in Copper Braids for HC Thermal Test

A SMC thermo-chiller (P/N: HRS060-AN-20) was used to remove heat from the SSCB by pumping cooled distilled water through the cold plate. The cooling capacity of the selected thermo-chiller is shown in Figure 68. This chiller is an air-cooled model, which requires proper ventilation during operation.

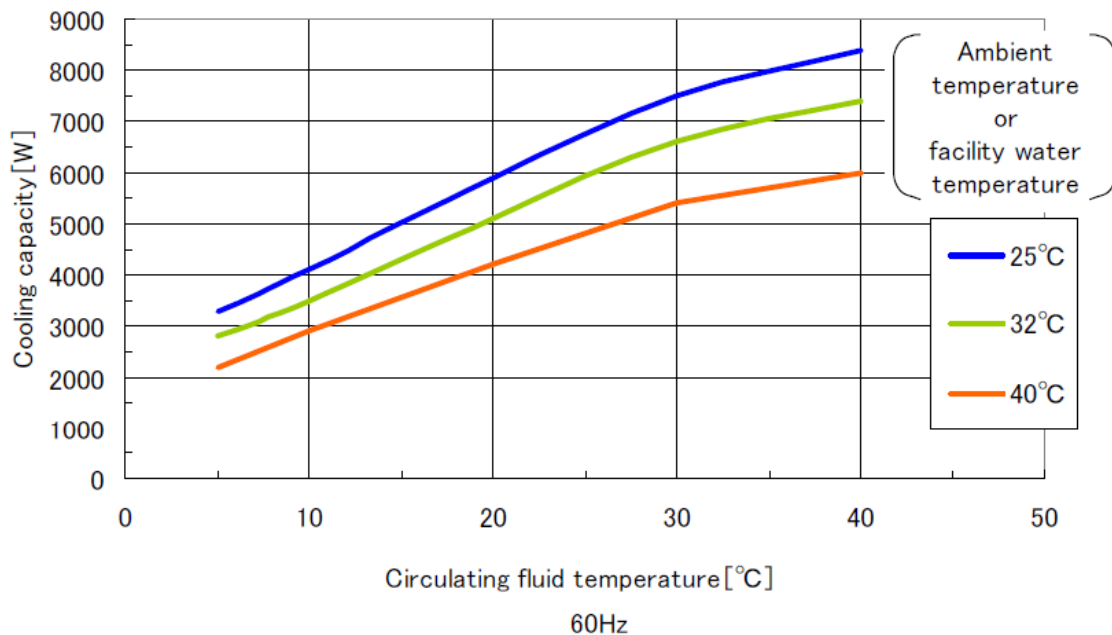


Figure 68. Cooling Capacity of SMC HRS060-AN-20 Thermal Chiller.
Source: [44].

The coolant loop consisted of the chiller, primary and secondary supply valves, a supply pressure gauge, a supply temperature transmitter, the cold plate, a flow meter, a return pressure gauge, a return temperature transmitter, primary and secondary return valves, and a bypass valve connecting the supply and return lines. The flow meter was connected to an oscilloscope to monitor the flow rate, which was controlled by adjusting the bypass valve. The supply and return coolant temperatures were measured with Littelfuse thermistor probes (P/N: USP10978) placed directly in the coolant path and wired to the data acquisition (DAQ) unit to collect the readings.

A Keysight DAQ system (P/N: DAQ970A), seen in Figure 69, was used in the thermal test for continuous data monitoring, visualization, and recording. It was

interfaced via a local area network connection using the Keysight BenchVue DAQ software. All temperature sensors and the voltage sensors for the IGBT modules were wired into one 16-channel multiplexer plug-in module (P/N: DAQM902A), seen in Figure 70, for the DAQ system. The multiplexer channel configuration with the variables measured is listed in Table 13.



Figure 69. Keysight DAQ970A Data Acquisition System. Source: [45].

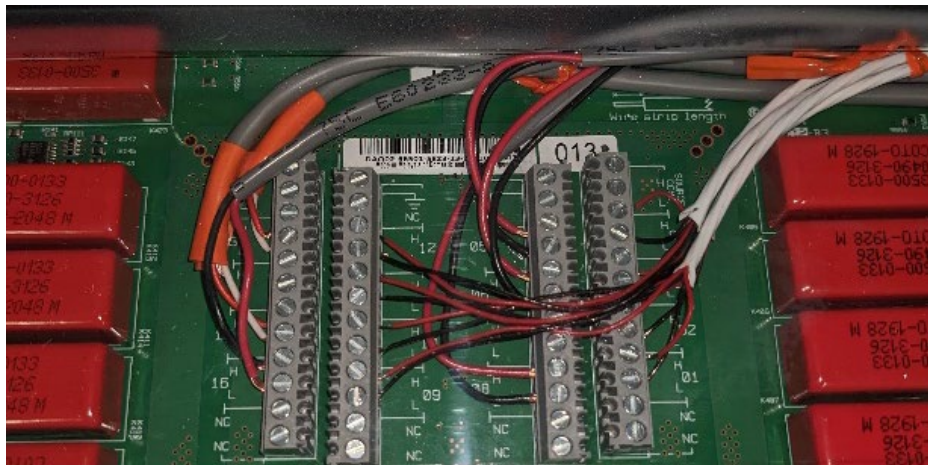


Figure 70. DAQM902A 16-Channel Multiplexer (2 / 4-Wire) Module

Table 13. Keysight DAQ System Channel Lineup

DAQM902A Module Channel Number and Configuration	Measured Variable
1: 4-Wire RTD	Temperature, Magna Power Supply Output Terminal (+)
2: 4-Wire RTD	Temperature, Magna Power Supply Output Terminal (-)
3: 4-Wire RTD	Temperature, HC Copper Rod Terminal (+)
4: 4-Wire RTD	Temperature, HC Copper Rod Terminal (-)
5: 2-Wire Thermistor	Temperature, Coolant, Cold Plate Inlet
6: 2-Wire Thermistor	Temperature, Coolant, Cold Plate Outlet
8: DC Voltage	Diode Forward Voltage Drop
16: DC Voltage	IGBT Conduction Voltage Drop
13: 2-Wire Thermistor	Temperature, Vertical Busbar (+)
14: 2-Wire Thermistor	Temperature, Flat Busbar
15: 2-Wire Thermistor	Temperature, Vertical Busbar (-)

The semiconductor conduction voltage drops were measured at the IGBT module Kelvin terminals. The copper busbar temperatures were measured with lug-type thermistors, which were installed at the later stage of thermal test, as detailed in IV.B.2. The 4-wire resistance temperature detector (RTD) sensors were used for additional temperature measurements at selected power cabling locations external to the vacuum chamber and were not directly related to SSCB thermal evaluation.

B. TEST EXECUTION, DATA ACQUISITION AND PROCESSING

The thermal test was conducted with the SSCB prototype installed in the vacuum chamber and the instrumentation set up as detailed in IV.A. It began with testing at the sea level condition, followed by testing at incrementally decreasing pressures corresponding to altitudes of interest. The DAQ system allowed continuous data acquisition, recording, and display. Two webcams provided additional real time condition monitoring and recording by focusing on the SSCB circuit and temperature-indicating labels.

A key aspect in this test is the thermal performance of the copper busbars used in the SSCB. These copper busbars are expected to carry HC continuously. Unlike the silicon chips inside the IGBT modules, it is ambiguous how the copper busbars are thermally interfaced with the environment and the cold plate. Initially, no thermal sensors

were attached to these copper busbars for accurate temperature measurement. Only a temperature-indicating label was attached to the busbar for rather coarse temperature reading. The top cover of the SSCB housing was removed so the label was visible. In addition, a free-hanging temperature-indicating label was used to indicate the air temperature inside the chamber. Later in the test, lug type thermistors were mounted on the busbars to better measure their temperature profile. These lugs allowed continuous busbar temperature reading and recording. The top cover could also be installed to better replicate the expected SSCB working condition in an aircraft.

The LV (up to 25 V), HC (up to 1200 A) Magna dc power supply provided a continuous current flow through the SSCB. This power supply was remotely controlled at the control room via an RS-232 communication link. One of the two IGBT modules in the SSCB was kept in the on state, while the other was held in the off state. The current flowed through the IGBT chips and freewheeling diode chips of these two IGBT modules, respectively. The current sourced by the power supply was increased incrementally until reaching the full load current rating, with sufficient time allowed in each step for the components in the SSCB to reach a thermal steady state.

The chiller was set to provide a coolant flow rate of 3 gal/min, with the supply temperature set at 15 °C in most test cases. The supply temperature can be adjusted to increase the thermal capacity of the chiller and to evaluate the response of the SSCB components to coolant temperature.

1. Incremental Test Execution: Sea Level – 10 000 ft – 35 000 ft – 51 000 ft

The thermal test was conducted by reducing the pressure inside the vacuum chamber in steps, with each step simulating an altitude of interest. At each simulated altitude, the SSCB conducted a steady state current, which was increased in steps from low magnitude toward the full rated current. At each current step, voltage readings from the Magna dc power supply output terminals, the chamber entry points for the HC feedthroughs, and across the silicon devices inside the IGBT modules were recorded.

In this stage of the thermal test, the variables measured and recorded by the DAQ system were:

- Coolant supply temperature
- Coolant return temperature
- IGBT voltage drop in SSCB
- Diode voltage drop in SSCB

A temperature-indicating label was attached to the flat copper busbar which connected the collectors of the two IGBT modules in the SSCB. It was believed that this busbar would be the most thermally challenged, since it has no apparent thermal path for any heat load. Another label hanging freely in the chamber provided the approximate chamber air temperature. It was of interest to know how the air temperature would change with increasing heat dissipation from the SSCB and connecting conductors and/or at higher altitude. These labels indicate the temperature through color-changing dots with a resolution of 5 °C. The collected data was processed and is presented in detail next.

Figure 71 shows the complete data recorded during the thermal test at sea level, covering the load range from 100 A up to 1000 A. The data indicates that the chiller could maintain a coolant supply temperature of 15 °C at its outlet. The coolant return temperature, after passing through the SSCB cold plate, increased with the current. Usually, the silicon devices in power modules reach a thermal steady state in seconds, which agrees with the step-like device voltage profiles recorded. The chiller has a much longer thermal time constant, in the range of four to eight minutes. Figure 72 presents the complete test records at altitudes of 10 000 ft, 35 000 ft, and 51 000 ft. The temperature and device voltage profiles at these altitudes do not show any noticeable difference, indicating that high altitude has little, if any, impact on the active cooling path and actively cooled components. More detailed data annotations and processing, as shown in Figure 73 through Figure 75 and Table 14 through Table 16, confirm this observation. In Figure 73 through Figure 75, the flat copper busbar and chamber air temperature are also added to the annotations, shown in green and red text boxes, respectively.

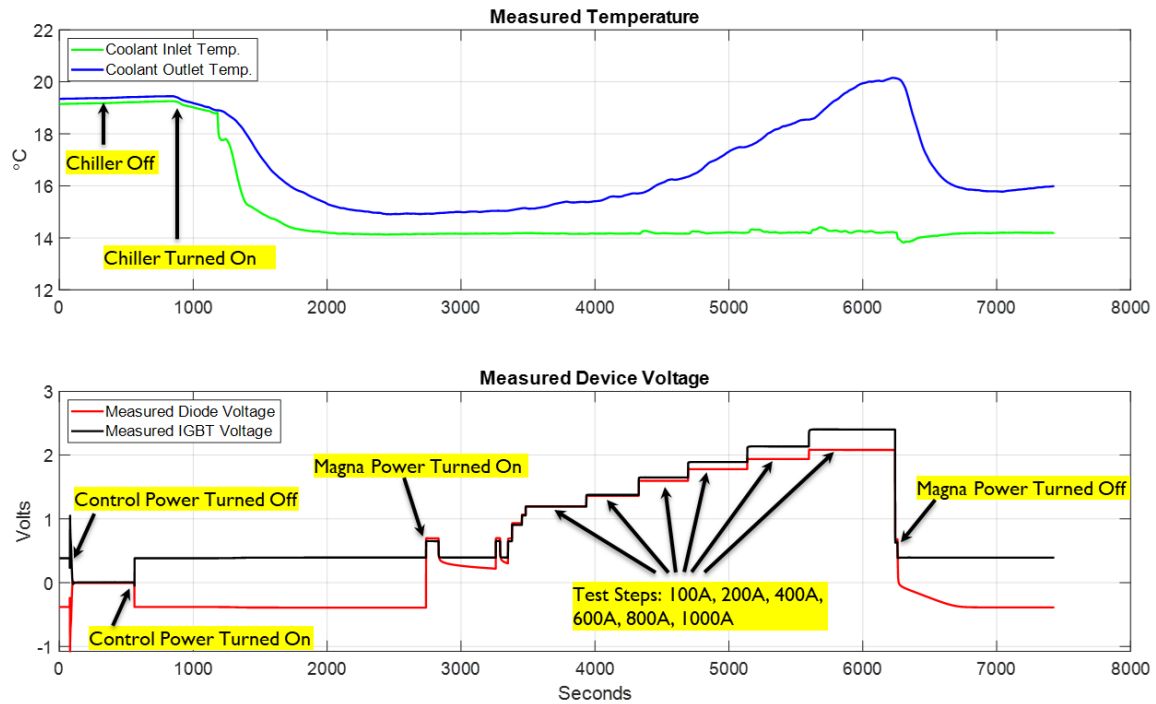


Figure 71. Thermal Test Record; Sea Level

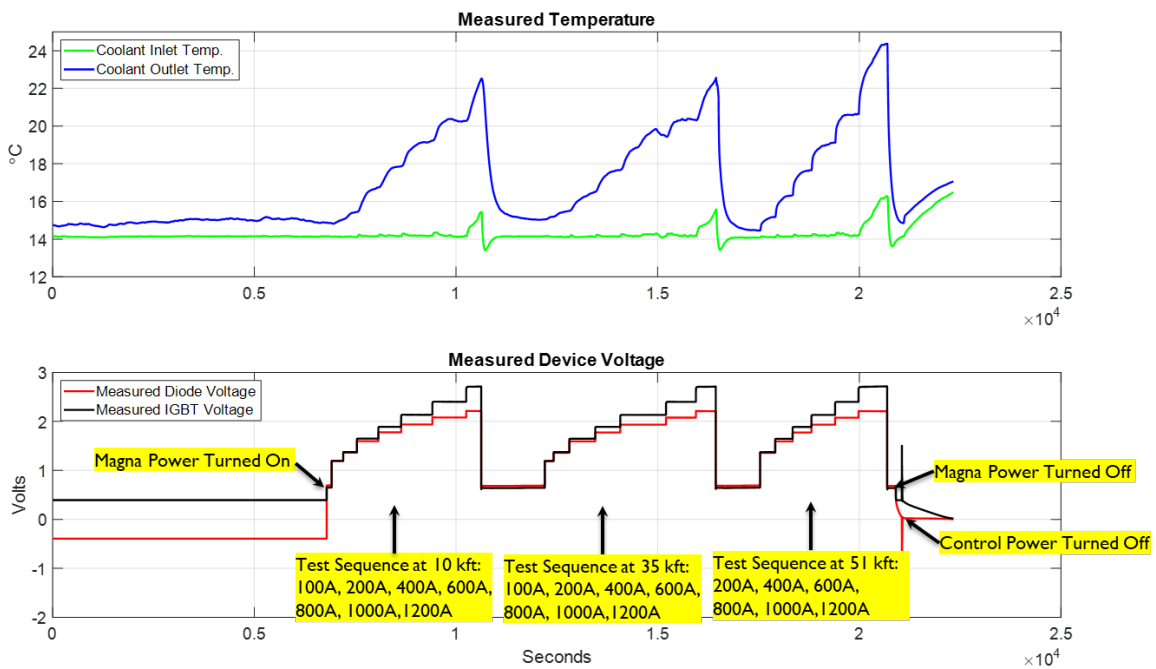


Figure 72. Thermal Test Record; 10 000 ft, 35 000 ft and 51 000 ft

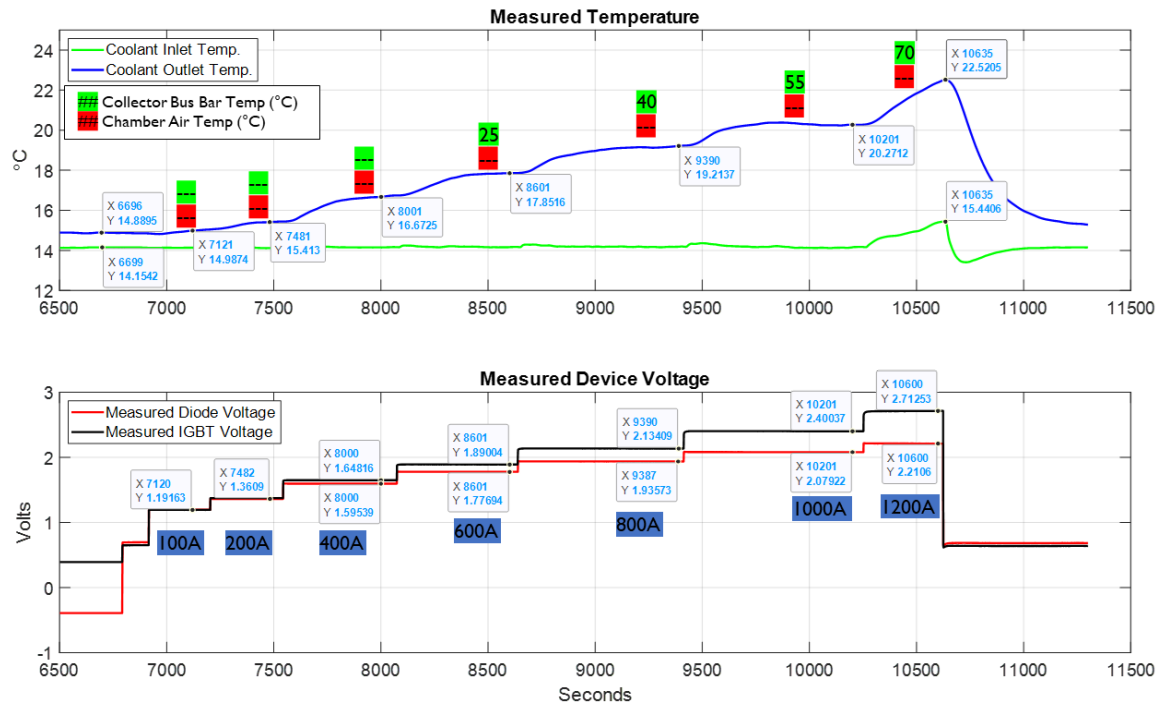


Figure 73. Detailed Thermal Test Data; 10 000 ft

Table 14. Voltage Drop and Dissipation Data; 10 000 ft

Current (A)	Magna Terminal Voltage (V)	Chamber Device Voltage Drop (V)	Chamber Total Voltage Drop (V)	Chamber Device Loss (W)	Chamber Copper Loss (W)	Total Copper Loss (W)
200	2.83	2.736	2.7700	547.2	6.8	18.8
400	3.41	3.243	3.3140	1297.2	28.4	66.8
600	3.93	3.667	3.7755	2200.2	65.1	157.8
800	4.41	4.071	4.2190	3256.8	118.4	271.2
1000	4.92	4.481	4.6745	4481.0	193.5	439.0
1200	5.47	4.921	5.1595	5905.2	286.2	658.8

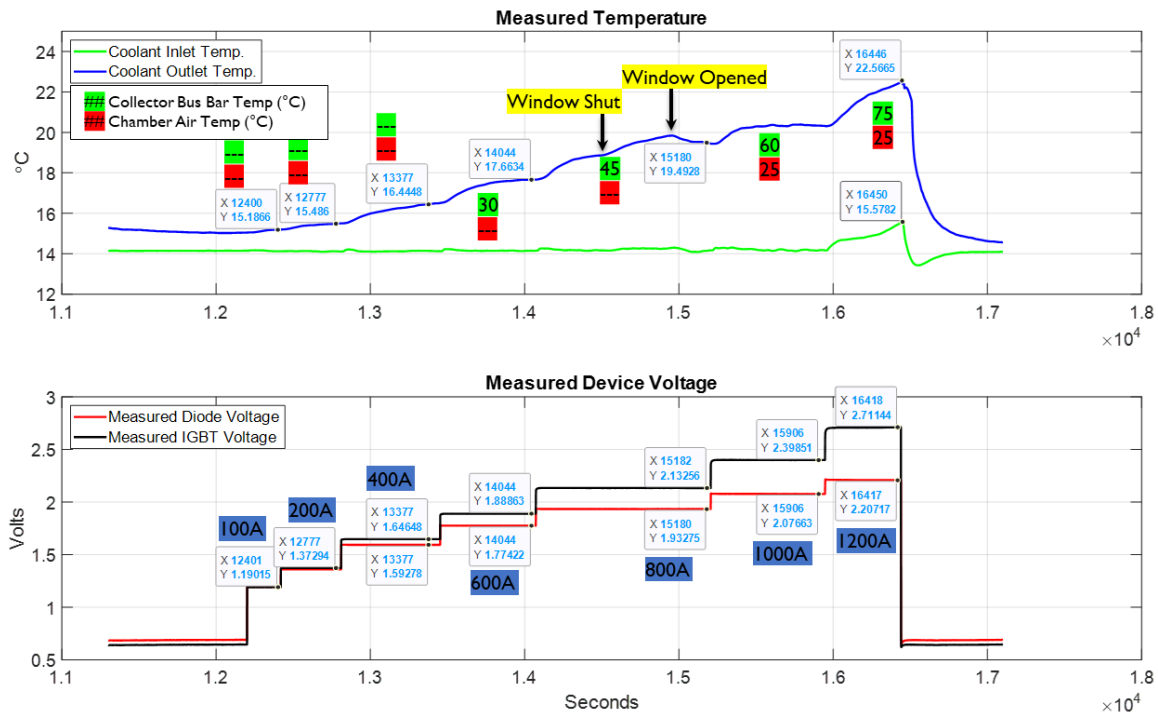


Figure 74. Detailed Thermal Test Data; 35 000 ft

Table 15. Voltage Drop and Dissipation Data; 35 000 ft

Current (A)	Magna Terminal Voltage (V)	Chamber Device Voltage Drop (V)	Chamber Total Voltage Drop (V)	Chamber Device Loss (W)	Chamber Copper Loss (W)	Total Copper Loss (W)
200	2.83	2.732	2.7675	546.4	7.1	19.6
400	3.41	3.239	3.3120	1295.6	29.2	68.4
600	3.93	3.662	3.7730	2197.2	66.6	160.8
800	4.41	4.066	4.2170	3252.8	120.8	275.2
1000	4.92	4.476	4.6730	4476.0	197.0	444.0
1200	5.47	4.916	5.1615	5899.2	294.6	664.8

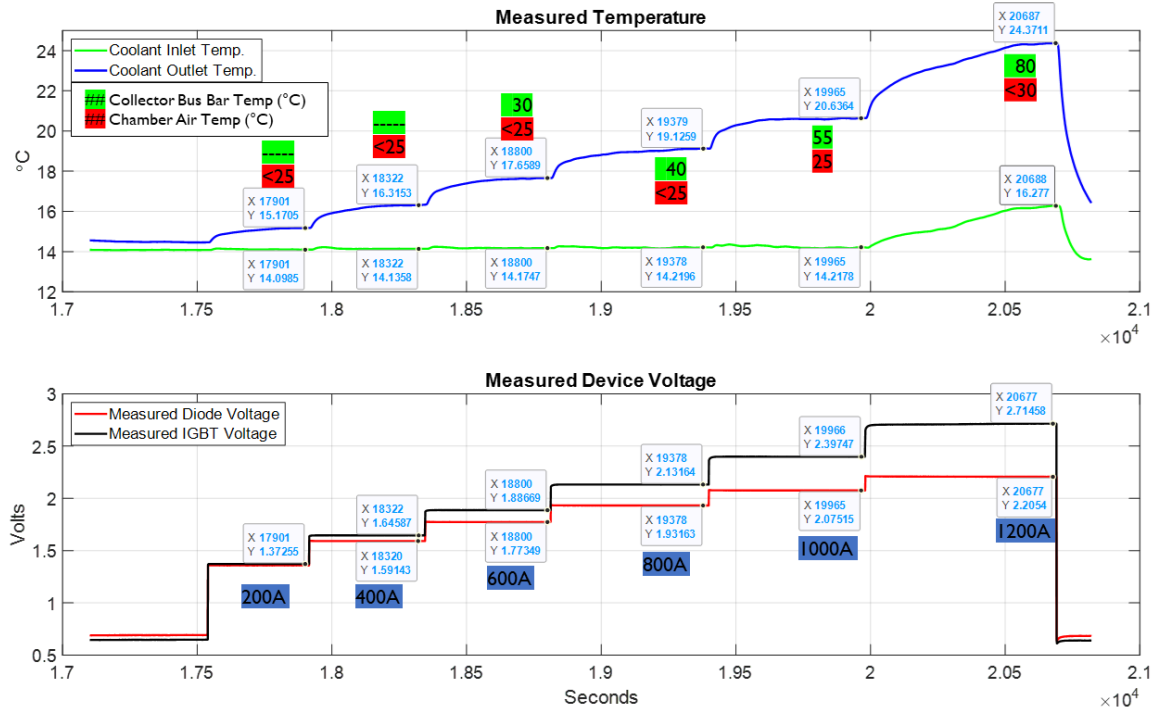


Figure 75. Detailed Thermal Test Data; 51 000 ft

Table 16. Voltage Drop and Dissipation Data; 51 000 ft

Current (A)	Magna Terminal Voltage (V)	Chamber Device Drop (V)	Chamber Total Voltage Drop (V)	Chamber Device Loss (W)	Chamber Copper Loss (W)	Total Copper Loss (W)
200	2.83	2.730	2.7660	546.0	7.2	20.0
400	3.41	3.238	3.3100	1295.2	28.8	68.8
600	3.92	3.660	3.7715	2196.0	66.9	156.0
800	4.41	4.064	4.2140	3251.2	120.0	276.8
1000	4.92	4.474	4.6690	4474.0	195.0	446.0
1200	5.47	4.913	5.1575	5895.6	293.4	668.4

The device conduction voltage drop at a given current is a function of the device temperature, and therefore it can be used as an indirect temperature indicator. In the earlier SSCB development stage, fiber-optic temperature probes were used to directly measure the silicon chip temperature [25]. No such probes were used in the high-altitude

SSCB thermal test. However, the earlier probed data and the device voltage record can confirm that there is no thermal concern for the silicon devices.

Looking at Figure 73 through Figure 75, it is apparent that the flat busbar has a significant time constant. To guarantee that it reached thermal steady state, an extended runtime thermal test was conducted at 500 A and 1000 A, at the simulated altitude of 51 000 ft. The results are shown in Figure 76 and Table 17. The coarse busbar temperature reading provided by the temperature label lacks resolution. No temperature readings for the two vertical busbars were available due to lack of good viewing angles of any attached temperature-indicating label. A solution was devised and detailed in the next subsection.

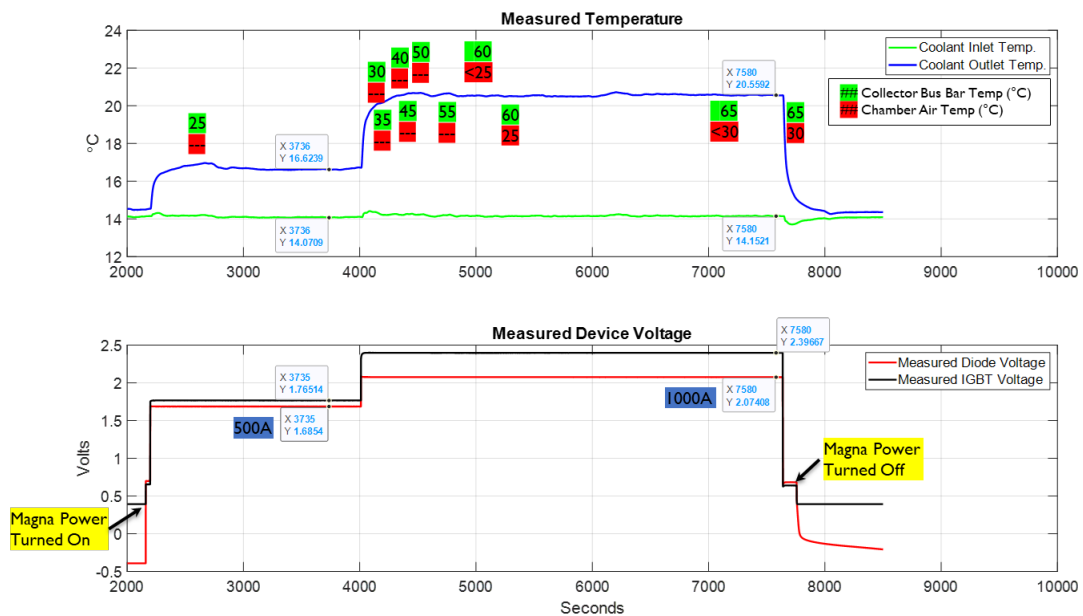


Figure 76. Extended Runtime Thermal Test Record; 51 000 ft

Table 17. Voltage Drop and Dissipation Data, Extended Runtime; 51 000 ft

Current (A)	Magna Terminal Voltage (V)	Chamber Device Drop (V)	Chamber Total Voltage Drop (V)	Chamber Device Loss (W)	Chamber Copper Loss (W)	Total Copper Loss (W)
500	3.67	3.451	3.5415	1725.5	45.3	109.5
1000	4.92	4.474	4.6690	4474.0	195.0	446.0

2. Instrumentation Enhancement for Busbar Temperature Measurement

The behavior of the busbars, which are expected to carry full load current continuously, is one of the focal points in the evaluation of the SSCB thermal performance. There is no active air cooling, and the natural air cooling is very limited considering the SSCB is tightly packaged inside the housing. In this sense, the effect of high altitude is negligible. The conduction cooling paths from the busbars are ambiguous. The vertical busbars could transfer heat to the cable conductors terminated on them if these conductors could maintain a lower operating temperature, but such a cooling path is dependent on the way the SSCB is installed in a system, and typically of limited effect. Conduction cooling via cabling is not applicable to the flat busbar. Another cooling mechanism is the radiative heat transfer. It is nontrivial to accurately quantify this cooling mechanism for the busbars due to intricacies related to the packaging and emissivities of the involved surfaces. However, a rough estimate can be obtained using

$$q = \varepsilon \sigma (T_h^4 - T_a^4) A_h, \quad (1)$$

where q is the radiated power, ε is the emissivity of the busbar surface, σ is the Stefan–Boltzmann constant, T_h is the busbar surface temperature, T_a is the surrounding surface or ambient temperature, and A_h is the busbar surface area. For the flat busbar, assuming T_h and T_a are 80 °C and 20 °C, respectively, the radiated power is estimated to span from 1.1 W with ε at 0.1 to 11.2 W with ε at 1.0. This indicates that thermal radiation is quite limited, even with high emissivity, and likely insufficient to keep the busbar temperature contained.

For improved temperature measurement accuracy, and to allow temperature reading while the cover was installed on the housing, a low-profile thermistor with a ring tongue terminal offered by Vishay / BC Components, shown in Figure 77, was selected. A small hole was drilled and tapped on the busbar for mounting the thermistor. Figure 78 shows the SSCB busbars, each with a thermistor mounted near the center. The thermistor wire leads were attached to a BNC breakout connector, so the BNC feedthroughs could be used to pass the thermistor signals through the chamber wall. These thermistor signals

were then fed into the DAQ system for real time monitoring and data recording. The housing cover was then installed prior to testing, as seen in Figure 79.



Figure 77. Vishay Lug-Type Negative Temperature Coefficient (NTC) Thermistor

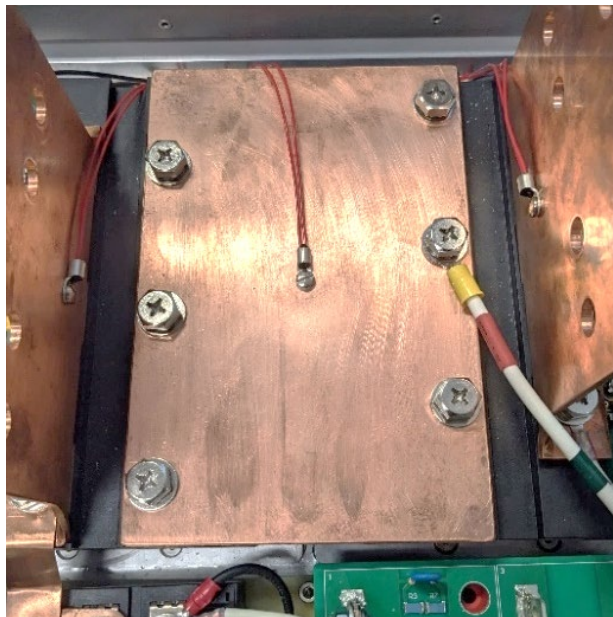


Figure 78. Lug-Type NTC Thermistors Installed for Busbar Temperature Measurement

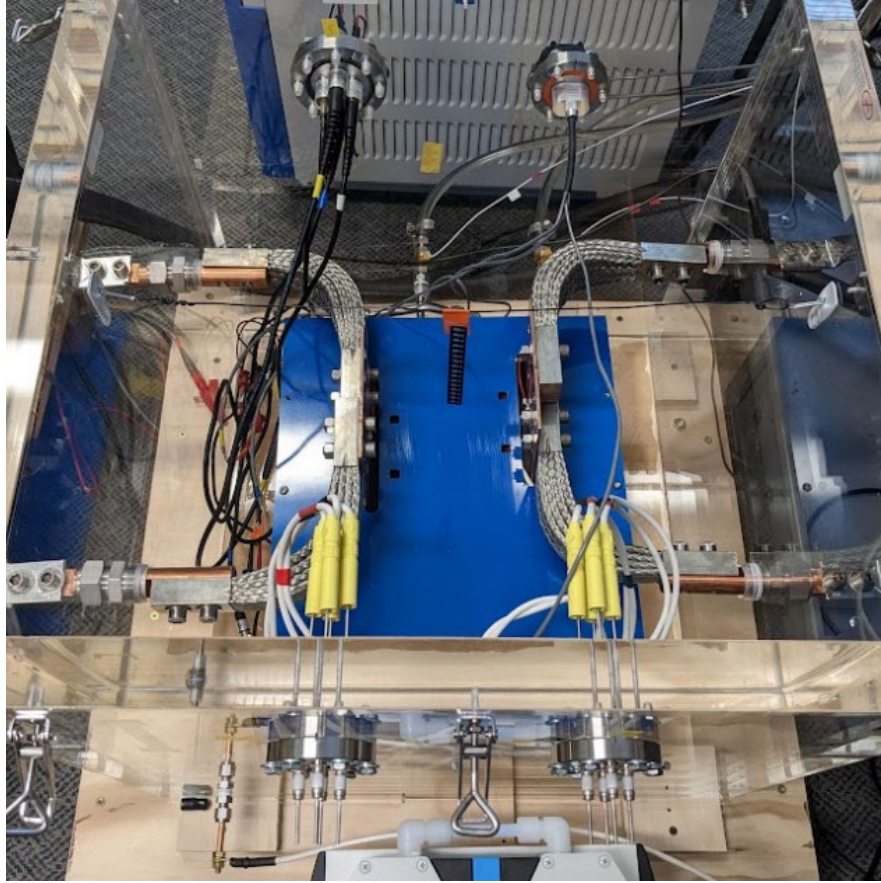


Figure 79. Housing Cover Installed for Thermal Testing

The thermal test was then performed again with the thermistors installed in the busbars and the top cover placed on the housing. Figure 80 presents the recorded data at sea level. It is noted that the chiller could not keep the cold plate inlet temperature at 15 °C when the load current was increased to 1200 A, which was also the case in earlier testing as shown in Figure 72. This indicates that IGBT dissipation at 1200 A exceeds the thermal capacity of the chiller when the chiller setting is kept at 15 °C and 3 gal/min. It is also apparent that the busbar has a thermal time constant longer than the time, which was approximately 15 min, allocated for each current step.

Figure 81 and Figure 82 present the thermal test results at 35 000 ft and 51 000 ft, respectively, with other test conditions maintained the same as those at sea level. Comparing these records, there was no noticeable change in the thermal and electrical profiles.

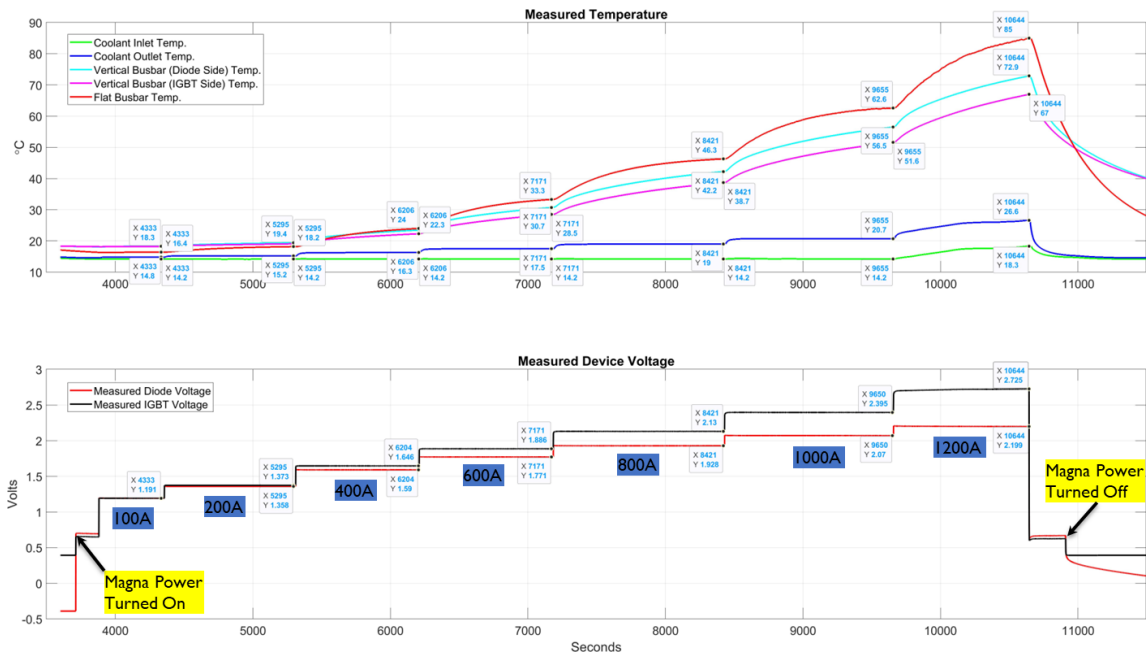


Figure 80. Thermal Test Record with Lug-Type Thermistors; Sea Level

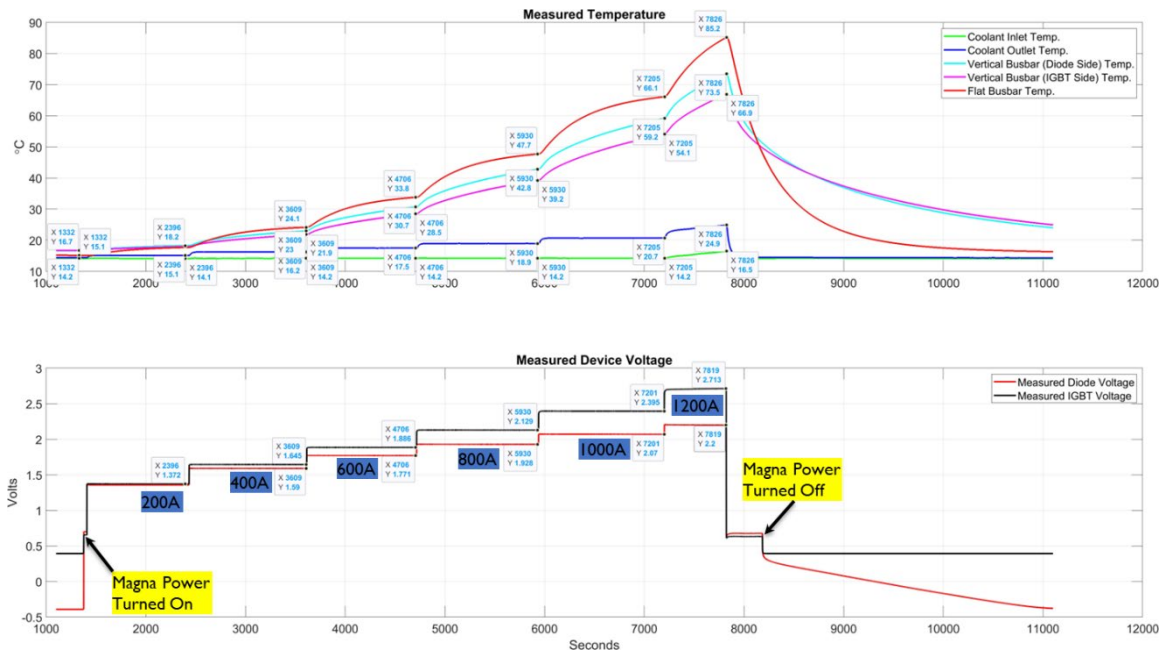


Figure 81. Thermal Test Record with Lug-Type Thermistors; 35 000 ft

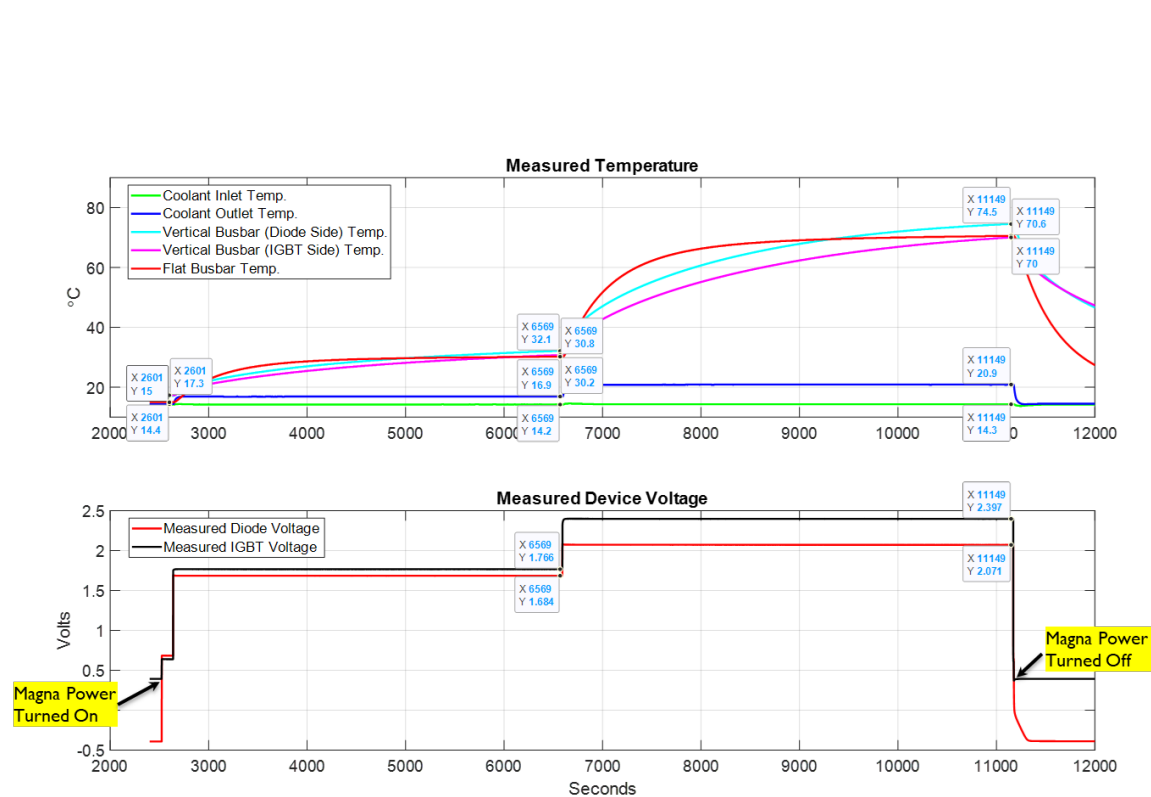


Figure 83. Extended Runtime Thermal Test Record with Lug-Type Thermistors; 51 000 ft

Table 18. Detailed Thermal Data for Extended Runtime; 51 000 ft

I_{Load} (A)	V_{Magna} (V)	$V_{Chamber}$ (V)	V_{Busbar} (V)	V_{Device} (V)	P_{Cable} (W)	P_{Copper} (W)	P_{Busbar} (W)	P_{Device} (W)	η_{SSCB} (%)
500	3.67	3.545	3.527	3.451	63	9	38	1726	99.65
1000	4.94	4.680	4.638	4.468	260	42	170	4468	99.54

I_{Load} : Load current

V_{Magna} : Voltage measured at the Magna power supply output terminals

$V_{Chamber}$: Voltage measured across the vacuum chamber HC feedthroughs

V_{Busbar} : Voltage measured across the copper braid termination points in the two vertical busbars

V_{Device} : Sum of the voltages measured at the Kelvin terminals in both IGBT modules

P_{Cable} : Dissipation incurred in the cables between the power supply and vacuum chamber

P_{Copper} : Dissipation incurred in the copper braid and HC feedthroughs

P_{Busbar} : Dissipation incurred in the copper busbars

P_{Device} : Dissipation incurred in the silicon devices in the IGBT modules

η_{SSCB} : Efficiency of complete installation in the dc system, accounting for a full two-pole SSCB

The dominant portion of the SSCB loss is incurred in the silicon devices in the IGBT power modules. The silicon devices are actively cooled via the cold plate, and their junction temperatures are maintained in the safe operating region with a comfortable margin, as can be seen from their conduction voltage drops. The dissipation in the busbars, both inside and outside the IGBT modules, is insignificant compared to the device dissipation. However, the busbar dissipation is much higher than what can be handled by radiative thermal transfer while maintaining a reasonable busbar temperature. On the other hand, the busbar profiles indicate that the temperatures of both the vertical emitter busbars and the flat collector busbar were well contained even at a steady current flow of 1000 A. The flat busbar temperature reached steady state in about 40 minutes, while the vertical busbars temperatures still appeared to rise at a very slow rate. It is noted that the vertical busbars were connected to the heavy copper braids, copper rods, and power cables. As a result, the aggregate copper mass is much higher compared with the flat busbar, which could be the major reason why the vertical busbars appeared to have a larger thermal time constant. Although the flat busbar lacked the thermal conduction path of the vertical busbars, it did not experience unacceptable temperature rise, even though the dissipation was much higher than the radiated heat. There must be an additional thermal path which facilitates the thermal transfer.

The IGBT module internal layout, shown in Figure 84, provides the clue to this path for thermal transfer. The IGBT internal copper busbar terminals are bonded to the direct bond copper (DBC) substrate using ultrasonic welding technology. Figure 85 presents a photograph zoomed in on an example of an ultrasonically welded busbar terminal. Unlike wire bonding, this type of welded contact results in direct attachment of the busbar terminals to the DBC, allowing an effective conduction cooling path from the busbar to the baseplate, similar to that of the silicon chips. The actively cooled cold plate can sink the heat from the external busbar as well as the internal busbar. This cooling mechanism explains the observed busbar temperature profiles. Note that the flat busbar is bolted to IGBT power terminals on both ends, while only one end of each vertical busbar is terminated at the IGBT module. As a result, the flat busbar has twice the thermal

conduction area to the DBC substrate, or half of the thermal resistance. Therefore, the flat busbar can be more effectively cooled, as apparent in the recorded temperature profile.



Figure 84. Infineon IHM/IHV B Module Package and Internal Layout.
Source: [46].

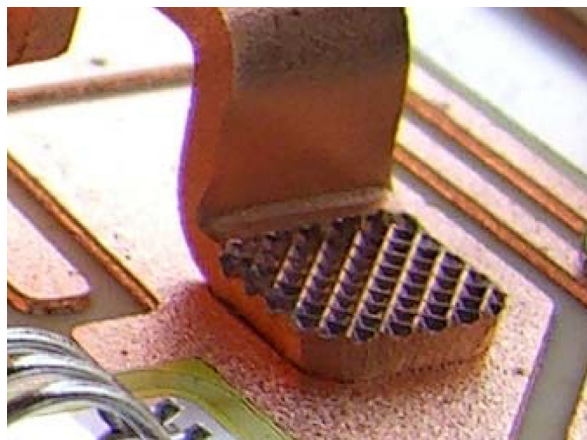


Figure 85. Copper Terminal Bonding Using Ultrasonic Welding.
Source: [47].

The vertical busbar temperature profiles shown in Figure 83 also led to questions such as whether the dissipation was higher due to too much contact resistance at the power terminals with the bolts insufficiently torqued. To eliminate this possibility, all the bolts were torqued to 9 N·m, per the IGBT power terminal connection torque specification of 8–10 N·m. Another extended thermal run was conducted at a simulated altitude of 51 000 ft, and the results are shown in Figure 86 and Table 19. It is interesting to compare the temperature profiles in Figure 83 and Figure 86. With all the power terminals torqued to 9 N·m, the busbar temperatures decreased by about 10–15 °C. In addition, the vertical busbars appeared to approach thermal steady state faster. The data in Table 19 also confirm that there is reduction in dissipation incurred in the copper busbars.

To further verify that the thermal conduction path from the busbars to the actively cooled cold plated is the dominant cooling mechanism, the coolant temperature at the cold plate inlet was increased by 10 °C to 25 °C and a thermal run at 1000 A was conducted. As shown in Figure 86, the flat busbar temperature settled down at about 10 °C higher at 71 °C. The vertical busbar temperatures were about 6 °C higher. These results confirm that the active cooling via the heat conduction to the cold plate is the only dominant cooling mechanism for the flat busbar. The vertical busbars, on the other hand, are cooled by heat conduction to both the cold plate and the copper conductors and cabling attached to busbar, and their cooling is not totally dependent on the coolant temperature. It is also worth noting that with higher coolant temperature, the IGBT chip voltage drop increased, while the freewheeling diode chip voltage drop decreased. Both changes are as expected, since the IGBT and diode chips have positive and negative temperature coefficients, respectively, in the full load range of the SSCB.

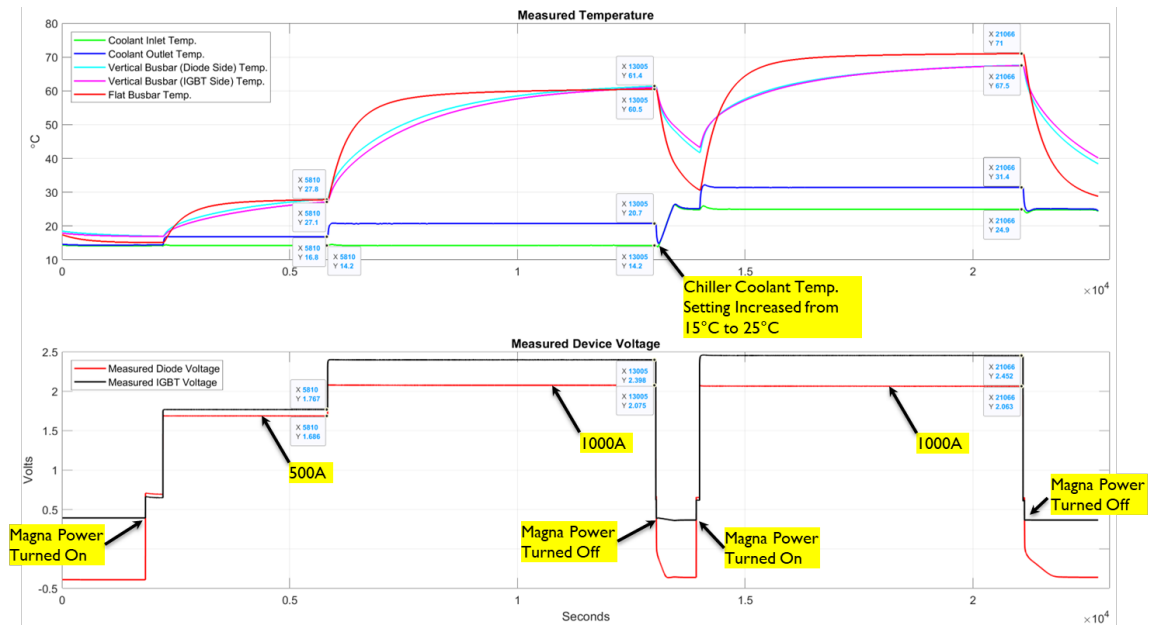


Figure 86. Extended Runtime Thermal Test Record with Lug-Type Thermistors; Busbar Bolts Torqued to 9 N·m; 51 000 ft

Table 19. Detailed Thermal Data for Extended Runtime; Busbar Bolts Torqued to 9 N·m; 51 000 ft

I_{Load} (A)	V_{Magna} (V)	$V_{Chamber}$ (V)	V_{Busbar} (V)	V_{Device} (V)	P_{Cable} (W)	P_{Copper} (W)	P_{Busbar} (W)	P_{Device} (W)	η_{SSCB} (%)
500	3.65	3.527	3.515	3.453	62	6	31	1727	99.65
1000	4.89	4.636	4.609	4.473	254	27	136	4473	99.54
1000*	4.94	4.683	4.655	4.517	257	28	138	4517	99.53

*: This test point was conducted with the cold plate inlet temperature set at 25 °C.

Although the thermal test results so far indicate quite convincingly that the radiative thermal transfer does not play any significant role in the cooling of the SSCB, an additional test was conducted to evaluate the effect of heat radiation. The flat copper busbar was polished and then painted with black paint to obtain a high surface emissivity. Figure 87 shows the SSCB with the painted flat busbar installed. The thermal run results are presented in Figure 88 and Table 20. There was no noticeable difference in temperature profiles and dissipations. These results confirm that the effect of the radiative heat transfer can be safely ignored in the evaluation and prediction of SSCB thermal performance.

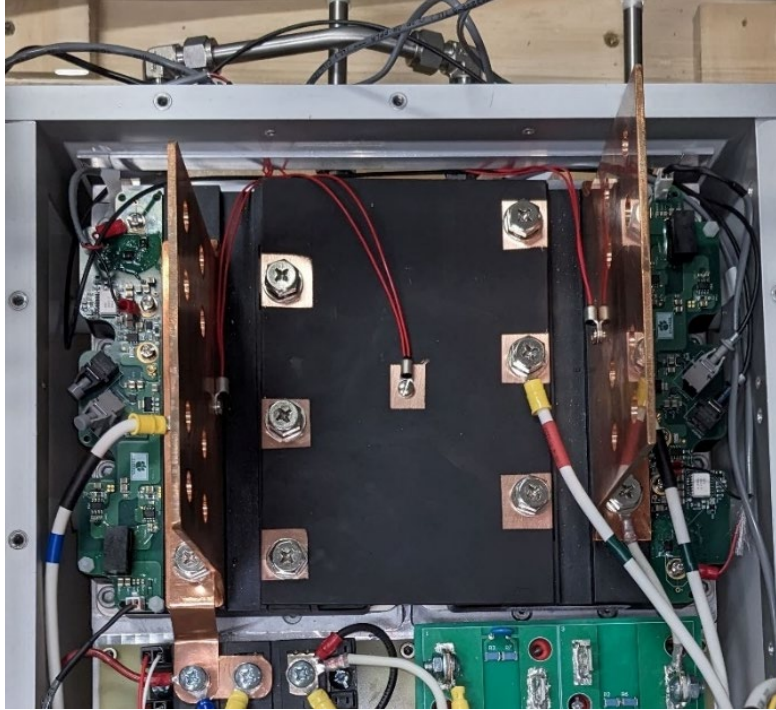


Figure 87. Flat Busbar Painted Black

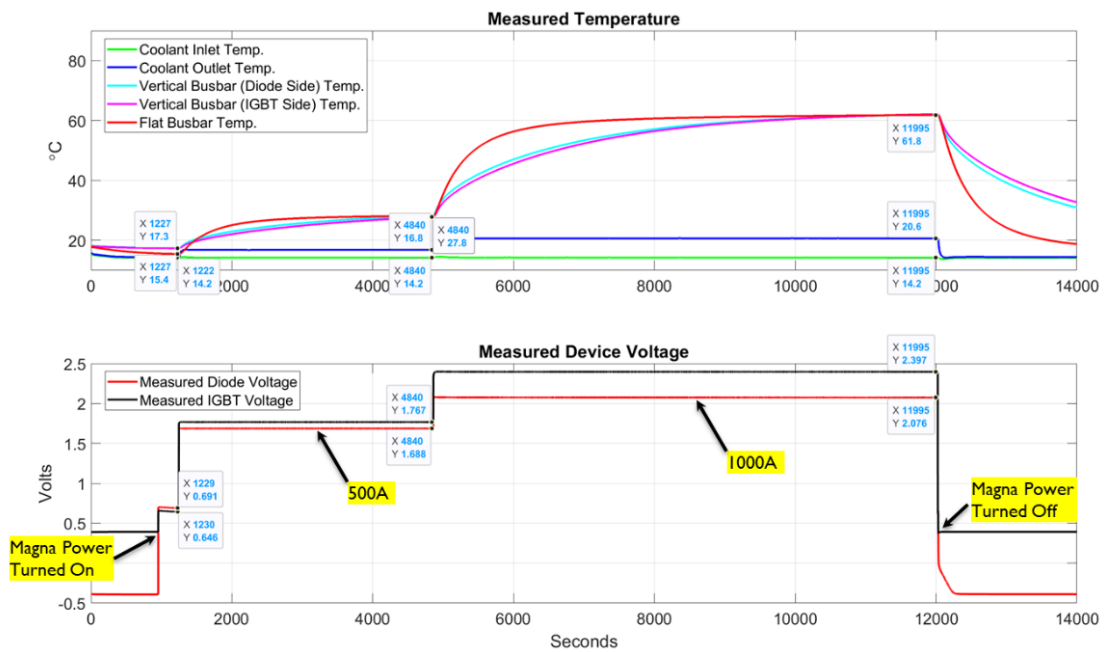


Figure 88. Extended Runtime Thermal Test Record with Flat Busbar Painted Black; 51 000 ft

Table 20. Detailed Thermal Data for Extended Runtime with Flat Busbar
Painted Black; 51 000 ft

I_{Load} (A)	V_{Magna} (V)	V_{Chamber} (V)	V_{Busbar} (V)	V_{Device} (V)	P_{Cable} (W)	P_{Copper} (W)	P_{Busbar} (W)	P_{Device} (W)	η_{SSCB} (%)
500	3.65	3.530	3.516	3.454	60	7	31	1727	99.65
1000	4.90	4.640	4.610	4.473	260	30	137	4473	99.54

C. CONCLUSIONS ON SSCB THERMAL PERFORMANCE

This chapter focused on the thermal testing of the SSCB prototype in high-altitude conditions to evaluate its steady state performance in the specified load range, including the component temperature rise and operating efficiency. The thermal test setup and instrumentation were described. The thermal test execution was presented with comprehensive test data.

The thermal test meticulously conducted incrementally from sea level to the target altitude of 51 000 ft confirms that the SSCB prototype can perform satisfactorily in high-altitude operating conditions. In fact, the SSCB thermal behavior did not show any noticeable dependence on the altitude. As expected, the actively cooled semiconductor devices in the IGBT modules maintained consistent performance in all the testing conditions, from sea level to 51 000 ft altitude. The copper busbars were a major focus of the thermal evaluation due to their ambiguous thermal interface with the working environment. Temperature-indicating labels were used during the initial test for coarse busbar temperature readings. In the later tests, lug-type thermistors were installed on the busbars for accurate temperature measurement. The test results confirmed that the temperatures of the busbars were well contained and changed little with the altitude. The cooling mechanisms of the busbars were analyzed. It was identified that thermal conduction to the actively cooled cold plate is the dominant cooling mechanism for the busbars.

The thermal test validates the SSCB thermal design. The low dependence of the SSCB thermal performance on the altitude it operates at translates to high reliability and robust thermal performance.

THIS PAGE INTENTIONALLY LEFT BLANK

V. SUMMARY AND FUTURE WORK

A. SUMMARY

The objective of this thesis was to test and validate the design and performance of an SSCB prototype in a simulated high-altitude environment. The SSCB was installed in a vacuum chamber with custom feedthroughs for power, signals, instrumentation, and cooling. Switching tests were conducted from sea level up to 51 000 ft, exceeding the 35 000 ft minimum project requirement. The switching tests were successful, with no flashover or insulation degradation observed, thus validating the insulation design.

Short-circuit testing revealed asymmetric SSCB behavior caused by the interaction between the current flowing through the busbars and the gate drive loop. This asymmetry was resolved by placing the snubber branch in a diagonal position across the SSCB, such that the snubber termination points are at the opposite ends of the IGBTs as the gate terminals.

The thermal performance of the SSCB was evaluated next. The SSCB was installed in the chamber and connected to the coolant loop. Testing was conducted from sea level up through 51 000 ft, again exceeding the 35 000 ft minimum project requirement. Results showed very little difference between the sea level and 51 000 ft tests, indicating that the thermal performance is not meaningfully dependent on altitude.

B. FUTURE WORK

While this thesis exhaustively proved the current SSCB prototype meets the specified design and performance requirements, a relatively small number of testing cycles were performed. To fully validate the design, a reliability study needs to be conducted to verify that all individual components, and the SSCB as a whole, will maintain satisfactory performance for the desired life cycle.

Additionally, while the current prototype successfully and repeatedly protects the load during faults, there is still an issue that needs resolved. At voltages above 1800 V, the MOV leakage current is greater than the SCR holding current. Further testing needs

to be conducted to identify a suitable SCR replacement that has a holding current greater than the MOV leakage current at 2000 V.

To ensure symmetrical SSCB operation, the results of the snubber branch placement research conducted during the benchtop switching tests need to be used to incorporate layout improvements for future SSCB prototype and housing iterations. Also, several functional SSCB design changes should be considered to improve ease of installation and maintenance, including:

- The fiber optic transmitter and receiver modules on the gate drive boards should be switched to 30° tilted packages and installed at 30° relative to the length-axis of the PCB. These modules should all be oriented toward the control board if feasible. If the modules are able to be oriented as such, the left and right sides of the control board will each need one transmit/receive module pair facing up, and another pair facing down. These changes will make it easier to insert the connectors into the terminals, increase the bending radius of the installed cables, and reduce clutter in the housing by allowing a shorter cable length.
- Permanent nuts, studs, and/or clamps should be incorporated into the G-10 mounting plate for the SCR, eMOV PCB, snubber capacitor, and possibly the MOV, depending on its future location, to facilitate the replacement of the individual components in situ vice removing the entire mounting plate.
- Solder permanent copper spacers onto the gate drive board terminals for easier mounting onto the IGBT Kelvin terminals.

LIST OF REFERENCES

- [1] E. Rodriguez-Diaz, M. Savaghebi, J. C. Vasquez, and J. M. Guerrero, “An overview of low voltage dc distribution systems for residential applications,” in *2015 IEEE 5th International Conference on Consumer Electronics - Berlin (ICCE-Berlin)*, 2015 [Online]. Available: <https://doi.org/10.1109/ICCE-Berlin.2015.7391268>
- [2] S. Rivera, R. Lizana F., S. Kouro, T. Dragičević, and B. Wu, “Bipolar dc power conversion: state-of-the-art and emerging technologies,” *IEEE Trans. Emerg. Sel. Top. Power Electron.*, vol. 9, no. 2, pp. 1192–1204, Apr. 2021 [Online]. Available: <https://doi.org/10.1109/JESTPE.2020.2980994>
- [3] C. Zhan, C. Smith, A. Crane, A. Bullock, and D. Grieve, “dc transmission and distribution system for a large offshore wind farm,” in *9th IET International Conference on ac and dc Power Transmission (ACDC 2010)*, 2010 [Online]. Available: <https://doi.org/10.1049/cp.2010.0981>
- [4] H. A. B. Siddique and R. W. De Doncker, “Evaluation of dc collector-grid configurations for large photovoltaic parks,” *IEEE Trans. Power Del.*, vol. 33, no. 1, pp. 311–320, Feb. 2018 [Online]. Available: <https://doi.org/10.1109/TPWRD.2017.2702018>
- [5] M. Stieneker and R. W. De Doncker, “Medium-voltage dc distribution grids in urban areas,” in *2016 IEEE 7th International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, 2016 [Online]. Available: <https://doi.org/10.1109/PEDG.2016.7527045>
- [6] H. Schefer, L. Fauth, T. H. Kopp, R. Mallwitz, J. Friebe, and M. Kurrat, “Discussion on electric power supply systems for all electric aircraft,” *IEEE Access*, vol. 8, pp. 84188–84216, 2020 [Online]. Available: <https://doi.org/10.1109/ACCESS.2020.2991804>
- [7] A. Barzkar and M. Ghassemi, “Electric power systems in more and all electric aircraft: a review,” *IEEE Access*, vol. 8, pp. 169314–169332, 2020 [Online]. Available: <https://doi.org/10.1109/ACCESS.2020.3024168>
- [8] T. C. Cano *et al.*, “Future of electrical aircraft energy power systems: an architecture review,” *IEEE Trans. Transp. Electrif.*, vol. 7, no. 3, pp. 1915–1929, Sep. 2021 [Online]. Available: <https://doi.org/10.1109/TTE.2021.3052106>
- [9] M. Ghassemi, A. Barzkar, and M. Saghaei, “All-electric NASA N3-X aircraft electric power systems,” *IEEE Trans. Transp. Electrif.*, vol. 8, no. 4, pp. 4091–4104, Dec. 2022 [Online]. Available: <https://doi.org/10.1109/TTE.2022.3158186>

- [10] Z. Jin, G. Sulligoi, R. Cuzner, L. Meng, J. C. Vasquez, and J. M. Guerrero, "Next-generation shipboard dc power system: introduction smart grid and dc microgrid technologies into maritime electrical networks," *IEEE Electr. Mag.*, vol. 4, no. 2, pp. 45–57, Jun. 2016 [Online]. Available: <https://doi.org/10.1109/MELE.2016.2544203>
- [11] A. Tassarolo, S. Castellan, R. Menis, and G. Sulligoi, "Electric generation technologies for all-electric ships with medium-voltage dc power distribution systems," in *2013 IEEE Electric Ship Technologies Symposium (ESTS)*, 2013 [Online]. Available: <https://doi.org/10.1109/ESTS.2013.6523746>
- [12] K. Satpathi, V. M. Balijepalli, and A. Ukil, "Modeling and real-time scheduling of dc platform supply vessel for fuel efficient operation," *IEEE Trans. Transp. Electr.*, vol. 3, no. 3, pp. 762–778, Sep. 2017 [Online]. Available: <https://doi.org/10.1109/TTE.2017.2744180>
- [13] H. Mahdi, B. Hoff, and T. Østrem, "A review of power converters for ships electrification," *IEEE Trans. Power Electron.*, vol. 38, no. 4, pp. 4680–4697, Apr. 2023 [Online]. Available: <https://doi.org/10.1109/TPEL.2022.3227398>
- [14] S. Zheng, R. Kheirollahi, J. Pan, L. Xue, J. Wang, and F. Lu, "DC circuit breakers: A technology development status survey," *IEEE Trans. Smart Grid*, vol. 13, no. 5, pp. 3915–3928, Sep. 2022 [Online]. Available: <https://doi.org/10.1109/TSG.2021.3123538>
- [15] N. Doerry and J. V. Amy, "System inductance for MVDC circuit breakers," in *2021 IEEE Electric Ship Technologies Symposium (ESTS)*, 2021 [Online]. Available: <https://doi.org/10.1109/ESTS49166.2021.9512350>
- [16] F. Mohammadi *et al.*, "HVDC circuit breakers: a comprehensive review," *IEEE Trans. Power Electron.*, vol. 36, no. 12, pp. 13726–13739, Dec. 2021 [Online]. Available: <https://doi.org/10.1109/TPEL.2021.3073895>
- [17] L. Liljestr nd, M. Backman, L. Jonsson, E. Dullni, and M. Riva, "Medium voltage dc vacuum circuit breaker," in *2015 3rd International Conference on Electric Power Equipment – Switching Technology (ICEPE-ST)*, 2015 [Online]. Available: <https://doi.org/10.1109/ICEPE-ST.2015.7368340>
- [18] A. Shukla and G. D. Demetriades, "A survey on hybrid circuit-breaker topologies," *IEEE Trans. Power Del.*, vol. 30, no. 2, pp. 627–641, Apr. 2015 [Online]. Available: <https://doi.org/10.1109/TPWRD.2014.2331696>
- [19] J. M. Meyer and A. Rufer, "A dc hybrid circuit breaker with ultra-fast contact opening and integrated gate-commutated thyristors (IGCTs)," *IEEE Trans. Power Del.*, vol. 21, no. 2, pp. 646–651, Apr. 2006 [Online]. Available: <https://doi.org/10.1109/TPWRD.2006.870981>

- [20] R. Rodrigues, Y. Du, A. Antoniazzi, and P. Cairoli, “A review of solid-state circuit breakers,” *IEEE Trans. Power Electron.*, vol. 36, no. 1, pp. 364–377, Jan. 2021 [Online]. Available: <https://doi.org/10.1109/TPEL.2020.3003358>
- [21] L. Qi *et al.*, “Solid-state circuit breaker protection for dc shipboard power systems: breaker design, protection scheme, validation testing,” *IEEE Trans. Ind. Appl.*, vol. 56, no. 2, pp. 952–960, Mar. 2020 [Online]. Available: <https://doi.org/10.1109/TIA.2019.2962762>
- [22] D. Zhang, “Fast light-weight altitude-ready solid-state circuit breaker for hybrid electric propulsion (FLASH),” National Aeronautics and Space Administration (NASA) Glenn Research Center, 2019.
- [23] L. Ravi, D. Zhang, D. Qin, Z. Zhang, Y. Xu, and D. Dong, “Electronic MOV-based voltage clamping circuit for dc solid-state circuit breaker applications,” *IEEE Trans. Power Electron.*, vol. 37, no. 7, pp. 7561–7565, Jul. 2022 [Online]. Available: <https://doi.org/10.1109/TPEL.2022.3149757>
- [24] D. Zhang, Y. Xu, J. Brandt, Z. Zhang, D. Qin, and D. Dong, “A solid-state circuit breaker without current limiting inductor,” in *2022 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2022 [Online]. Available: <https://doi.org/10.1109/ECCE50734.2022.9948197>
- [25] J. J. Brandt, “Medium voltage dc solid state circuit breaker bench test,” M.S. thesis, Dept. of Electr. and Comput. Eng., NPS, Monterey, CA, USA, 2022 [Online]. Available: <https://hdl.handle.net/10945/71047>
- [26] I. Cotton, R. Gardner, D. Schweickart, D. Grosean, and C. Severns, “Design considerations for higher electrical power system voltages in aerospace vehicles,” in *2016 IEEE International Power Modulator and High Voltage Conference (IPMHVC)*, 2016 [Online]. Available: <https://doi.org/10.1109/IPMHVC.2016.8012771>
- [27] I. Cotton, A. Nelms, and M. Husband, “Higher voltage aircraft power systems,” *IEEE Aerosp. Electron. Syst. Mag.*, vol. 23, no. 2, pp. 25–32, Feb. 2008 [Online]. Available: <https://doi.org/10.1109/MAES.2008.4460728>
- [28] T. Shahsavarian, D. Zhang, P. McGinnis, S. Walker, Z. Zhang, and Y. Cao, “Altitude readiness of high-voltage igbts subjected to the partial discharge at harsh environmental conditions for hybrid electric aircraft propulsion,” *IEEE Trans. Power Electron.*, vol. 37, no. 4, pp. 3733–3736, Apr. 2022 [Online]. Available: <https://doi.org/10.1109/TPEL.2021.3123462>
- [29] A. Azizi, M. Ghassemi, and J. M. Lehr, “Heat transfer challenges for MVDC power cables used in wide body all electric aircraft under low pressures,” *IEEE Access*, vol. 10, pp. 111811–111819, 2022 [Online]. Available: <https://doi.org/10.1109/ACCESS.2022.3216300>

- [30] C.-W. Chang, X. Zhao, R. Phukan, D. Dong, R. Burgos, and A. PLAT, “Weight-minimizing optimization of microchannel cold plate for SiC-based power inverters in More-Electric Aircraft,” in *2022 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2022 [Online]. Available: <https://doi.org/10.1109/ECCE50734.2022.9947530>
- [31] L. Buller and B. McNelis, “Effects of radiation on enhanced electronic cooling,” *IEEE Trans. Compon. Packag. Manuf. Technol.*, vol. 11, no. 4, pp. 538–544, Dec. 1988 [Online]. Available: <https://doi.org/10.1109/33.16695>
- [32] A. Boglietti, A. Cavagnino, M. Parvis, and A. Vallan, “Evaluation of radiation thermal resistances in industrial motors,” *IEEE Trans. Ind. Appl.*, vol. 42, no. 3, pp. 688–693, May 2006 [Online]. Available: <https://doi.org/10.1109/TIA.2006.873655>
- [33] National Aeronautics and Space Administration, “World’s largest vacuum chamber,” March 20, 2015 [Online]. Available: <https://www1.grc.nasa.gov/facilities/sec/#:~:text=The%20SEC%20Vacuum%20Chamber%2C%20known,sid e%20leading%20to%20high%20bays>
- [34] Terra Universal, *Vacuum chambers*, 1800-60, 2021 [Online]. Available: https://www.terrauniversal.com/media/asset-library/1/8/1800-60-vacuum_chambers_manual.pdf
- [35] Swagelok, *Gaugeable tube fittings and adapter fittings*, MS-01-140, 2023 [Online]. Available: <https://www.swagelok.com/downloads/webcatalogs/en/ms-01-140.pdf>
- [36] Solid Sealing Technology, “0.094 conductor diameter 4 pin 5kV 28 amp molybdenum conductor in a CF2.75.” Accessed: May 02, 2023 [Online]. Available: <http://www.solidsealing.com/products/1249/0-094-Conductor-Diameter-4-Pin-5kV-28-Amp-Molybdenum-Conductor-in-a-CF2-75/>
- [37] Solid Sealing Technology, “High voltage air side plug, 48 inch cable, 0.094 diameter silver plated contact, 20kV, 30 amp.” Accessed: May 02, 2023 [Online]. Available: <http://www.solidsealing.com/products/239/High-Voltage-Air-Side-Plug-48-inch-Cable-0-094-Diameter-Silver-Plated-Contact-20kV-30-Amp/>
- [38] Solid Sealing Technology, “BNC grounded shield recessed 500V 3.6 amp 4 each in a CF3.375 flange with plug.” Accessed: May 04, 2023 [Online]. Available: <http://www.solidsealing.com/products/635/BNC-Grounded-Shield-Recessed-500V-3-6-Amp-4-each-in-a-CF3-375-Flange-With-Plug/>

- [39] Solid Sealing Technology, “9 pin sub D 24308 series 500V 5 amp 0.040 stn. stl. gold plated conductor in a CF2.75 without plug.” Accessed: May 04, 2023 [Online]. Available: <http://www.solidsealing.com/products/1115/9-Pin-Sub-D-24308-Series-500V-5-Amp-0-040-Stn-Stl-Gold-Plated-Conductor-in-a-CF2-75-Without-Plug/>
- [40] KNF, *Laboport diaphragm vacuum pumps*, 2020 [Online]. Available: https://knf.com/fileadmin/Local_files/USA/Downloads/Lab_downloads/datasheets/Datasheet_Lab_Laboport_UN_820FTP_KNF_USA.pdf
- [41] LACO Technologies, *Altitude-pressure conversion table* [Online]. Available: https://lacotech.com/system/resources/attachments/000/000/131/original/altitude_press_conv_table__low.pdf?1480452827
- [42] Dow, *DOWSIL 3-4155 HV dielectric gel*, 11-1276-01 B, 2017 [Online]. Available: <https://www.dow.com/en-us/pdp/dowsil-3-4155-hv-dielectric-gel-kit.02821508z.html#tech-content>
- [43] Berg Engineering, “Check out the Buehler EpoxiCure 2.” Accessed: May 13, 2023 [Online]. Available: <https://www.bergeng.com/product/EpoxiCure-2.html>
- [44] SMC, *Operation manual*, HRX-OM-R005-M, 2020 [Online]. Available: <https://content2.smcetech.com/pdf/manuals/HRX-OM-R005-M.pdf>
- [45] Keysight, “DAQ970A / DAQ973A data acquisition system.” Accessed: May 16, 2023 [Online]. Available: <https://www.keysight.com/us/en/products/modular/data-acquisition-daq/digital-acquisition-benchtop-system/daq970a-data-acquisition-system.html>
- [46] Infineon, *Application and mounting instructions for IHM and IHV modules*, AN2014-12, 2014 [Online]. Available: https://www.infineon.com/dgdl/Infineon-Mounting_Instructions_IHM_IHV-AN-v01_01-EN.pdf?fileId=5546d46255dd933d0155e3176d1177f5
- [47] Y. Nishimura, K. Kido, F. Momose, and T. Goto, “Development of ultrasonic welding for IGBT module structure,” in *2010 22nd International Symposium on Power Semiconductor Devices & IC's (ISPSD)*, 2010 [Online]. Available: <https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5544018>

THIS PAGE INTENTIONALLY LEFT BLANK

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
Ft. Belvoir, Virginia
2. Dudley Knox Library
Naval Postgraduate School
Monterey, California



DUDLEY KNOX LIBRARY

NAVAL POSTGRADUATE SCHOOL

WWW.NPS.EDU

WHERE SCIENCE MEETS THE ART OF WARFARE