CHAR SYSTEM OPERATION & TRAINING

Module 3

Frequency Domain Reflectometry (FDR) Testing

AT CONCLUSION OF THIS MODULE, THE STUDENT WILL BE FAMILIAR WITH:

- Understanding multiple views of FDR data
- Fundamental FDR theory
- Acquiring FDR data in WinCharm software
- Analyzing FDR data in WinCharm software
- Practical applications
- Calibrating the VNA and test lead for acquisitions

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ABOUT THE FDR TEST TECHNIQUE

- Frequency Domain Reflectometry (FDR) is an in-situ test that locates & quantifies insulation material degradation in a cable circuit
- FDR is more sensitive than TDR to changes in dielectric permittivity that correspond to insulation material degradation

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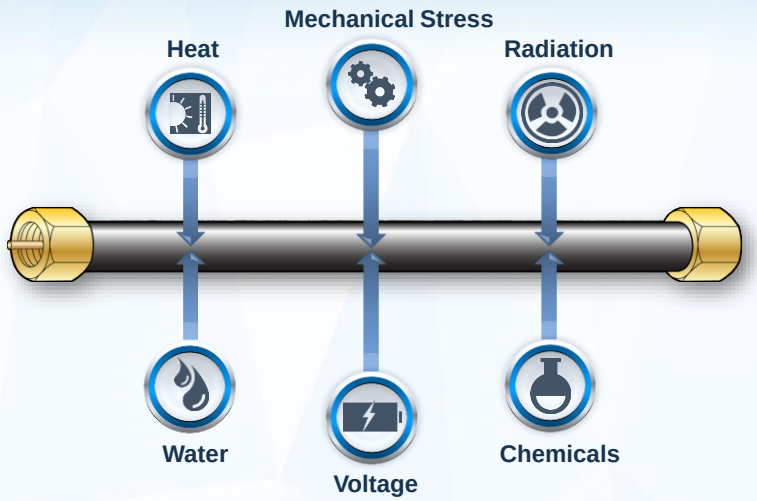
ENVIRONMENTAL STRESSORS ON CABLES



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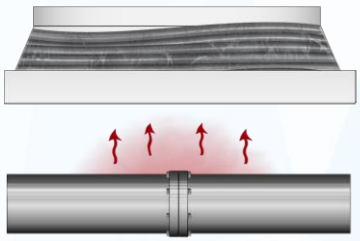
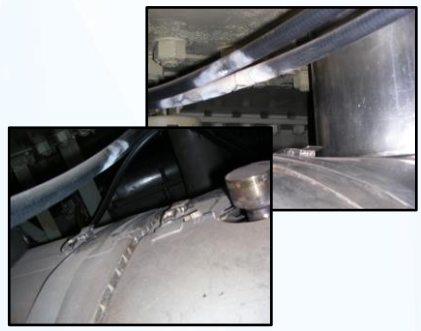
HEAT STRESS IS THE BIGGEST ISSUE FOR CABLE AGING

- As cables are exposed to environmental heat stress, they become susceptible to hardening and cracking
- Indenter and reflectometry testing are used to identify cable aging





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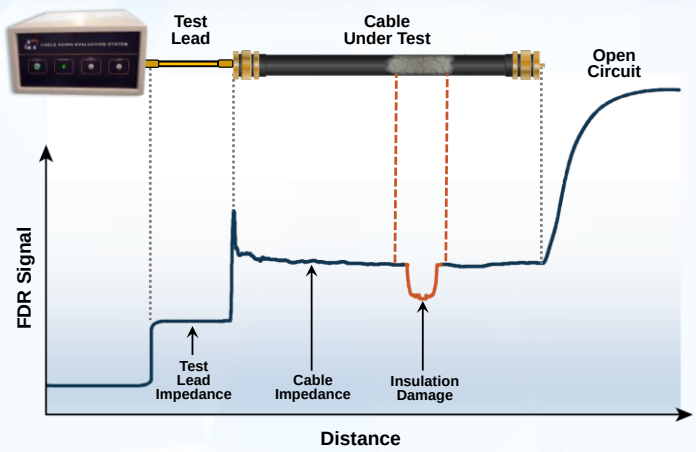
EXAMPLE OF FDR DATA (IDENTIFYING INSULATION DEGRADATION)



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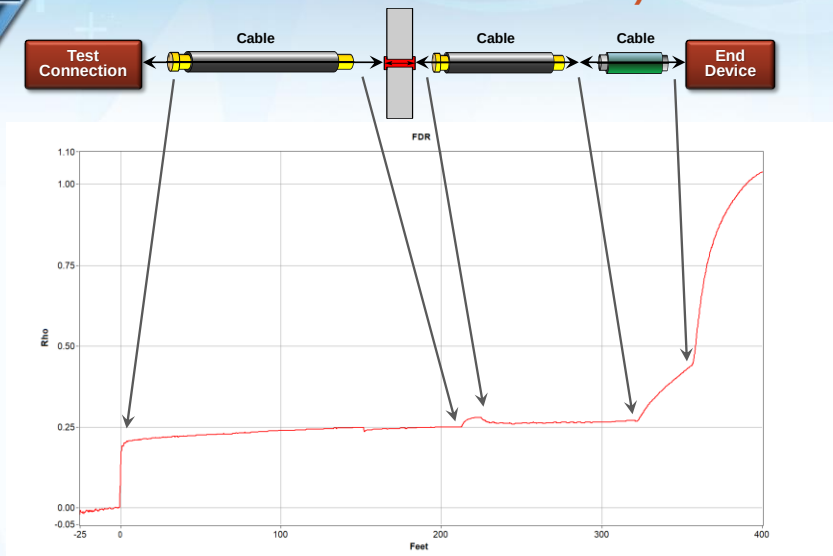
EXAMPLE OF FDR DATA (IDENTIFYING KEY COMPONENTS IN CABLE CIRCUIT)



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TDR AND FDR BOTH USE STEP RESPONSE AND IMPULSE RESPONSE

- TDR uses step response or impulse response to perform test
- FDR determines step and impulse responses from raw data (S_{11}, often referred to as return loss, represents the power sourced from and reflected back to port 1 of a vector network analyzer. This scattering parameter is a way to characterize an electrical device versus frequency).
- Raw FDR data is acquired then algorithms are used to view data in various ways (i.e., step response, bandpass impulse response)

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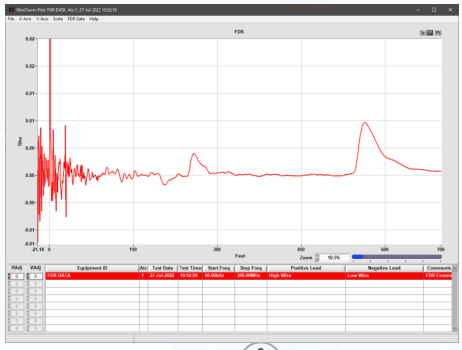
ABOUT IMPULSE RESPONSE

- Data must be acquired with a frequency range that is harmonic (f_{start} * *Points* = f_{stop})

VNA → S11 (Frequency Domain) → IFFT → Impulse Response (Time Domain)



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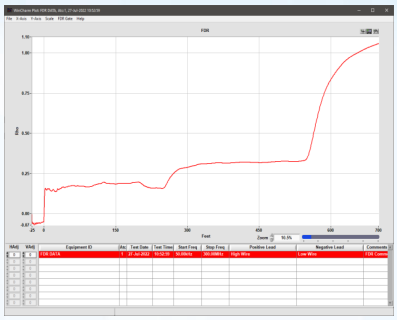
ABOUT STEP RESPONSE

- Data must be acquired using a frequency range that is harmonic (f_{start} * *Points* = f_{stop})
- Step response provides a TDR-like display of the FDR data (Y-axis is unitless voltage ratio called Rho)
- This signal processing method can be helpful for cable circuits that are shorter in length (i.e., <5 km)



VNA → S11 (Frequency Domain) → IFFT → Impulse Response (Time Domain) → Integrate → Step Response

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EXAMPLES OF STEP AND IMPULSE RESPONSE DATA

CABLE280

Cabling Issues	Step Response	Impulse Response
Open Connection		
Shorted Connection		
Resistive Connection		
Mechanical Anomalies (e.g. splice, kink, separation of conductors)		
Localized Aging (e.g. change in permittivity)		

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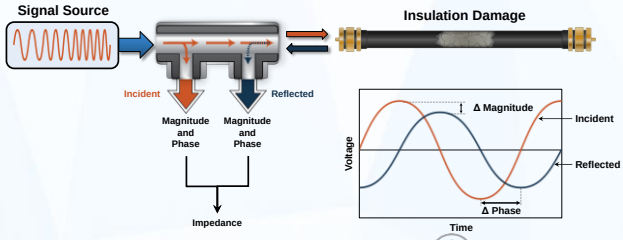
FDR TEST METHOD THEORY

- Raw data (S11, a scattering parameter representing the power reflected from and back to port 1 of the VNA) is saved then algorithms are used to derive ways to view the data.
- A Vector Network Analyzer (VNA) transmits sine waves at various frequencies into a cable under test and measuring both the transmitted incident wave and the reflected wave
- The cable under test consists of two cable conductors, a conductor and cable shield, or a conductor and ground plane.
- Reflected voltage waves occur when the transmitted signal encounters an impedance mismatch or discontinuity in the cable.
- The reflected signals are then analyzed in the frequency domain and the result is converted to the time domain and presented in terms of the FDR reflection coefficient, Rho, as a function of distance along the cable.



$$Rho = \frac{V_{reflected}}{V_{incident}}$$

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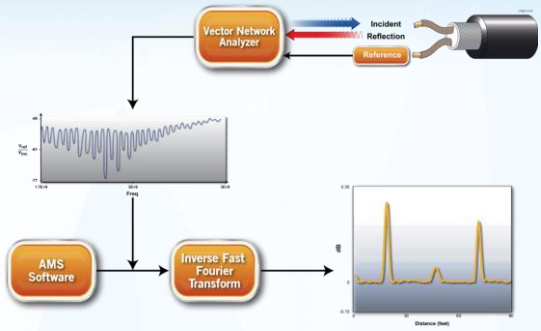
FDR TEST METHOD THEORY (CONTINUED)

- An Inverse Fast Fourier Transform (IFFT) is used to obtain the time domain impulse response which is then integrated to obtain the time domain step response.
- The time axis of the impedance step response is converted to distance using the velocity of propagation (Vp) that is specific for each cable type. The Vp of a cable is a percentage of the speed of light (Vs) in a vacuum (Vs = 0.3 m/ns)
- Distance to fault is determined by multiplying the Vp of the cable by half the time it takes for the incident wave to travel to the impedance change and get reflected back to the CHAR System



$$Distance = \frac{V_P T}{2}$$

Vp = Velocity of propagation

T = Transit time from CHAR System to the impedance change and back to the CHAR System

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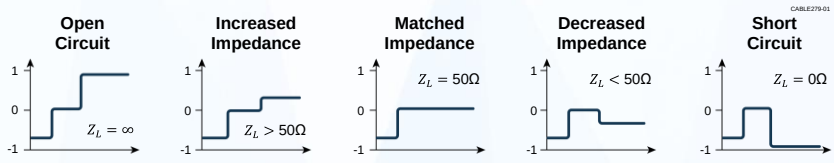
FDR TEST METHOD THEORY (CONTINUED)

Localized cable impedance changes are measured as changes in the FDR reflection coefficient, which is expressed as a unitless impedance ratio called Rho (ρ).



$$Rho = \frac{V_{reflected}}{V_{incident}} = \frac{Z_L - Z_0}{Z_L + Z_0}$$

$$Z_0 = 50\Omega$$

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VARIATIONS OF WAYS TO ANALYZE FDR DATA
IMPULSE RESPONSE VERSUS STEP RESPONSE

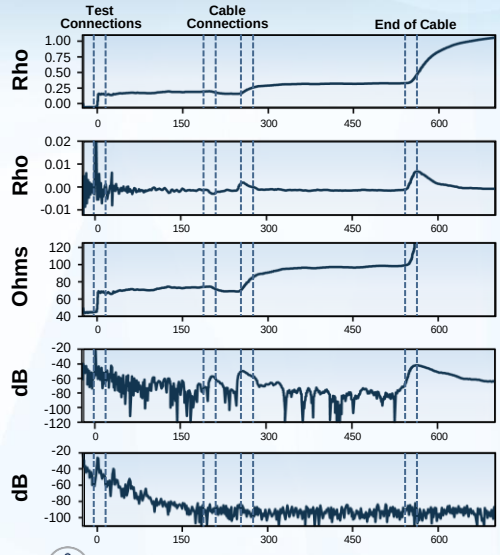
STEP RESPONSE

IMPULSE RESPONSE

IMPEDANCE

MAGNITUDE

BANDPASS IMPULSE RESPONSE



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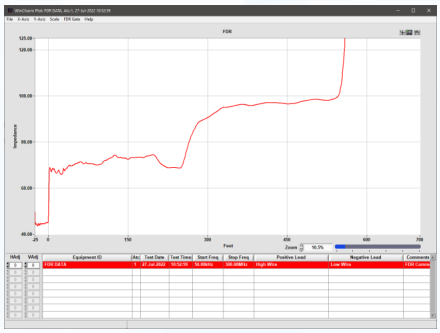
FDR DATA EXAMPLE (IMPEDANCE)

- Data must be acquired using a frequency range that is harmonic (f_{start} * *Points* = f_{stop})
- Step response provides a TDR-like display of the FDR data (Y-axis is Rho)
- This signal processing method help determine the impedance of a cable or the deviation in a resistive change at a key component in a cable circuit

VNA → S11 (Frequency Domain) → IFFT → Impulse Response (Time Domain) → Integrate → Step Response → Convert Rho to Z → Impedance



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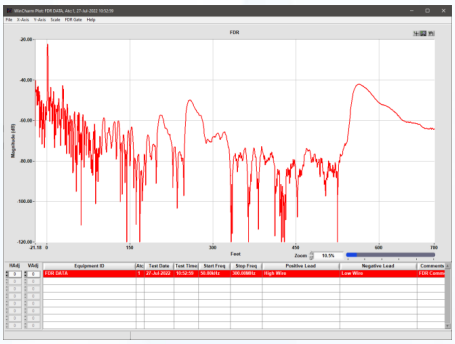
FDR DATA EXAMPLE (MAGNITUDE)

Data must be acquired using a frequency range that is harmonic

VNA → S11 (Frequency Domain) → IFFT → Impulse Response (Time Domain) → 20log (Base10) → Magnitude



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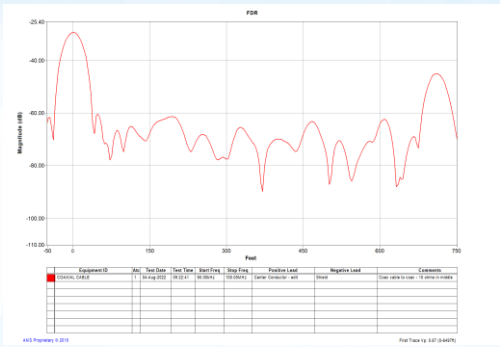
FDR DATA EXAMPLE (BANDPASS IMPULSE RESPONSE)

- More flexible with frequencies spans since data not need to be harmonic
- This signal processing method can be helpful for cable circuits that are longer in length (i.e., > 5 km)
- Cannot calculate Rho or impedance from this data



VNA → S11 (Frequency Domain) → IFFT → Impulse Response (Time Domain) → Bandpass Impulse Response (Time Domain)

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CALCULATING THE STEP SIZE (RESOLUTION) FOR AN FDR TEST

$$\text{Span} = f_{start} - f_{stop}$$

f_{start} is the start frequency

f_{stop} is the stop frequency

$$\text{Step Size} = \frac{Span * 1000000}{\frac{Points}{2}}$$

Step size is the distance between each frequency

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CALCULATING MAXIMUM DISTANCE FOR AN FDR TEST

$$\text{Ambiguity range } (time\ domain) = \frac{1}{Step\ size}$$

$$\text{Maximum distance } (feet) = \text{ Ambiguity range } * (V_p * c)$$

V_p is velocity of propagation

C is speed of light

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ESTABLISHING HARMONIC DATA POINTS

$$\text{Points} = \frac{f\ stop}{f\ start}$$

$$\text{Multiple of Points} = (Points\ *2) - 1$$

f_{start} *is the start frequency*

f_{stop} *is the stop frequency*

- Data is harmonic if $f_{start} * Points = f_{stop}$
- Multiples of points can be used to increase the maximum distance for a test
- Data needs to be harmonic for lowpass processing alternative (i.e., impulse and step responses) because a DC component is required for analysis. Lower start frequencies yield more accurate DC component estimates.

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DETERMINING TEST PARAMETERS BASED ON CABLE CIRCUIT LENGTH

- The span and number of points most affect the maximum distance and data resolution (distance between each data point acquired)
- Helpful to know the approximate length of the cable under test
- A broader span can test longer cables but has less resolution between each data point
- A lower span may be best to use low stop Frequency and obtain more resolution between each data point
- Adjust the number of Points to be harmonic (or a multiple of the harmonic) to ensure the entire cable circuit under test can been seen by the test signal

Example of how frequency ranges affect the maximum distance and data resolution

Item	Equipment ID	Start Frequency (MHz)	Stop Frequency (MHz)	# of Points Needed to be Harmonic	# of Points used for Testing	Multiple of Harmonic or Harmonic	Max. Distance (km)	Bandpass Resolution (m)	Step Response Resolution (m)
1	1km - Test 1	0.05	1080	21,600	21,600	Harmonic	2.0	0.014	0.047
2	1km - Test 2	0.05	450	9,000	9,000	Harmonic	2.0	0.032	0.113
3	1km - Test 3	0.05	90	1,800	1,800	Harmonic	2.0	0.162	0.567
4	1km - Test 4	0.05	10.8	216	431	Multiple of Harmonic	4.1	1.354	4.727

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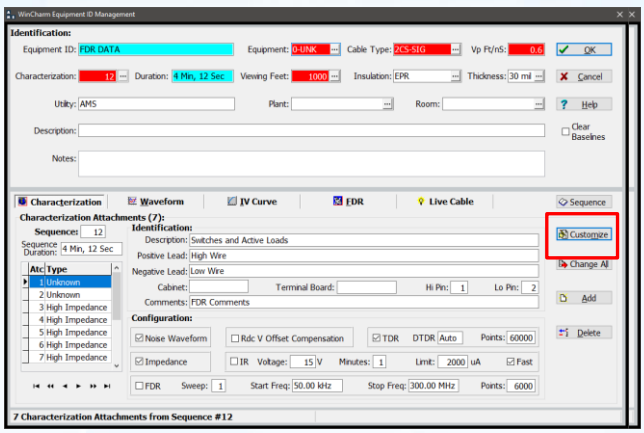
ACQUIRING FDR DATA FROM THE CHARACTERIZATION TAB

EDIT EID TO PERFORM FDR FROM THE CHARACTERIZATION TAB

- On EID Management screen, click EID then click “Edit”
- Click “Customize” to edit a Characterization attachment



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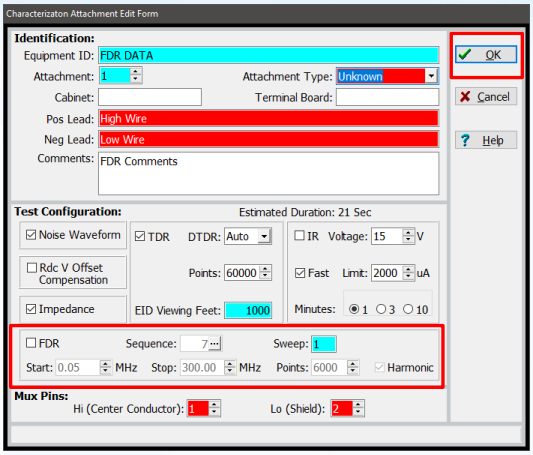
EDIT EID TO PERFORM FDR FROM THE CHARACTERIZATION TAB (CONTINUED)

- Click to toggle box next to “FDR” to set the test configuration
- Enter Start frequency, Stop frequency, and Points
- Click “OK” to save changes to test attachment



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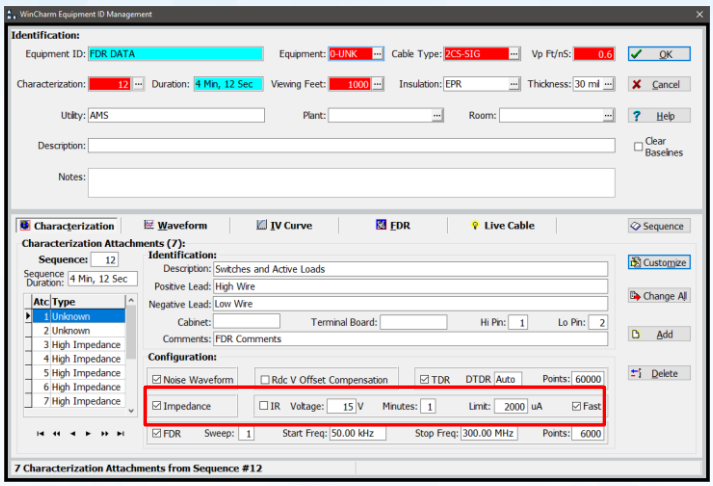
VERIFY THE FDR TEST CONFIGURATION IS PROPERLY SET



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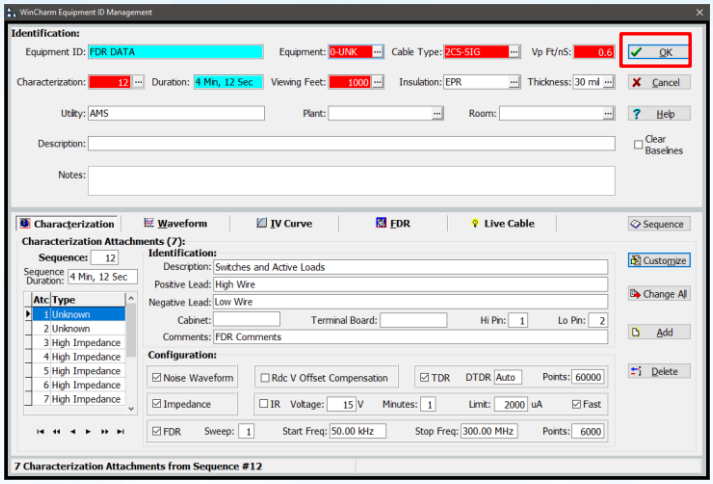
CLICK OK TO SAVE TEST CONFIGURATION



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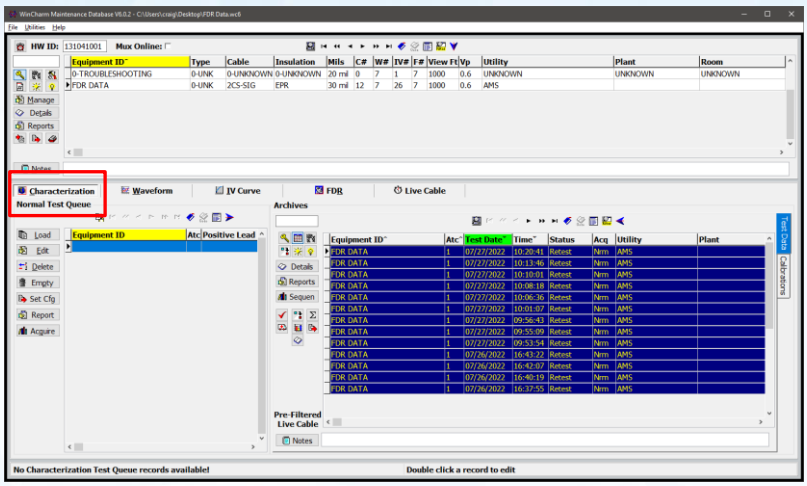
ACQUIRE FDR DATA FROM THE CHARACTERIZATION TAB

Click the Characterization tab



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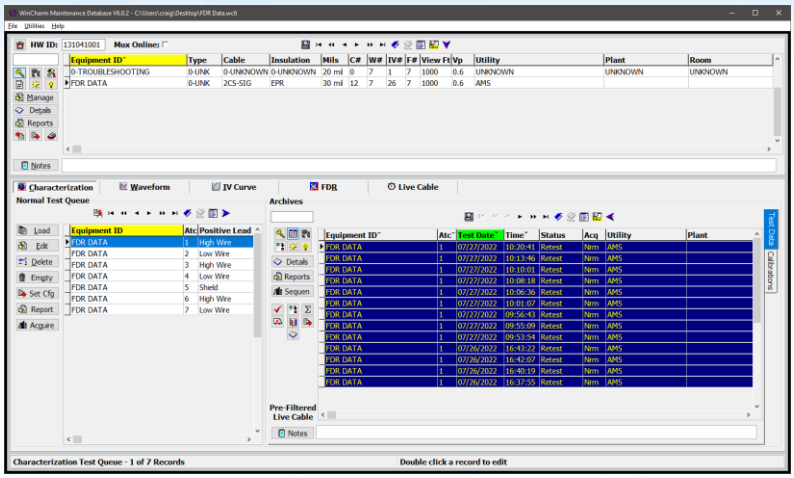
LOAD THE TEST QUEUE BY DOUBLE CLICKING THE EID



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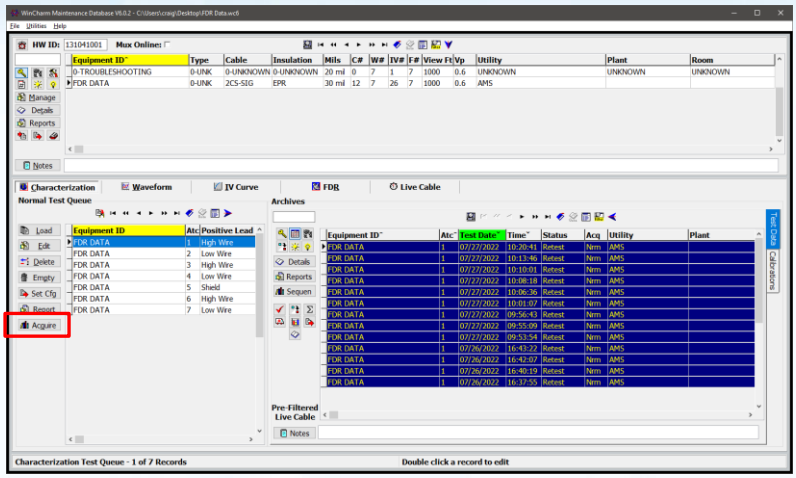
CLICK ACQUIRE



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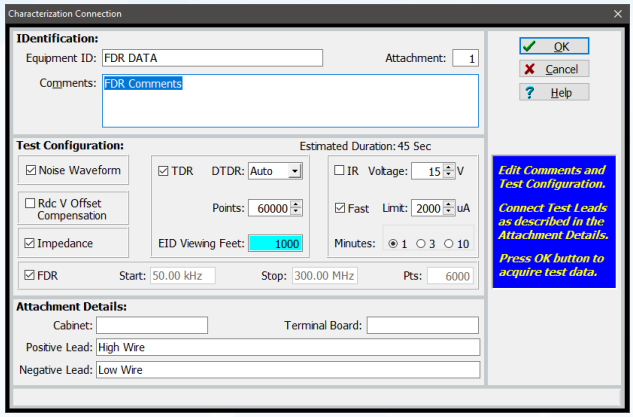
VERIFY TEST PARAMTERES, ADD COMMENTS, THEN CLICK “OK” TO PERFORM TEST



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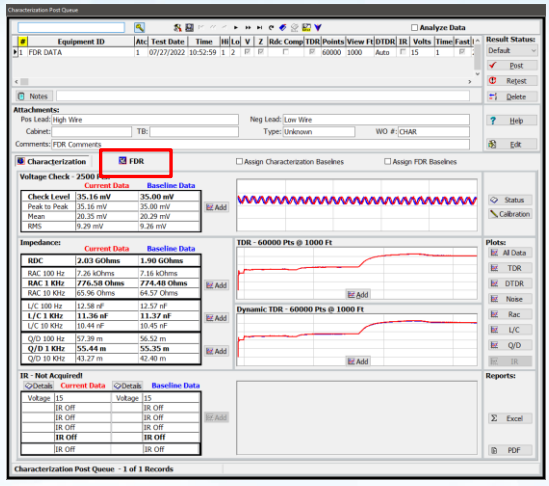
CLICK THE FDR TAB TO REVIEW THE FDR TEST RESULTS IN THE POST QUEUE



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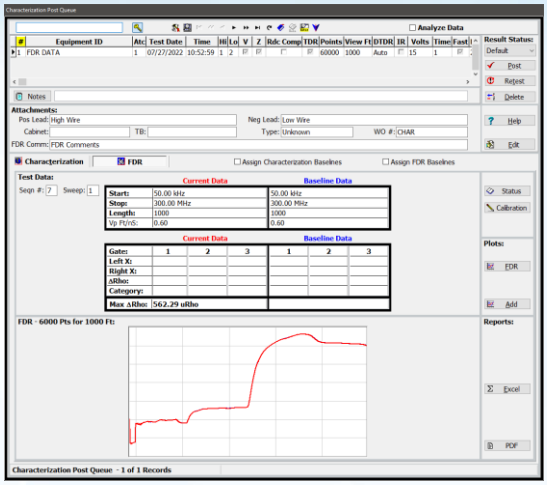
REVIEW THE FDR TEST RESULTS IN THE POST QUEUE

- Click “Post” or “Retest” to save the data to the Archives
- Clicking “Post” will save the data then remove the attachment from the test queue.
- Clicking “Retest” will save the data and keep the attachment from the test queue



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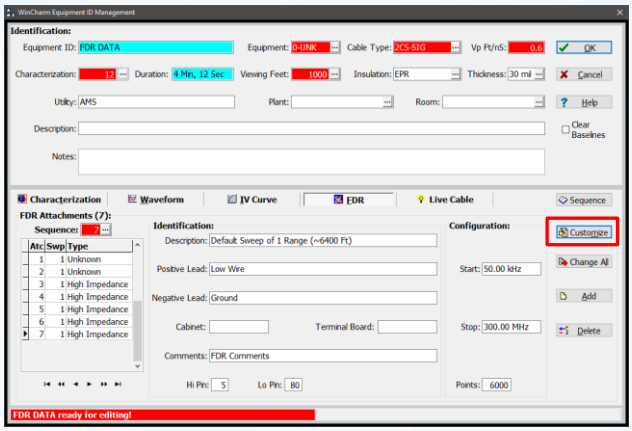
ACQUIRING FDR DATA FROM THE FDR TAB

EDIT EID IN FDR TAB

- On EID Management screen, click EID then click “Edit”
- Click “Customize” to edit an FDR attachment



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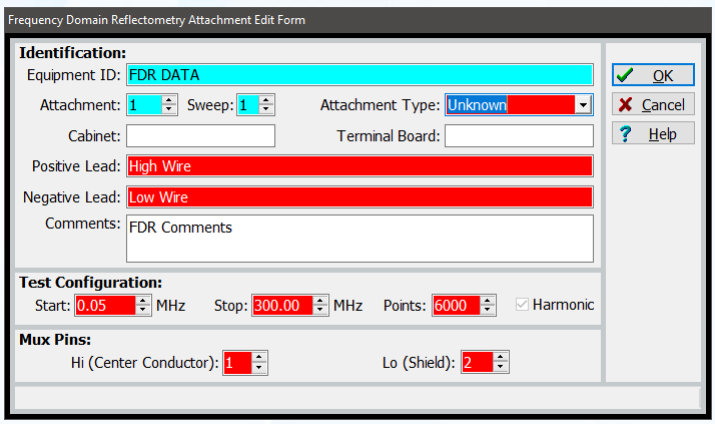
EDIT TEST PARAMTERS THEN CLICK OK TO SAVE CHANGES



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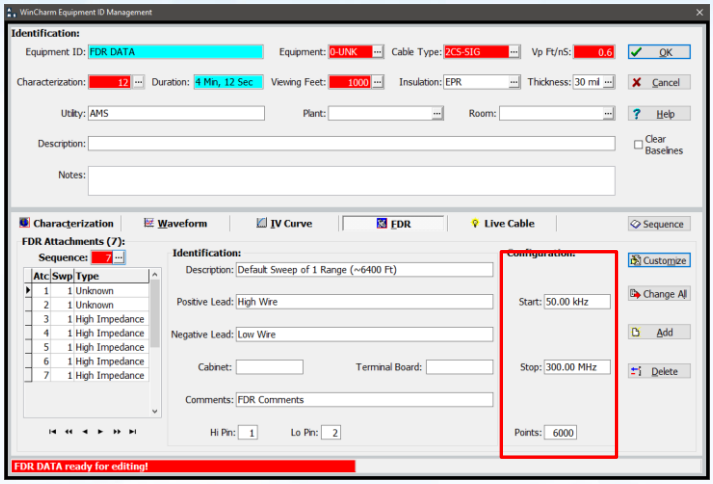
VERIFY THE FDR TEST CONFIGURATION ARE PROPERLY SET



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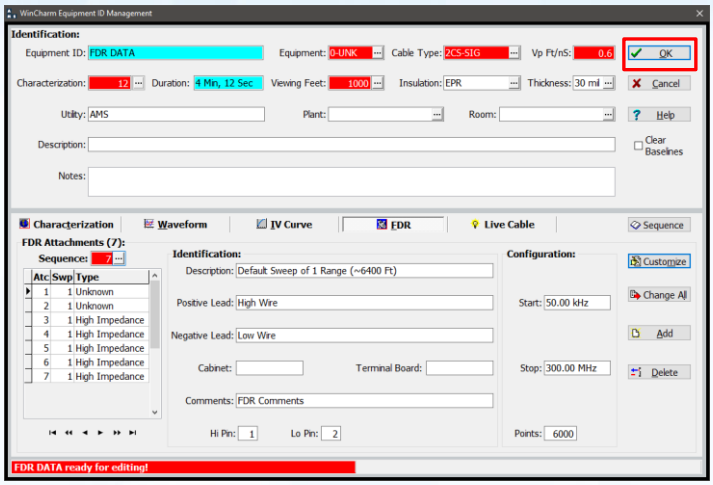
CLICK OK TO SAVE THE TEST CONFIGURATION



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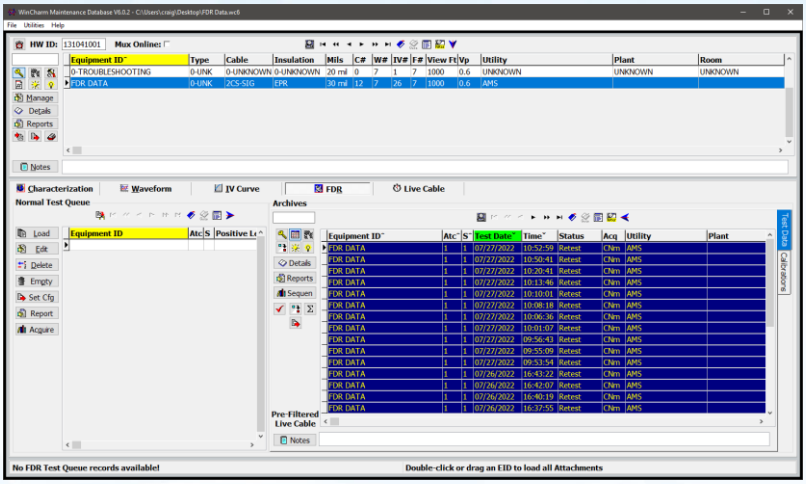
CLICK THE FDR TAB



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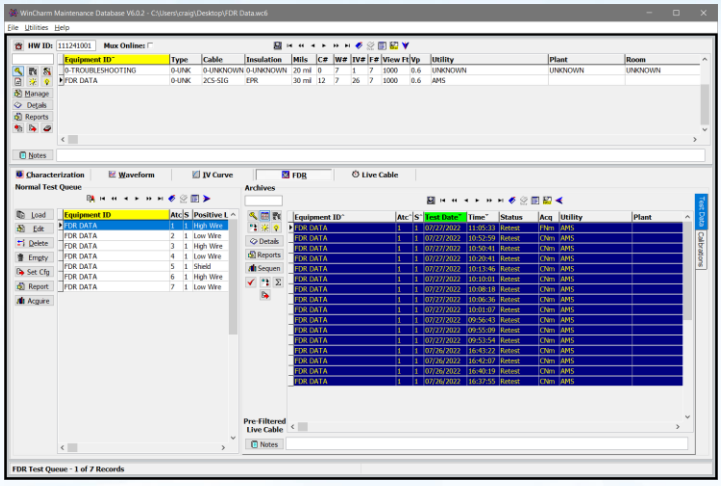
LOAD THE TEST QUEUE BY DOUBLE CLICKING THE EID



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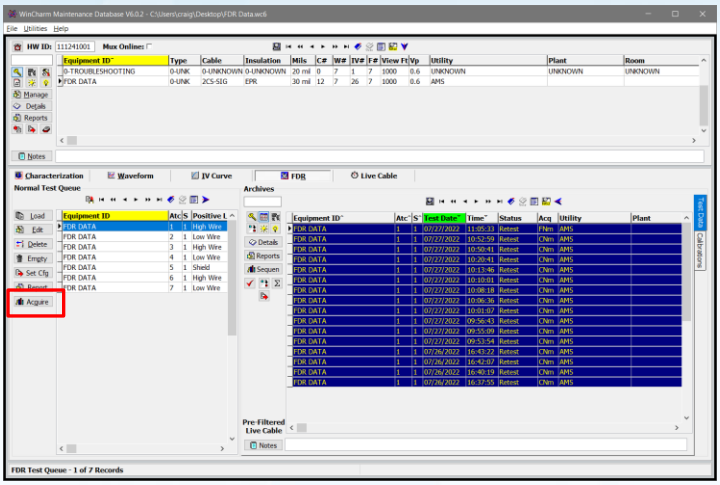
CLICK ACQUIRE



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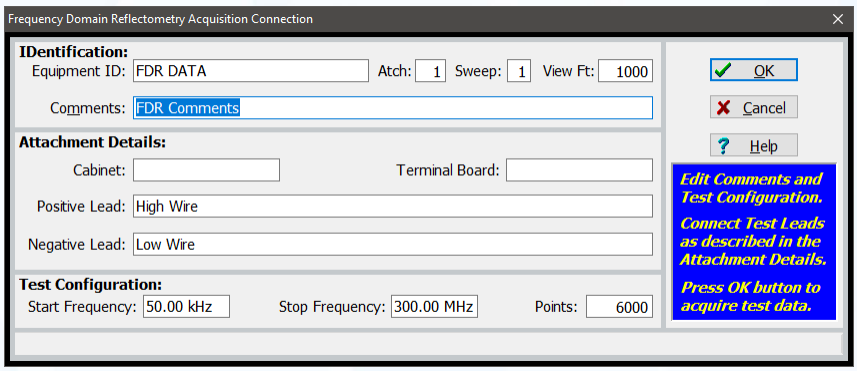
VERIFY TEST PARAMTERES, ADD COMMENTS, THEN CLICK "OK" TO PERFORM TEST



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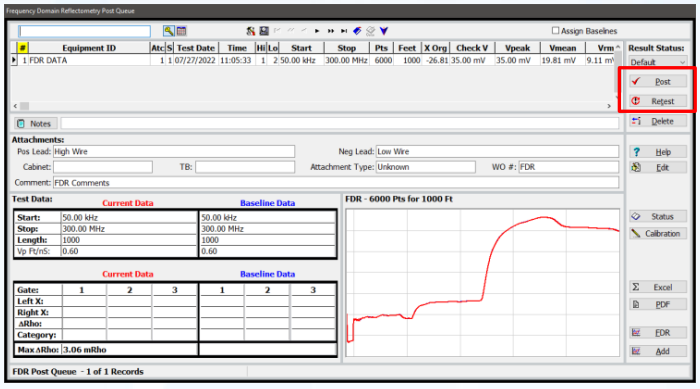
REVIEW THE FDR TEST RESULTS IN THE POST QUEUE

- Click “Post” or “Retest” to save the data to the Archives
- Clicking “Post” will save the data then remove the attachment from the test queue.
- Clicking “Retest” will save the data and keep the attachment from the test queue



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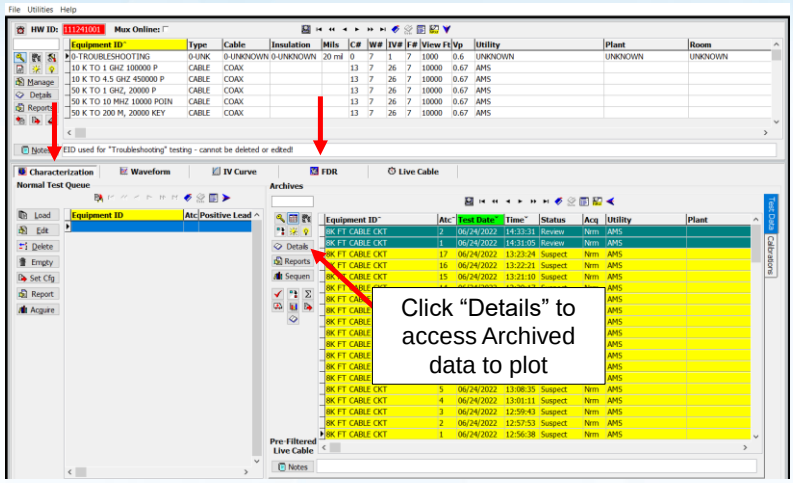
ANALYZING ARCHIVED FDR DATA IN THE WINCHARM SOFTWARE

FDR DATA CAN BE ANALYZED FROM THE CHARACTERIZATION OR FDR TAB



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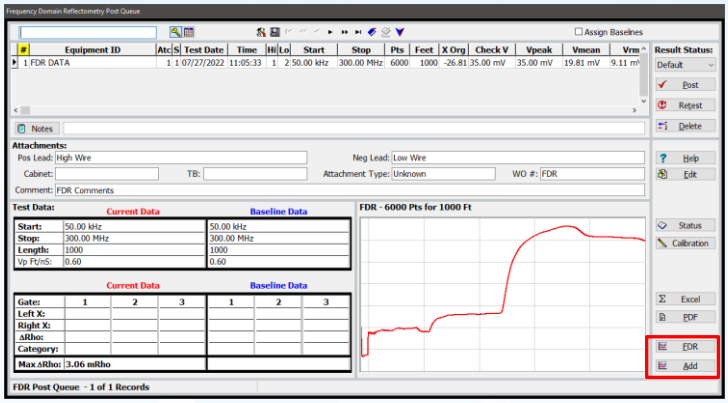
CLICK "FDR" OR "ADD" TO PLOT FDR DATA

- Clicking "FDR" will plot current data with baseline (if available)
- Clicking "Add" will plot the current data or add it to an already opened plot



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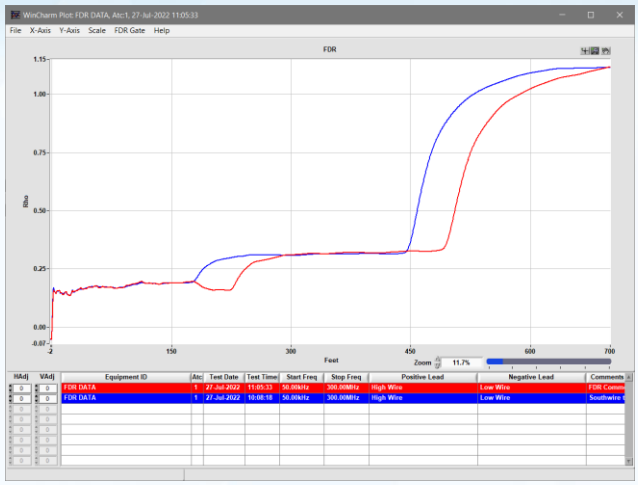
FDR OVERLAY OF CURRENT DATA (RED TRACE) COMPARED TO BASELINE DATA (BLUE TRACE)



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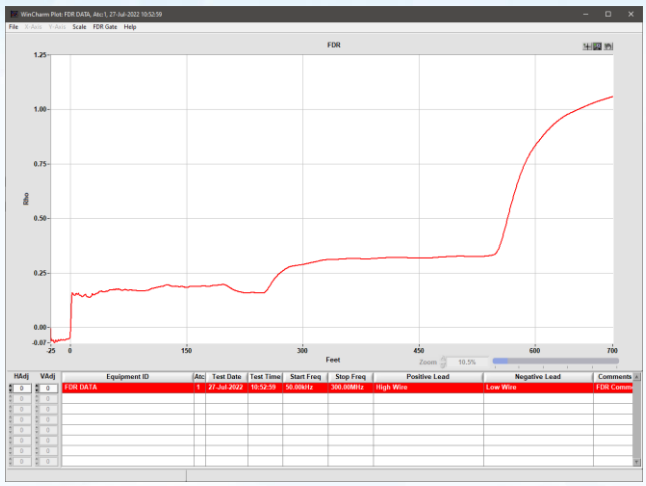
EXAMPLE FDR PLOT



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THE VELOCITY OF PROPOGATION (Vp) CAN BE MODIFIED

- Cables have different Vp values based on their configuration
- Modifying the Vp changes the cable length of the FDR data
- Using the proper Vp for a cable provides more accurate distances to connections, faults, or overall cable circuit length
- To determine the Vp, consult manufacturer specs or measure length of cable then perform TDR or FDR test and adjust the Vp until the plot matches the actual cable length

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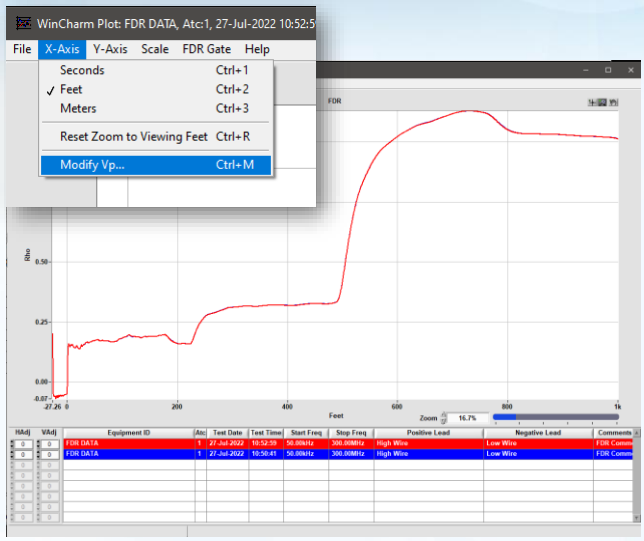
MODIFYING THE VELOCITY OF PROPOGATION (Vp)

- **Click "X-axis" from menu bar then select "Modify Vp"**
- **These modifications can apply to both TDR and FRD data**



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ADJSUT THE Vp BY MANUALLY TYPING VALUE IN FIELD OR USING RADIO DIALS

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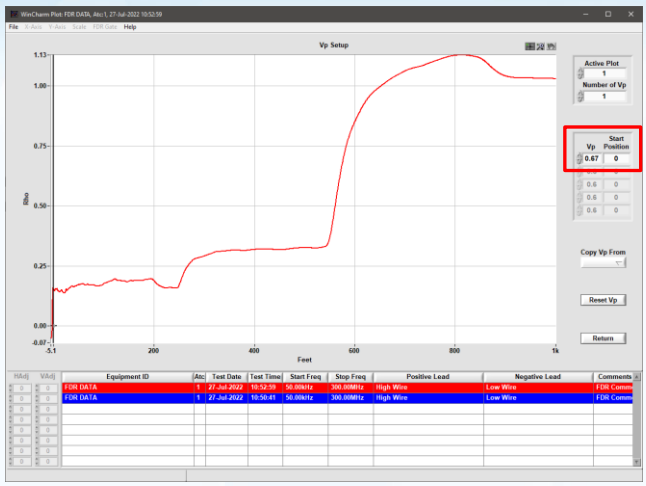
EXAMPLE OF MODIFYING THE Vp FROM 0.6 TO 0.67



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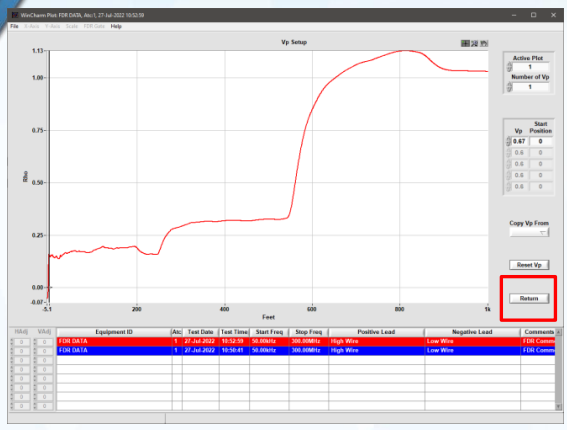
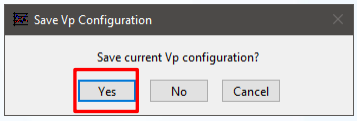
CLICK "RETURN" THEN "YES" TO SAVE Vp MODIFICATION





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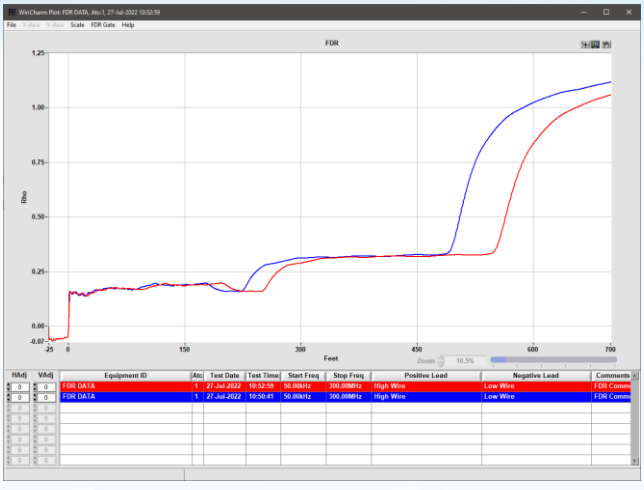
OBSERVE THE CHANGE IN CABLE LENGTH OF FDR DATA (RED TRACE) DUE TO Vp MODIFICATION

- Red trace has a Vp = 0.67
- Blue trace has a Vp = 0.6



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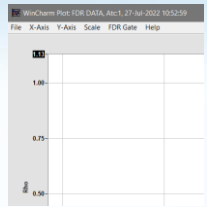
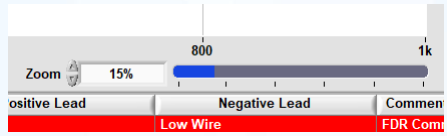
THERE ARE NUMEROUS WAYS TO ADJUST THE SCALE OF A PLOT

- Double clicking on minimum and maximum values then manually typing in desired value



- Using the plotting tools

- Using the zoom bar



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EXAMPLE PLOT WITH A SCALE TO BE MODIFIED USING VARIOUS METHODS

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DOUBLE CLICK THE X-AXIS AND Y-AXIS LIMITS AND MANUALLY INPUT DESIRED VALUE

- In this example, the limits were changed to
- X-Axis: -25 to 600
- Y-axis -0.10 to 1.00

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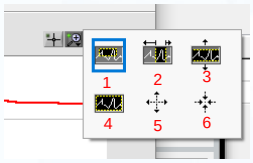
WINCHARM CONTAINS MULTIPLE PLOTTING TOOLS AVAILABLE IN THE UPPER-RIGHT OF EACH PLOT



1. Click and hold to drag and zoom
2. Zoom-in on the x-axis
3. Zoom-in on the y-axis
4. Zoom-out to full range of data
5. Zoom-in (approximately 2% zoom per click)
6. Zoom-out (approximately 2% zoom per click)

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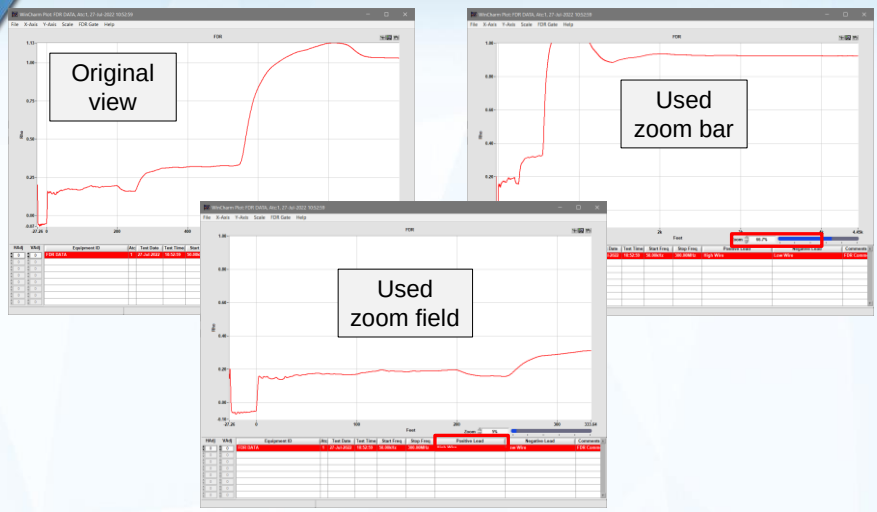
CHANGE THE X-AXIS BY ADJUSTING THE BAR OR MANUALLY INPUTTING A VALUE IN THE ZOOM FIELD



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A SCALE CAN BE SAVED AND APPLIED TO MULTIPLE PLOTS

- Once satisfied with a plot scale, the user can save that scale, then apply that scale to all new plots generated
- Scale is used until the software is closed or the user turns off the "Use Saved Scale" feature

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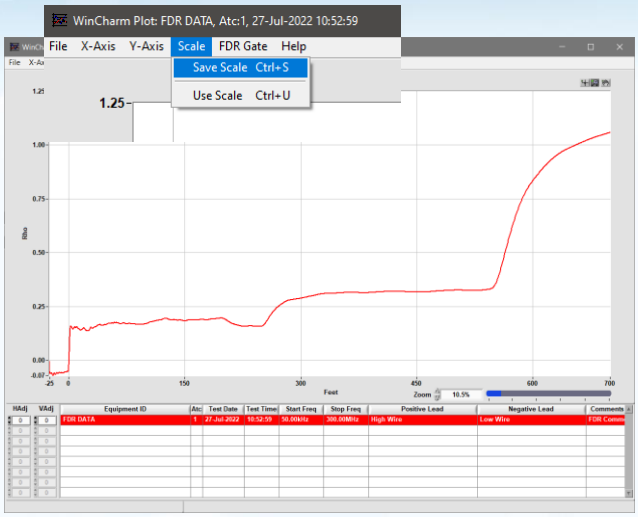
ADJUST THE SCALE THEN SELECT "SAVE SCALE" FROM THE SCALE DROPDOWN MENU



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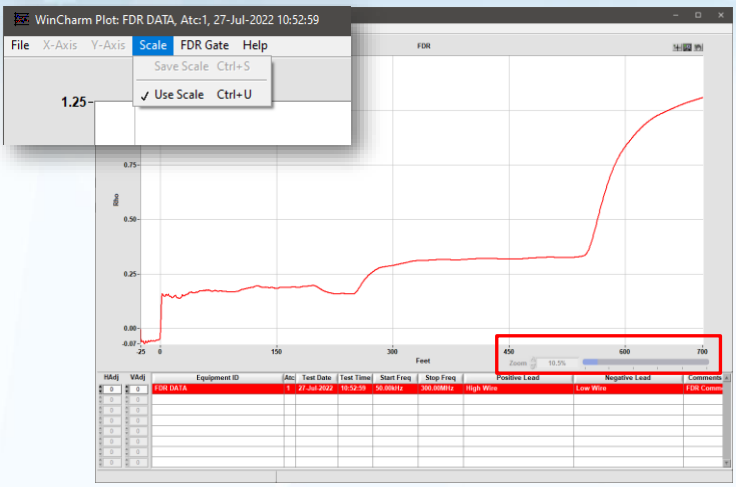
CLICK "USE SCALE" TO APPLY THE SAVED SCALE TO EXISTING (AND ALL NEW) PLOTS



When a saved scale is being used, the zoom bar is grayed out

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GATES CAN BE APPLIED TO A PLOT FOR ANALYSIS

- Gates are used to measure the maximum change in a viewing window from a single point of reference
- The user sets cursors to create a viewing window,. This creates a gated window.
- The gate normalizes the left-cursor value in the gated window to 0 then measures the maximum change observed in the viewing window
- Gates can be used to analyze and quantify age-related degradation.
- Software has aging categories built in for various polymers.
- Up to 3 gates can be applied to each FDR plot

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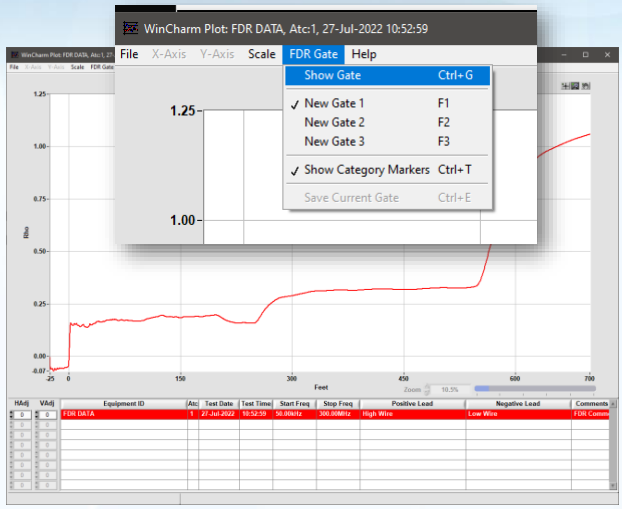
GATES CAN BE APPLIED TO A PLOT FOR ANALYSIS

- **To set gate, click "FDR Gate" then "Show Gate" from the dropdown menu**



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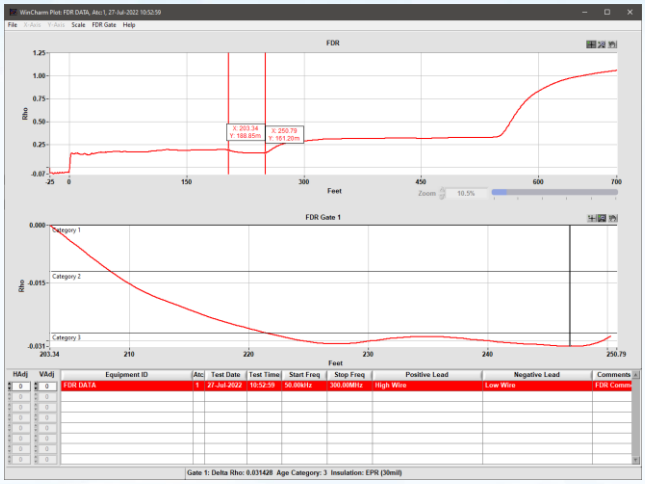
DRAG THE CURSORS TO CREATE GATED WINDOW

Gated window



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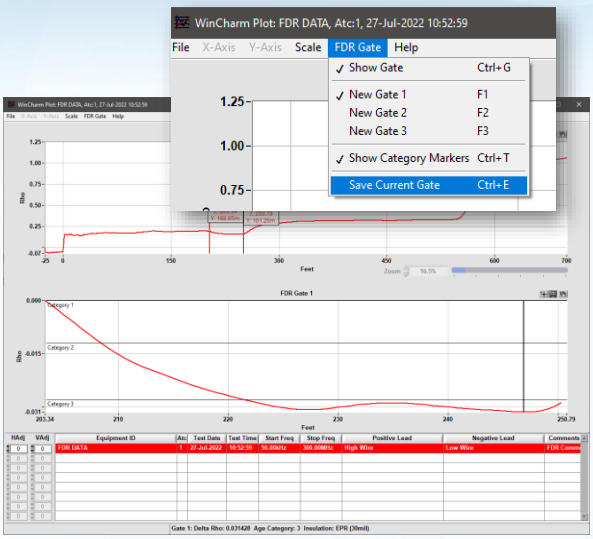
ONCE THE CURSORS ARE SET, CLICK "SAVE CURRENT GATE"

- Repeat this process for up to 3 gates for an FDR plot



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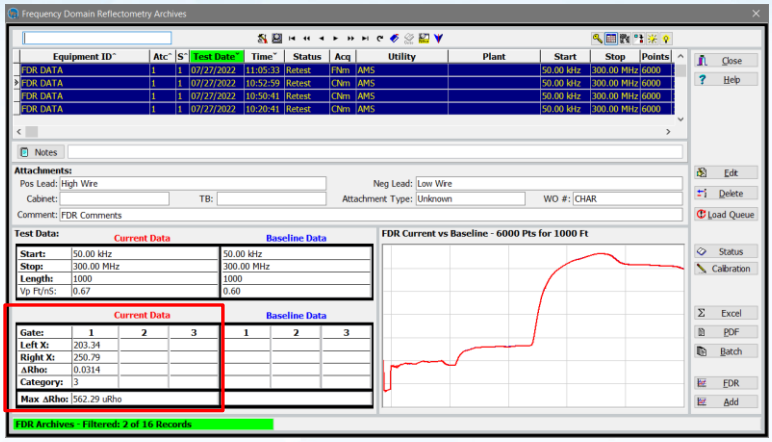
GATE DETAILS CAN BE VIEWED IN THE ARCHIVES



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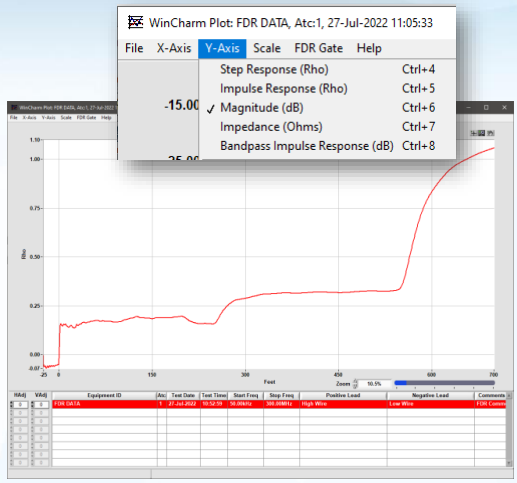
THERE ARE FIVE WAYS TO VIEW FDR DATA

- Step response (Rho)
- Impulse response (Rho)
- Magnitude (dB)
- Impedance (Ohms)
- Bandpass impulse response (dB)



Each of these ways to view FDR data has unique advantages

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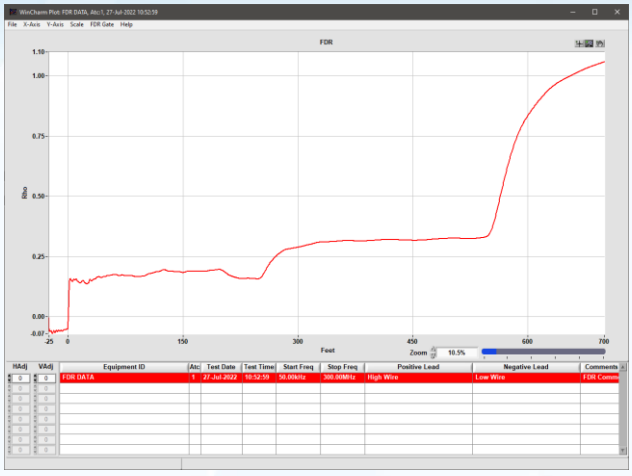
EXAMPLE OF FDR DATA (STEP RESPONSE)



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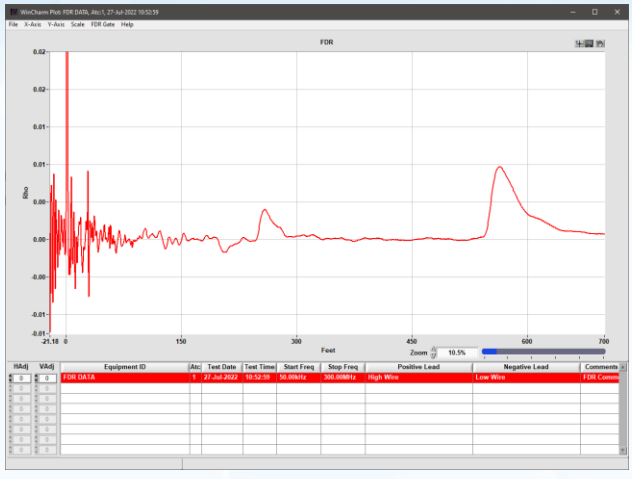
EXAMPLE OF FDR DATA (IMPULSE RESPONSE)



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EXAMPLE OF FDR DATA (IMPEDANCE)

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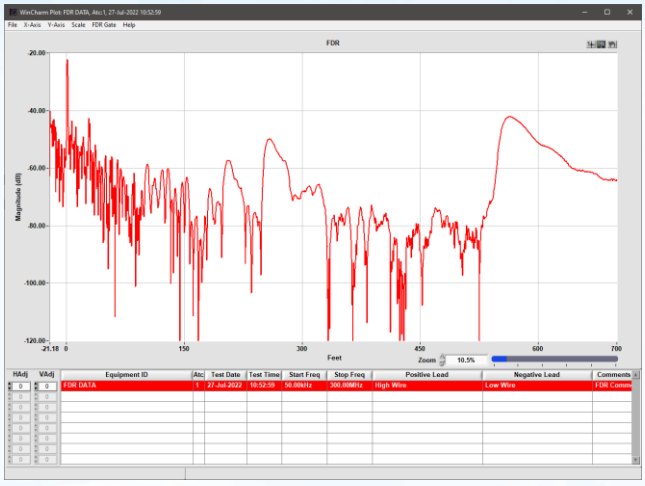
EXAMPLE OF FDR DATA (MAGNITUDE)



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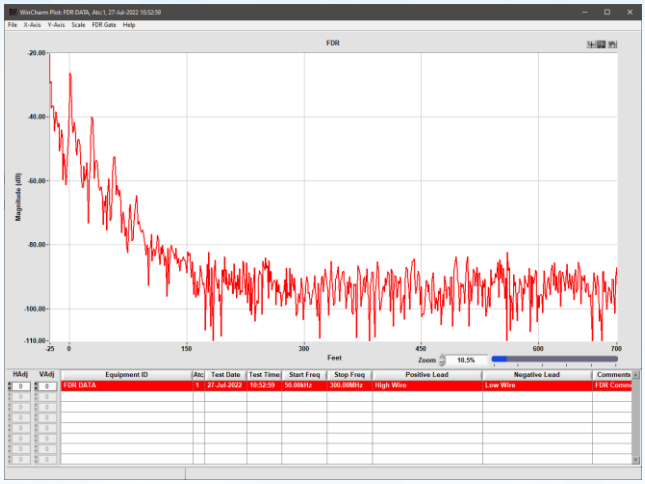
EXAMPLE OF FDR DATA (BANDPASS IMPULSE RESPONSE)



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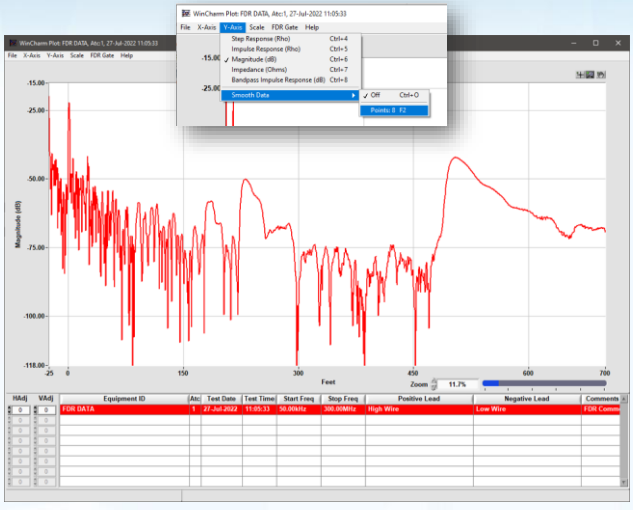
SOME VIEWS OF DATA CAN BE ENHANCED BY SMOOTHING DATA POINTS

- Click "Y-axis" then "Smooth Data" then "Points"



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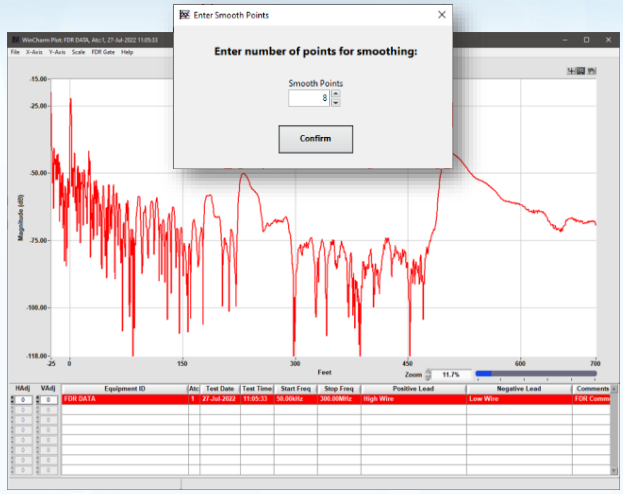
TYPE IN NUMER OF SMOOTH POINTS

- 10 points or below are recommended
- Higher volumes of smooth points can filter out details in the FDR data



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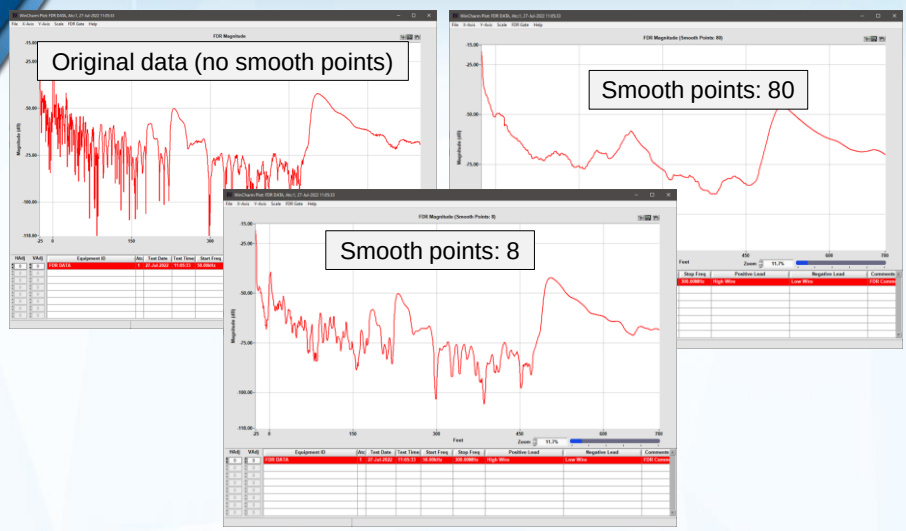
EXAMPLES OF SMOOTHED DATA



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PRACTICAL APPLICATIONS OF FDR TESTING

- Locating thermal 'hot spots'
- Trending insulation material degradation
- Identifying global insulation degradation
- Identifying and locating impedance changes such as key components in a cable circuit (i.e., connections, splices, transitions)
- Identifying anomalies in a cable circuit (i.e., short or open circuit, degraded connection)

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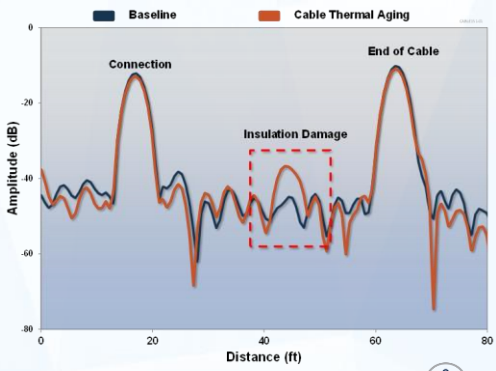
FDR LOCATES THERMAL 'HOT SPOTS' DEGRADING INSULATION MATERIAL



Benefits
• Non-destructive
• In-situ test
• Performed remotely from one end of the cable
• End Device can be connected
• Identify and trend insulation aging
• Also used to locate mechanical damage and moisture degradation

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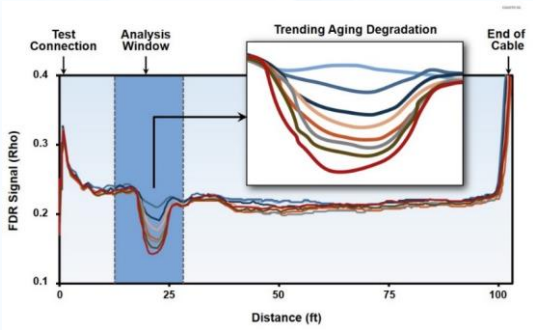
FDR TRENDS POLYMER DEGRADATION AS A RESULT OF THERMAL AGING OVER TIME COMPARED TO A HEALTHY BASELINE (LIGHT BLUE TRACE)

- The aging of cable insulation changes the permittivity of the polymer which can be identified with the FDR technique.
- The FDR test has demonstrated increased sensitivity as compared to other reflectometry methods for detecting subtle impedance changes that occur in insulation properties that result from aging



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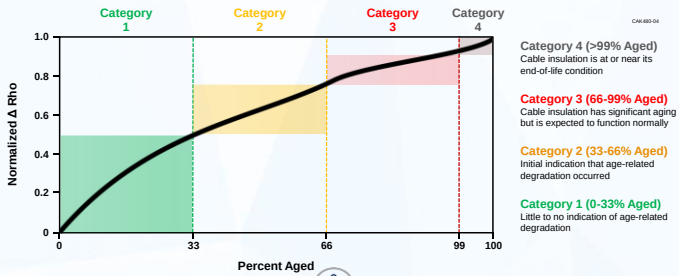
EXAMPLE FDR AGING CATEGORIES USED FOR QUANTIFYING THE DEGRADATION OF CABLE INSULATION MATERIAL

- **AMS has performed extensive aging research on a variety of cable polymers used in commercial power plants in the U.S. and worldwide.**
- **The results of these tests have shown that FDR can identify and locate age related degradation.**
- **The age-related degradation for polymeric cable insulation types have been categorized by AMS based on the percent of their aged life to define general acceptance criteria that can be used when performing in-plant testing. These four FDR aging categories for cable insulation are divided as shown Each category represents a "Percent (%) Aged" estimation for the cable under test as it relates to its end-of-life condition.**



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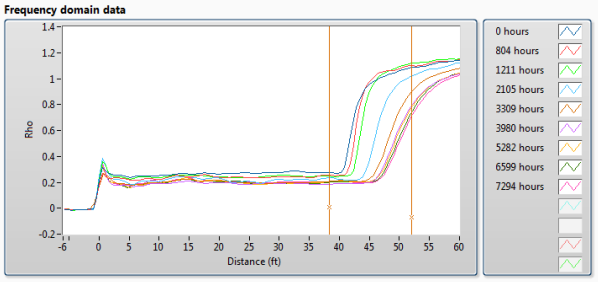
FDR TRENDS GLOBAL INSULATION DEGRADATION



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GLOBAL AGING AFFECTS THE VELOCITY OF PROPAGATION (VP) AND CAPACITANCE OF THE CABLE

Hours Aged	Distance (ft)	Δft	V_P	ΔV_P (%)
0	40.3	0.0	0.630	0.00
804	40.8	0.5	0.621	-1.37
1211	41.8	1.6	0.606	-3.85
2105	43.4	3.2	0.581	-7.83
3309	44.2	4.0	0.568	-9.81
3980	44.5	4.3	0.563	-10.56
5282	45.1	4.9	0.554	-12.05
6599	45.4	5.2	0.549	-12.80
7294	45.6	5.3	0.547	-13.17

$$C\left({}^{pF}/_{inch}\right) = \left(\frac{0.7065}{ln\frac{2s}{d}}\right) * \mathcal{E}_r$$

$\mathcal{E}_r$ - Relative Permittivity

$$Vp = \frac{1}{\sqrt{LC}}\ feet/sec$$

Hours	Vp	L (nH)	C (nF)
0	0.63	2.7	0.931
7294	0.54	2.7	1.25

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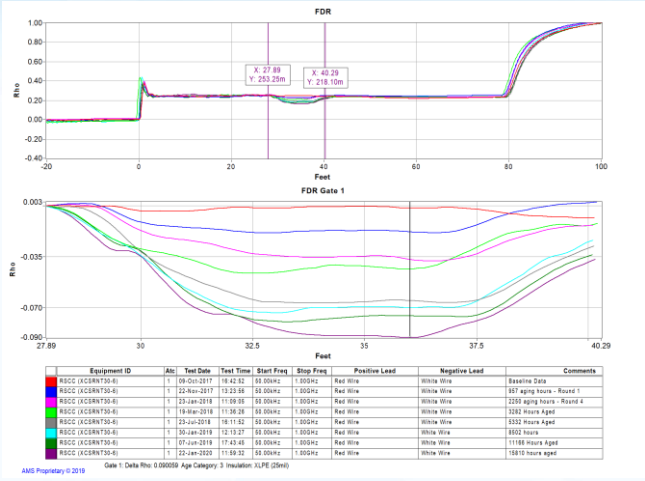
WINCHARM SOFTWARE SHOWING GATES USED TO QUANTIFY AGING DEGRADATION



	Equipment ID	Atc	Test Date	Test Time	Start Freq	Stop Freq	Positive Lead	Negative Lead	Comments
	RSCC (XCSRNT50-6)	1	09-Oct-2017	18:42:52	50.00kHz	1.00GHz	Red Wire	White Wire	Baseline Data
	RSCC (XCSRNT50-6)	1	22-Nov-2017	13:23:56	50.00kHz	1.00GHz	Red Wire	White Wire	667 aging hours - Round 1
	RSCC (XCSRNT50-6)	1	23-Jan-2018	11:09:05	50.00kHz	1.00GHz	Red Wire	White Wire	2250 aging hours - Round 4
	RSCC (XCSRNT50-6)	1	19-Mar-2018	11:36:26	50.00kHz	1.00GHz	Red Wire	White Wire	3282 Hours Aged
	RSCC (XCSRNT50-6)	1	23-Jul-2018	16:11:52	50.00kHz	1.00GHz	Red Wire	White Wire	5332 Hours Aged
	RSCC (XCSRNT50-6)	1	30-Jan-2019	12:13:27	50.00kHz	1.00GHz	Red Wire	White Wire	8602 hours
	RSCC (XCSRNT50-6)	1	07-Jun-2019	17:43:48	50.00kHz	1.00GHz	Red Wire	White Wire	11166 Hours Aged
	RSCC (XCSRNT50-6)	1	22-Jan-2020	11:59:32	50.00kHz	1.00GHz	Red Wire	White Wire	15810 hours aged

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REFLECTOMETRY TESTING CONSIDERATIONS

- The cable configuration must have parallel transmission lines such as multi-conductors, conductor and shield, or conductor and ground plane.
- For large frequency spans, the test signal is attenuated over the length of a cable circuit, which results in a lower resolution (distance between data points).
- The test results of a cable circuit are normally very repeatable over time. Impedance changes from an unexpected short or open connection are obvious and easily located on an FDR plot relative to baseline. However, smaller changes in impedance from a baseline are subtle and can be difficult to identify. These small impedance changes can be caused by localized degradation such as corrosion, loose or damaged connectors, resistive connections, cuts and gouges, moisture intrusion, or localized aging of the cable insulation.

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PERFORMING A FULL VNA CALIBRATION

- A full calibration must be performed for every frequency range used in an EID (i.e., 50 kHz – 300 MHz with 6000 points)
- Software will not allow user to acquire data if full FDR calibration is not present in the database
- Tools needed include a Philips screwdriver, calibration tee, N-to-SMA adapter, torque wrench, test lead, and test clips to create a short circuit

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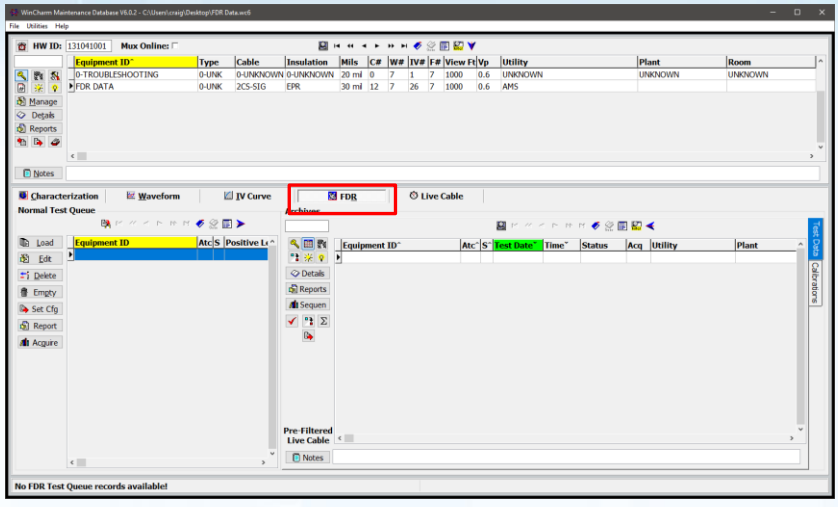
TO PERFORM A CALIBRATION, GO TO THE "FDR" TAB



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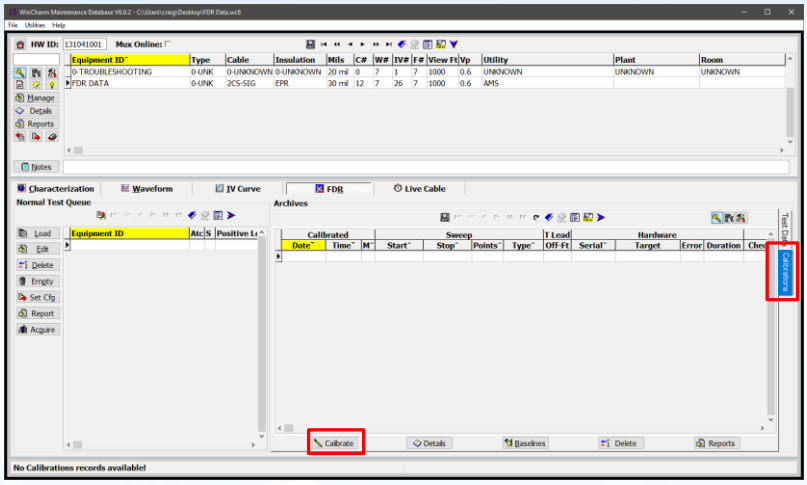
CLICK THE "CALIBRATIONS" TAB AND CLICK "CALIBRATE"



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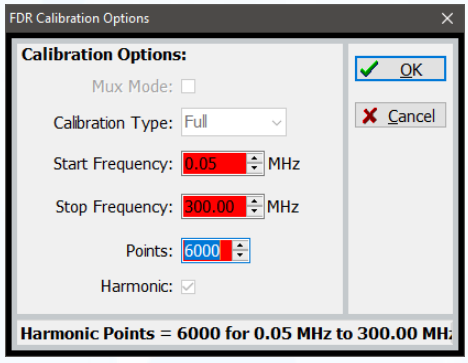
VERIFY CALIBRATIONT YP EIS "FULL" THEN MODIFY THE PARAMETERS AND CLICK "OK"



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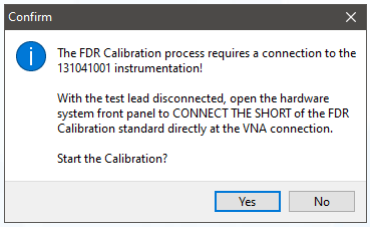
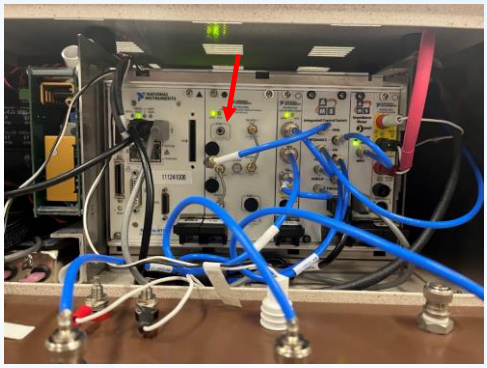
FOLLOW THE PROPMPT TO CONTINUE CALIBRATION

- Remove front panel to access the VNA
- Using the torque wrench, remove cable from Port 1 of the VNA





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INSTALL THE "SHORT" CONNECTOR OF THE CALIBRATION TEE AND ADAPTER ONTO PORT 1 OF THE VNA

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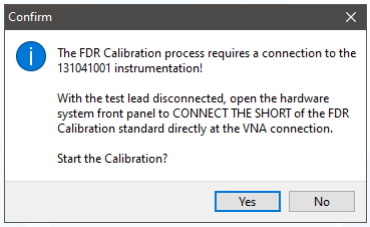
FOLLOW THE PROMPT TO CONTINUE CALIBRATION

- Once properly connected to Port 1, click “Yes” to continue calibration process



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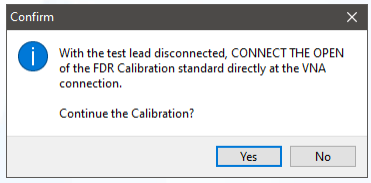
FOLLOW THE PROMPT TO CONTINUE CALIBRATION

- Remove the calibration tee and connect the “Open” connector to Port 1
- Click “Yes” to continue the calibration process



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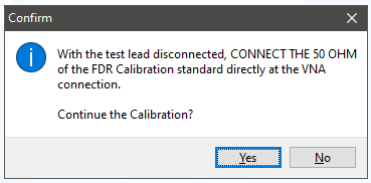
FOLLOW THE PROMPT TO CONTINUE CALIBRATION

- Remove the calibration tee and connect the “Load” connector to Port 1
- Click “Yes” to continue the calibration process



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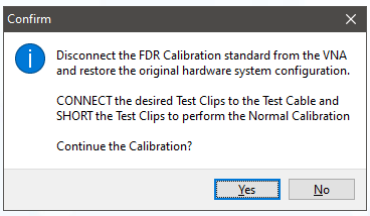
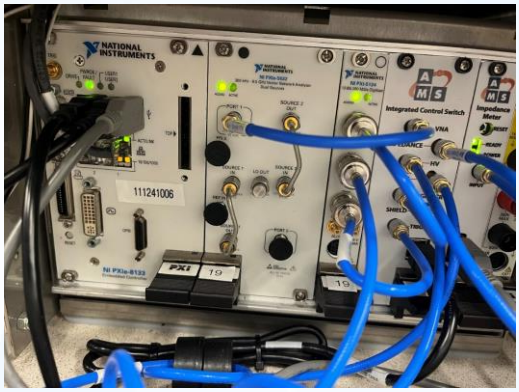
FOLLOW THE PROPPT TO CONTINUE CALIBRATION

- Remove the calibration tee
- Install the cable to Port 1 using the torque wrench (turn until hear a click)





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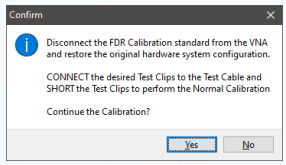
FOLLOW THE PROMPT TO CONTINUE CALIBRATION

- Connect the yellow test lead to Channel 1 on front of the CHAR System
- Connect the test adapter onto the test lead and short the wires
- Click “Yes” to continue the calibration process



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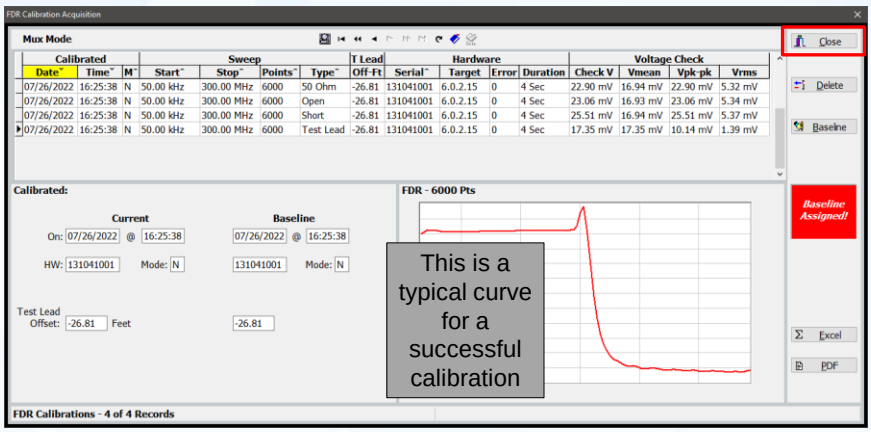
REVIEW THE CALIBRATION RESULTS

Click “Close” to return to the main screen in WinCharm software



This is a typical curve for a successful calibration

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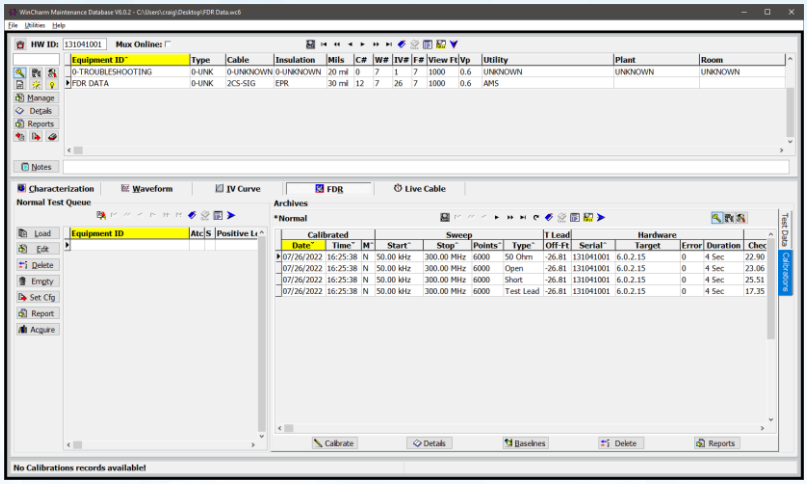
REVIEW THE CALIBRATION DETAILS



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PERFORMING A TEST LEAD CALIBRATION ONLY

- A test lead calibration should be done if the CHAR System has cycled power or if the user has changed test leads
- A test lead calibration determines the length of the test lead and compensates its length and electrical parameters from the acquired FDR data.
- The test lead calibration skips the short, open, load portions of the full calibration; therefore, is not impacted by the frequency span or number of points set in the EID.
- Tools needed include the test lead and test clips to create a short circuit

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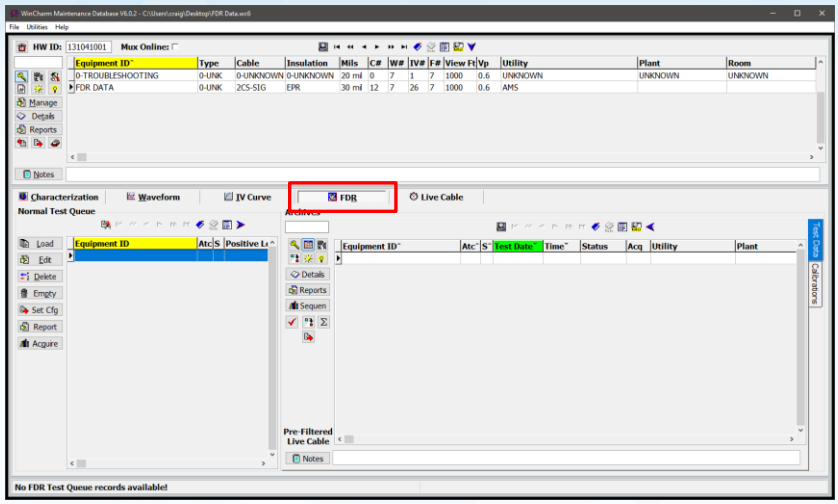
TO PERFORM A CALIBRATION, GO TO THE "FDR" TAB



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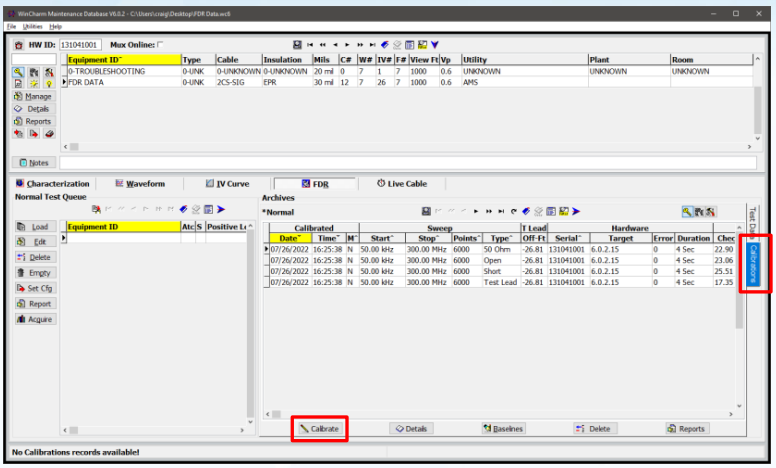
CLICK THE "CALIBRATIONS" TAB AND CLICK "CALIBRATE"



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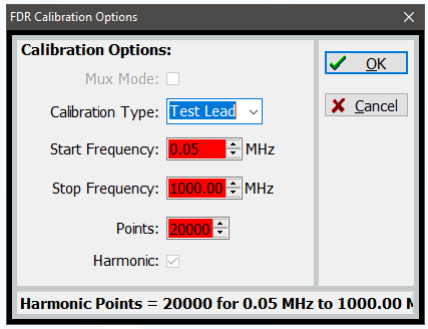
VERIFY THE CALIBRATION TYPE IS "TEST LEAD" THEN CLICK "OK"



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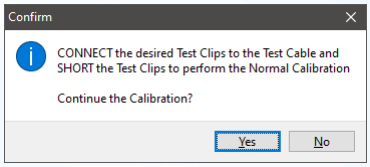
FOLLOW THE PROMPT TO CONTINUE THE TEST LEAD CALIBRATION



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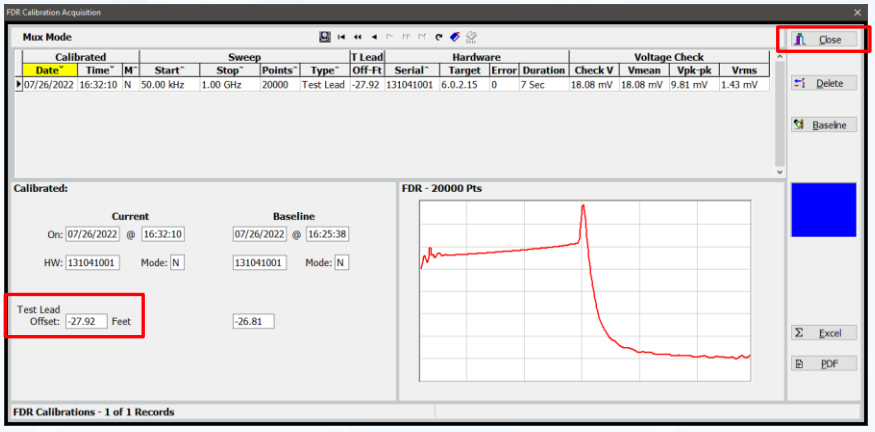
REVIEW THE TEST LEAD CALIBRATION RESULTS

Click "Close" to return to the main screen in WinCharm software



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Thank You!

Questions?