



High Voltage Design for a 138 kV Superconducting Fault Current Limiter

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HTS Solutions for a New Dimension in Power
IEEE – CEIDP 2005 Workshop on Cryogenic Dielectrics



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Kasegn Tekletsadik, SuperPower, Inc.

HTS Solutions for a New Dimension in Power

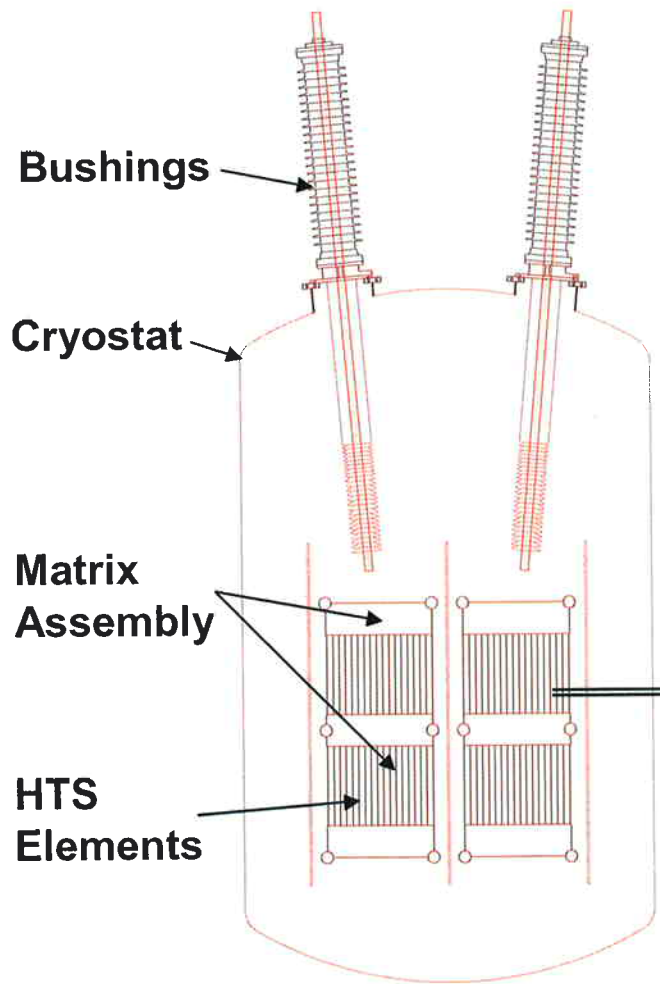
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High Voltage Development - Objectives

Objectives

1. **Build confidence in designing a 138 kV, 650 kV BIL transmission line Fault Current Limiter per AEP requirements**
 - Improve understanding of the dielectric performance of Insulation materials in a cryogenics environment
 - Published information is scarce at transmission line voltage levels
 - Develop experimental test setups and test to voltages higher than device ratings
 - Develop Finite Element Analysis Simulation tools to computed Electric Field Distribution
 - Develop Transfer Function between FEA and test results
 - Develop design tools based on the experimentally verified transfer functions
2. **Identify and Study the Main Insulation Areas**
 - Bushings/Leads
 - Matrix Assembly – Internal Insulation and Impulse Voltage Distribution
 - Bushings/Leads and Matrix Assembly to Cryostat – External Insulation
3. **Design a 138 kV, 650 kV BIL transmission line Fault Current Limiter**

MFCL Design - Main Components



Single Phase of Alpha

High Voltage Insulation System

1. Bushings
2. Cryostat insulation system
3. Matrix internal insulation

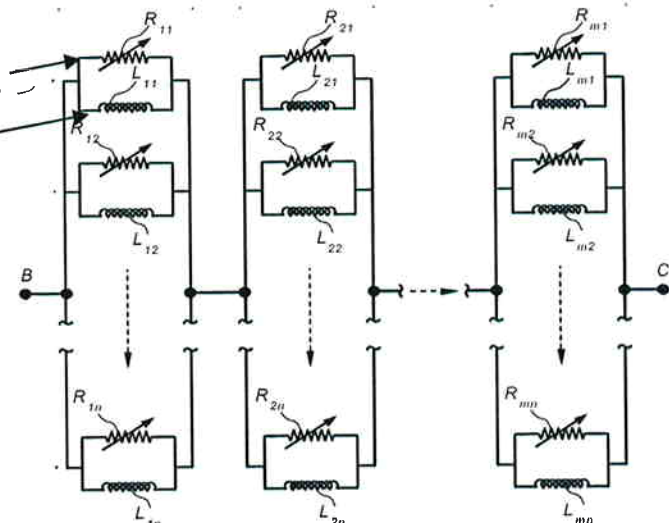
Matrix Assembly

1. HTS Elements
2. Connections of HTS elements and current limiting coils

Cryostat System

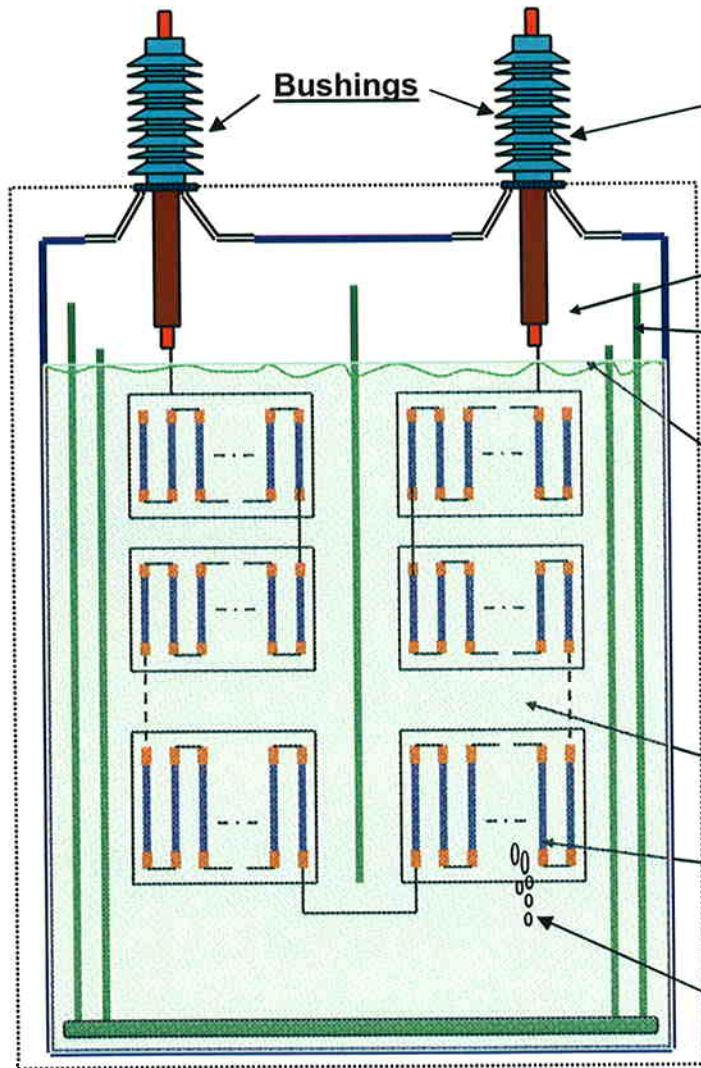
1. Vessels to provide stable pressurized sub-cooled environment
2. Cryogenics and cryo-coolers

HTS Element
Shunt Impedance



Simplified Matrix Assembly Schematic

High Voltage Development – Main Dielectrics



Main Dielectrics

1. Bushings

- Custom bushing using modified conventional bushings
- Special bushing based on HTS Cable terminations

2. Gas Nitrogen (GN2)

- Gas breakdown mechanisms

3. Gas/Solid Composite

- Partial breakdown of gas dielectric
- Puncture strength of solid insulation and
- Surface Flashover

4. Gas/Solid/Liquid (GN2/Solid/LN2) Composite

- Partial breakdown of GN2 and LN2
- Field enhancement and Partitioning
- Puncture strength of solid insulation and
- Surface Flashover

5. Liquid Nitrogen (LN2)

- LN2 breakdown strength

6. Liquid/Solid Composite

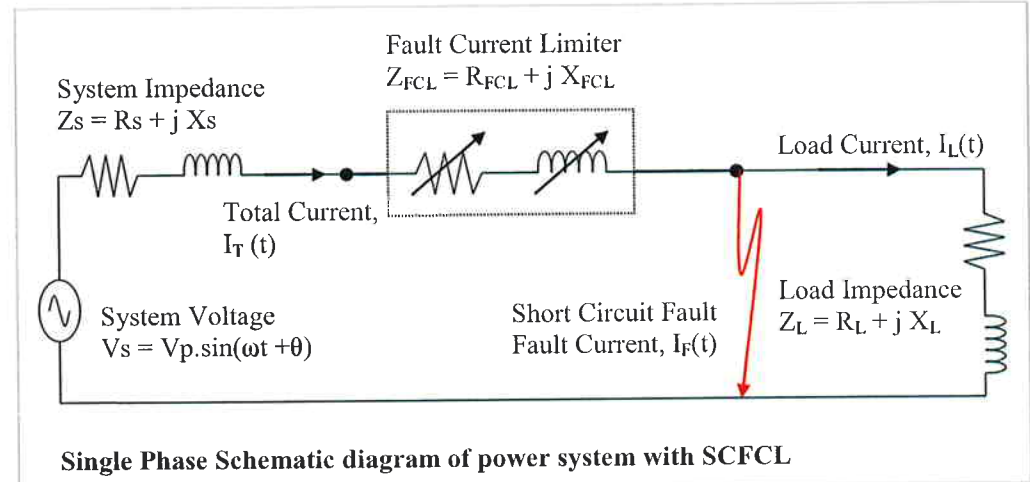
- LN2 partial breakdown and Partial Discharge (PD)
- Solid insulation puncture and Surface flashover

7. Bubble effects

Matrix Fault Current Limiter (MFCL) – An Alternative

New concept with no conventional counterpart:

- Passive - no active controls needed
- No Burden on system during normal operation
- Modular and Scalable
- Environmental benefit

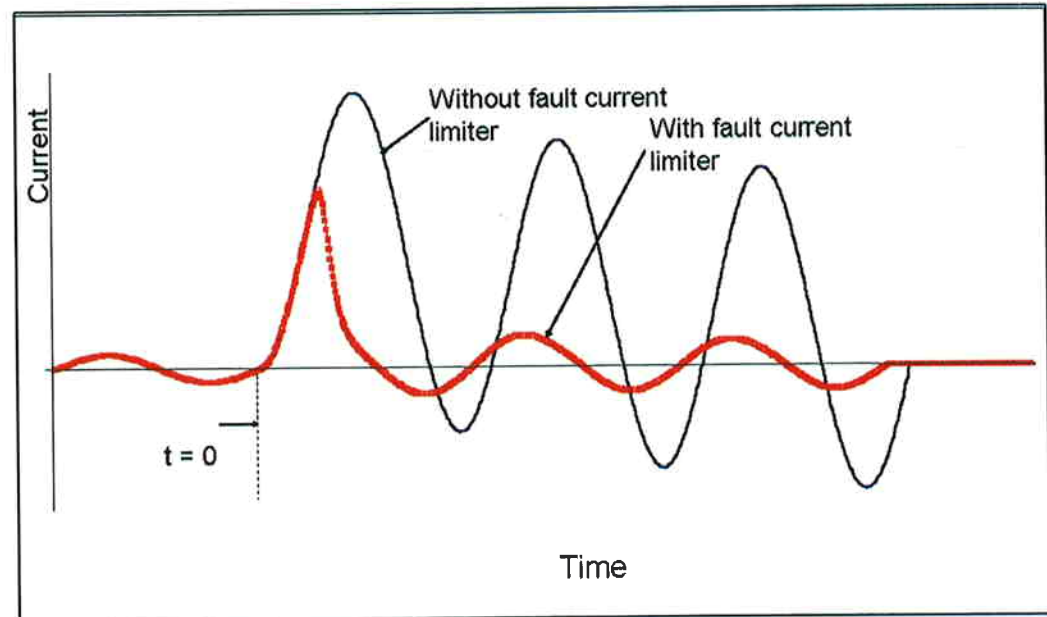


Operating conditions – HV design considerations

- Under normal operating condition
- Under short circuit fault conditions

HV Test Conditions

- AC withstand tests
- PD measurement
- Impulse Tests



Matrix Fault Current Limiter (MFCL) – Operating Conditions

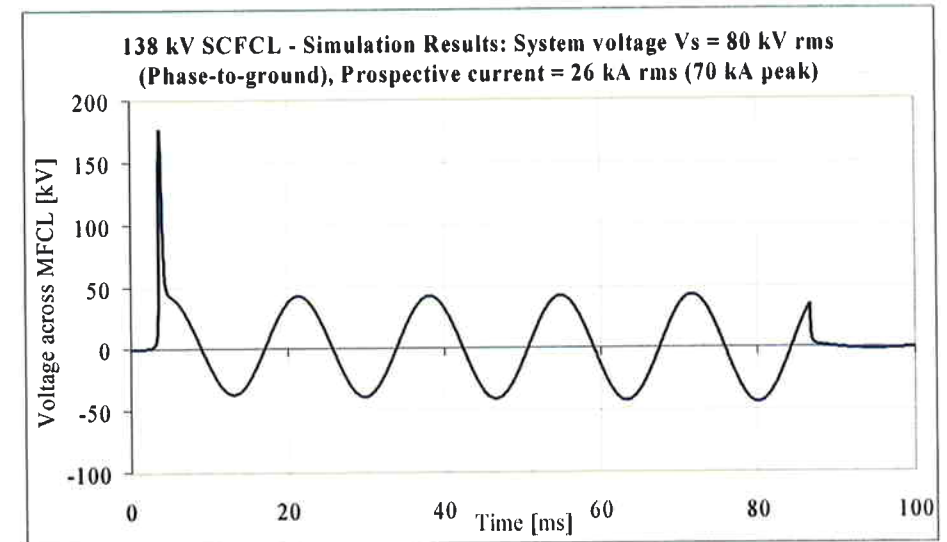
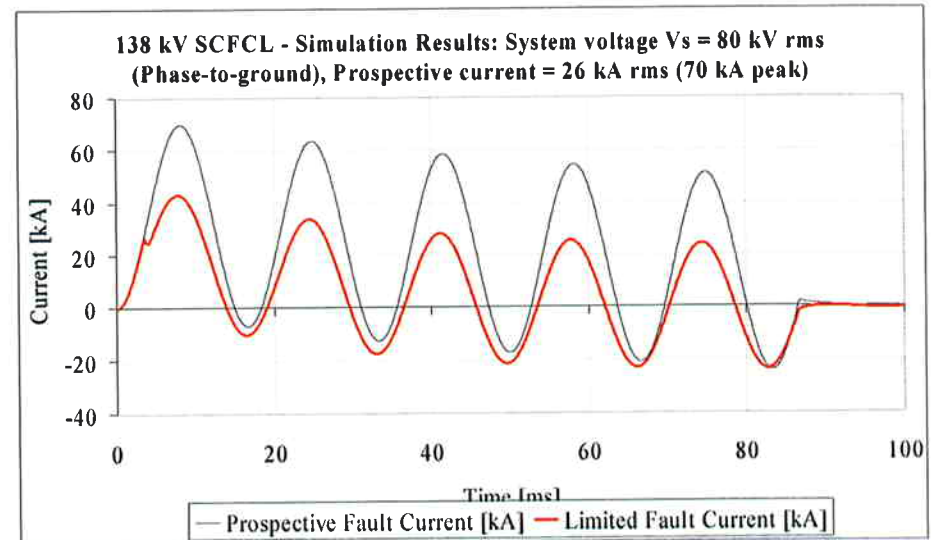
Operating conditions – HV design considerations

Under normal operating condition

- MFCL is invisible to the system
- It has very low impedance
- Negligible voltage drop and minimal steady state losses
- HV design – Bushings and assembly to cryostat insulation

Under short circuit fault conditions

- Critical current exceeded and the superconductor transitions to a resistive state
- Introduces current limiting impedance
- Generates voltage drop (steady state and transient overvoltages) across MFCL
- HV Design Issues
 - Bushings
 - Assembly to cryostat and
 - Internal MFCL assembly insulation

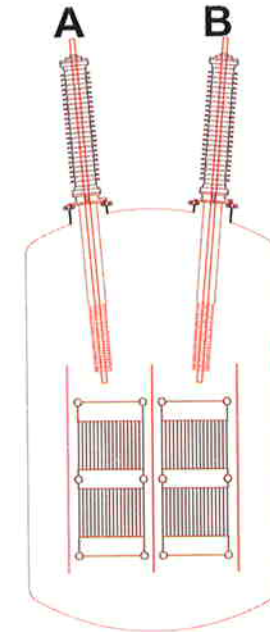


High Voltage Test Requirements

Tests based on typical 138kV requirements for Breakers, Transformers and Current Limiting Reactors

Based on input from AEP and NEETRAC Members

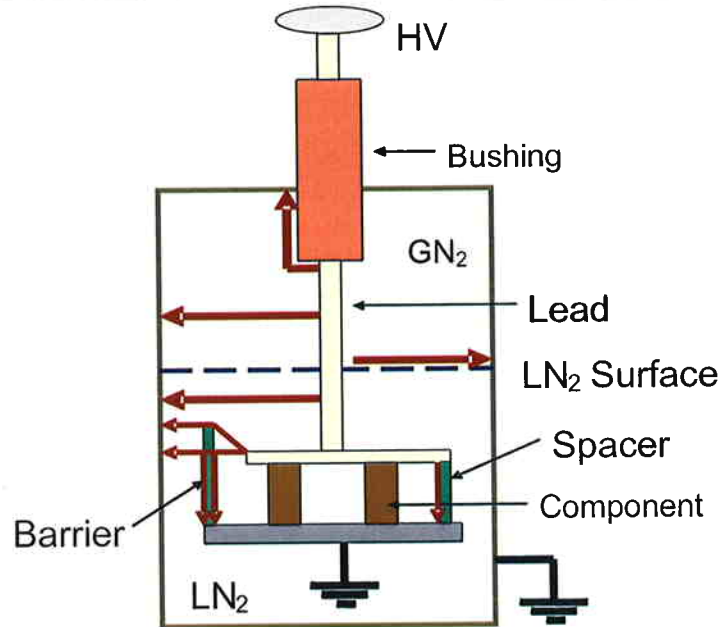
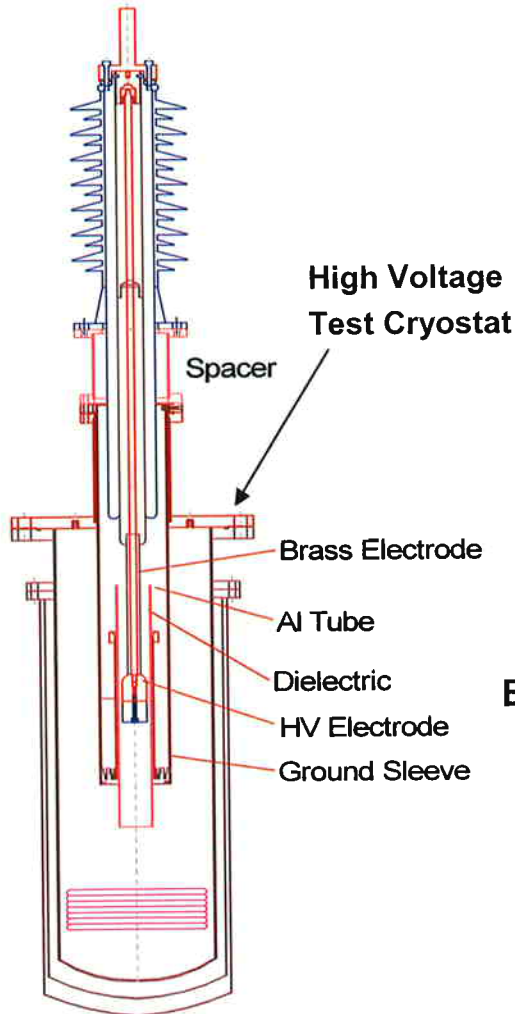
| Tests to be Conducted | Proposed MFCL Requirement |
|-----------------------|---------------------------------------------|
| 60Hz Withstand | Based on ANSI Breaker C37.06 Table 4 |
| Partial Discharge | Based on ANSI Transformer C57.12.00 Table 6 |
| BIL Lightning Impulse | Based on ANSI Reactor C57.16 Table 5 |
| Chopped Wave | Based on ANSI Transformer C57.12.00 Table 6 |
| Switching Impulse | Based on ANSI Transformer C57.12.00 Table 6 |



Configurations for impulse testing:

- Impulse terminal A wrt to ground, with B open
- Impulse terminal B wrt to ground with A open
- Tie A & B together and impulse wrt to ground

High Voltage Development – Test Configurations



HV Test rig to test the dielectric strength of GN₂, LN₂, Flashover and solid insulation (G10) puncture under various electrode configurations, bubble activities, pressure & temperature

Bushing designs

- Conventional bushings tested for cryogenic applications
- Focus on insulation integrity - must not crack when exposed to cold gas or immersed in LN₂
- Two bushings a 38 kV AC (200 kV BIL) and 52 kV AC (250 kV BIL) from two different manufacturers were tested
- PD tests done before and after cooling and immersing – Meets IEEE standards on PD
- Similar type bushings considered for scaling up to 138 kV class

High Voltage Development – Predictive Design Tools

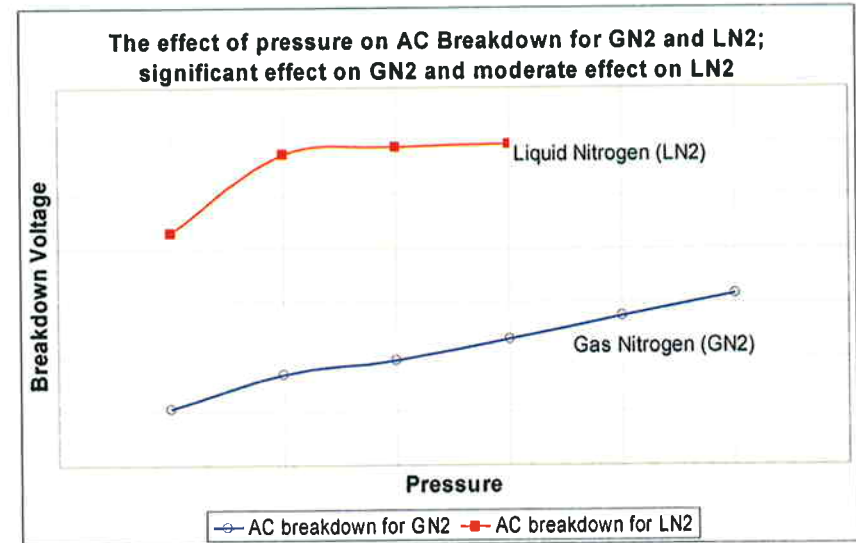
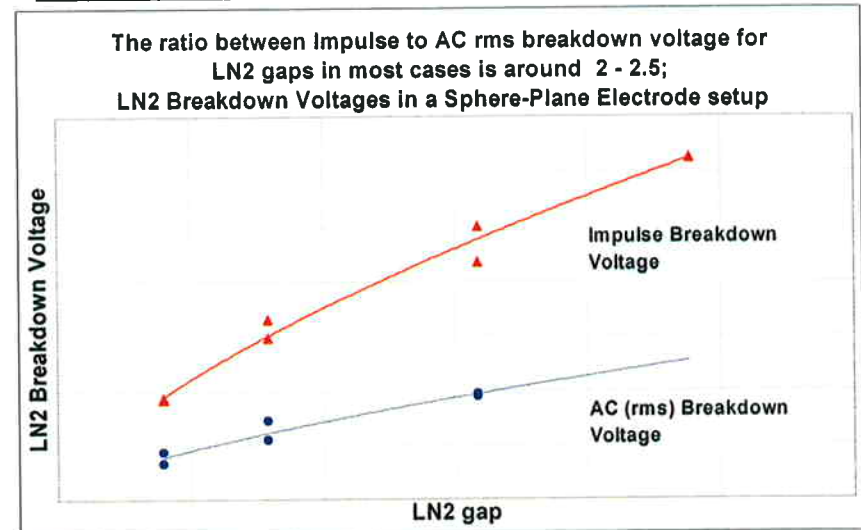
Transfer Function – Predictive Design Tool

- ◆ Based on Experimental and Computed (FEA) results
- ◆ Experimental test rigs were tested up to 200 kV AC rms and 900 kV Impulse
- ◆ Defined the mean Breakdown Voltage (V_{BD}) or Mean Breakdown Field (E_{BD})
- ◆ Main Parameters considered for the transfer function are;
 - g = Dielectric gap
 - η = Utilization factor = E_{av}/E_{max}
 - v = Volume of LN2 under stress
 - P = Pressure, T = Temperature and Bubble effects
- ◆ V_{BD} or $E_{BD} = f(g, \eta, v, P, T, \text{Bubble effects})$
- ◆ Well defined experimentally verified design tools are emerging

Why do we need to do basic research?

- ◆ Information is scarce at higher voltages and larger gaps
- ◆ Usually limited to distribution voltage levels
- ◆ Extending the range to transmission voltage levels
- ◆ Voltages higher than 200 kV AC rms and 650 kV BIL

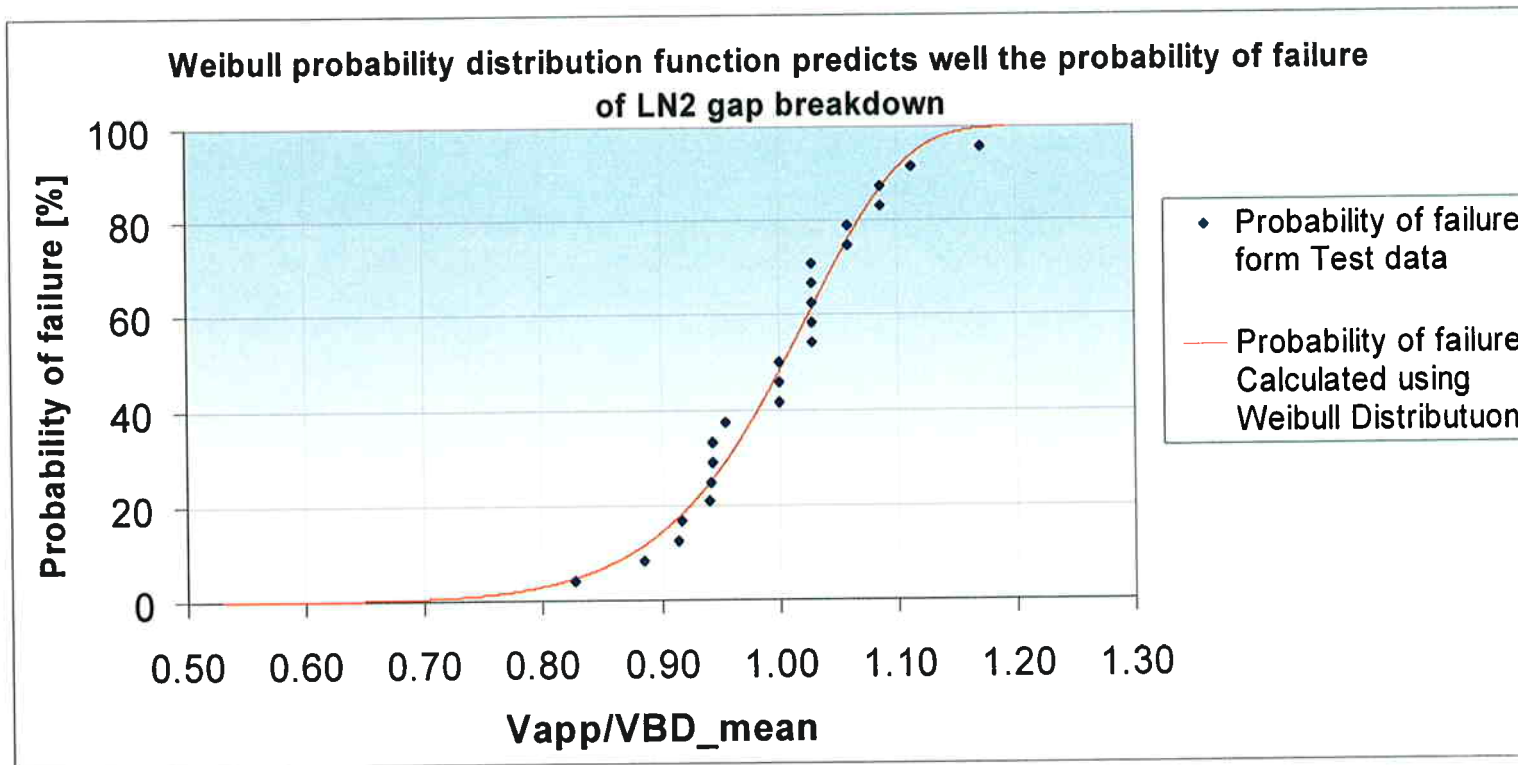
Plots of HV test results used to develop design tools



High Voltage Development – Predictive Design Tools

Probability of Failure – Predictive Tool

- ◆ Experimental data and Weibull probability distribution with two parameters, α and β , used
- ◆ Predicts the probability of the dielectric failure at a given applied voltage or Field



$$P(f) = 1 - e^{-(V / \beta)^\alpha}$$

α and β are the two Weibull parameters