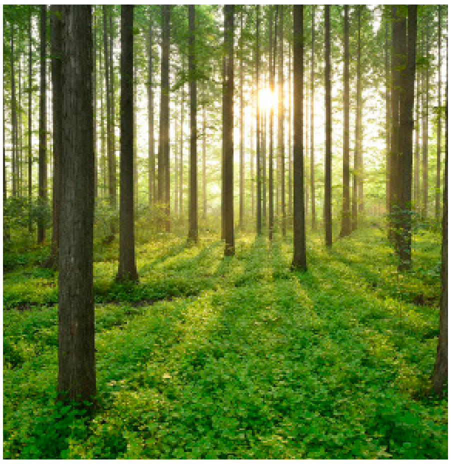
WIRELESS EMC TESTING OF NUCLEAR POWER PLANT EQUIPMENT FOR ENERGIFORSK

REPORT 2023:956



ENERGIFORSK NUCLEAR SAFETY RELATED I&C, ENSRIC

Energiforsk

Wireless EMC Testing of Nuclear Power Plant Equipment for Energiforsk

Radiated Susceptibility Testing

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Foreword

Wireless technologies can provide many positive aspects for a nuclear facility, such as easier and faster ways to connect equipment and monitor plant and equipment status or provide a more cost-effective way to do test measurements or temporary installations compared to hardwired systems. One problem with wireless systems within nuclear power plants is that a large share of the existing equipment in the plant is developed and installed prior to many EMC standards and hence it is difficult to really know which equipment that can be affected by wireless networks and how this effect manifest into the equipment functionality. Also, many prior tests that has been performed have been against wireless or radio protocols and techniques that are no longer in use.

To investigate the sensitivity of the existing equipment at the Nordic nuclear power plants this project has been carried out to perform standardized tests that subject the equipment to well defined electromagnetic disturbances. The test has been performed within frequency ranges that covers today mobile and wireless technologies, in an environment that is very close to the real nuclear power plants.

Besides the result from the testing, the procedures used can also be valuable in validation of wireless solutions at site to identify critical and sensitive equipment.

The testing was carried out by a team from Analysis and Measurement Services (AMS) Corporation Whitney Kirby, Chad Kiger at the KSU testing facility in Forsmark. The ENSRIC programme is a part of the Energiforsk nuclear portfolio, financed by Vattenfall, Uniper, Fortum, TVO, Skellefteå Kraft and Karlstads Energi.

Summary

This report provides the final results and details of the radiated Electromagnetic Compatibility (EMC) susceptibility testing of Nuclear Power Plant (NPP) equipment located in the KSU training facility.

This work was performed between November 14th, 2022 and November 18th, 2022 by Analysis and Measurement Services (AMS) Corporation. The EMC testing that was performed consisted of a "specialized" Electromagnetic Interference/ Radio Frequency Interference (EMI/RFI) wireless coexistence test. The susceptibility testing was performed based on guidance from EPRI TR-102323 Revision 5, "Guidelines for Electromagnetic Compatibility Testing of Power Plant Equipment," using the RS103 Radiated Susceptibility (Electric Field, High Frequency) test method of MIL-STD-461G, "Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment," as outlined in the approved AMS test plan, EGF221101R0-T.

High frequency radiated susceptibility testing (RS103) was performed on three (3) cabinets, twelve (12) sensors, and one (1) equipment panel at the KSU facility. The purpose of this testing was to provide an understanding of the vulnerability of representative plant equipment to electromagnetic interference from wireless signals. While a majority of the equipment was found to be immune to the RS103 test signal, there were several pieces of equipment which exhibited susceptibility to the RF energy. As time permitted, AMS attempted to identify methods for improving the immunity of the equipment to RF energy and/or established the threshold RF level at which the equipment was not affected during the testing.

Additionally, a walkdown of the Forsmark Nuclear Plant was performed to compare the equipment, and its installation in a nuclear power plant, with the equipment installation at the KSU facility to determine the applicability of extending the results at the KSU facility to the fleet of nuclear power plants.

Keywords

Electromagnetic Compatibility (EMC) - Elektromagnetisk Kompatibilitet, Electromagnetic Interference (EMI) - Elektromagnetisk Störning, Radiated Susceptibility - Utstrålad Mottaglighet, Wireless Coexistence - Trådlös Samexistens, Exclusion Zones – Uteslutningszoner, Nuclear Power - Kärnkraft

Sammanfattning

Den här rapporten innehåller de slutliga resultaten och detaljerna för den elektromagnetiska kompatibiliteten (EMC) hos kärnkraftverkets (NPP) utrustning som finns i KSU:s utbildningsanläggning.

Arbetet utfördes mellan den 14 november 2022 och den 18 november 2022 av Analysis and Measurement Services (AMS) Corporation. EMC-testningen som utfördes bestod av ett "specialiserat" trådlöst samexistenstest för elektromagnetisk störning/radiofrekvensstörning (EMI/RFI). Känslighetstestet utfördes baserat på riktlinjer från EPRI TR-102323 Revision 5, "Guidelines for Electromagnetic Compatibility Testing of Power Plant Equipment", med hjälp av testmetoden RS103 Radiated Susceptibility (Electric Field, High Frequency) i MIL-STD-461G, "Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment", som beskrivs i den godkända AMS-testplanen, EGF221101R0-T.

Mätning av känsligheten för högfrekvent strålning utfördes på tre skåp, tolv sensorer och en utrustningspanel vid KSU:s anläggning. Syftet med testet var att få en uppfattning om hur känslig den representativa anläggningsutrustningen är för elektromagnetisk störning från trådlösa signaler. Även om en majoritet av utrustningen visade sig vara immun mot RS103-testsignalen, fanns det flera utrustningsdelar som visade sig vara känsliga för RF-energin. I mån av tid försökte AMS identifiera metoder för att förbättra utrustningens immunitet mot RF-energi och/eller fastställa den RF-nivå vid vilken utrustningen inte påverkades under provningen.

På Forsmarks kärnkraftverk jämfördes en rundtur (walkdown) för att jämföra med den utrustning som använts vid anläggningen på KSU för att fastställa om det är möjligt att tillämpa resultaten till de faktiska kärnkraftverken.

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Energiforsk

1 Introduction

The objective of the wireless susceptibility testing at the KSU training facility was to determine the immunity of various pieces of representative nuclear power plant equipment to RF energy from wireless signals. The RF energy was generated at frequencies typical of cellular phones and Wi-Fi enabled devices. By performing this testing on installed equipment, Energiforsk can have a level of confidence that the devices tested, and those of the same manufacturer and similar installation, will be immune to the signals generated by cellular phones and other wireless electronic devices. The testing was performed at power levels which were higher than the test levels used during Electromagnetic Compatibility (EMC) qualification testing to reduce the distance that wireless devices should remain away from sensitive plant equipment. For equipment which was found to be immune to the RF energy, no further investigation was necessary. For equipment which was found to be susceptible, further measures were taken to identify the threshold of susceptibility and/or to improve its immunity to the wireless signals.

AMS was contracted by Energiforsk to perform this testing at the KSU facility which allowed for the testing to be completed without the potential of causing adverse actions in a nuclear power plant. The equipment at the KSU facility is intended to represent typical equipment installed in Swedish nuclear power plants.

2 Abbreviations and Acronyms

AMS	Analysis and Measurement Services
EMC	Electromagnetic Compatibility
EMI/RFI	Electromagnetic Interference/ Radio Frequency Interference
EPRI	Electric Power Research Institute
EUT	Equipment Under Test
IEC	International Electrotechnical Commission
KSU	Kärnkraftsäkerhet och Utbildning (Nuclear Safety and Education)
NPP	Nuclear Power Plant
RF	Radio Frequency
RS	Radiated Susceptibility

3 Description of Testing

RF immunity testing was performed to verify the ability of Nuclear Power Plant equipment installed at KSU to withstand radiated electric field strengths and frequency ranges typical of those emitted by wireless technology such as tablets, cellular phones, and other wireless mobile devices. This section describes the wireless immunity test method that was used to verify the performance of the KSU equipment in the presence of RF energy. This section also contains a list of the KSU equipment which was subjected to the wireless immunity testing.

3.1 RS103 RADIATED SUSCEPTIBILITY, ELECTRIC FIELD, HIGH FREQUENCY

The EMC testing was conducted using guidance from the High Frequency, Radiated Susceptibility (RS103) test method of MIL-STD-461G. The equipment under test (EUT) was subjected to radiated electric fields of at least 30 V/m using a 1 kHz, pulse modulated, 50% duty cycle signal in specific wireless communication frequency bands. The frequency bands were between 420 MHz to 5.85 GHz and are listed in Table 1. Within each frequency band, an RF field strength of 30V/m was subjected to the EUT. Figure 1 shows the amplitude of the injected RF energy for the various frequency bands during testing. To comply with the requirements of RS103, each EUT was required to operate within the bounds of the acceptance criteria listed in Section 3.3 when subjected to the test signal.

In order to simulate a wireless device in close proximity to the EUT, AMS used a signal generator, high frequency broadband power amplifier, and an antenna to generate the interfering signal and direct it toward selected piece(s) of equipment. A physically small, electrically short, electric field sensor was placed directly opposite from the transmit antenna at the front of the EUT to provide electric field data from the EUT location during susceptibility testing to establish the desired electric field. Figure 2 shows a block diagram of the system used to generate and monitor the immunity test signal. This testing was performed with the transmitting antenna at least one meter from the EUT, when possible, and in both the vertical and horizontal antenna polarizations. If one meter was not achievable due to EUT positioning or surrounding obstacles, the furthest possible distance was used. Table 2 is a list of the transmitting antennas and their associated frequencies that were used during this testing.

Table 1 – RS103 wireless communication frequency bands

Frequency Range	Typical Emitter Type
420 to 490 MHz	Plant Radios and Crane Controls
698 to 960 MHz	Cellular Phones and ISM Devices
1428 to 2700 MHz	Cellular Phones, Wi-Fi Devices, Bluetooth Devices
3300 to 3800 MHz	Cellular Phones
5150 to 5875 MHz	Wi-Fi Devices

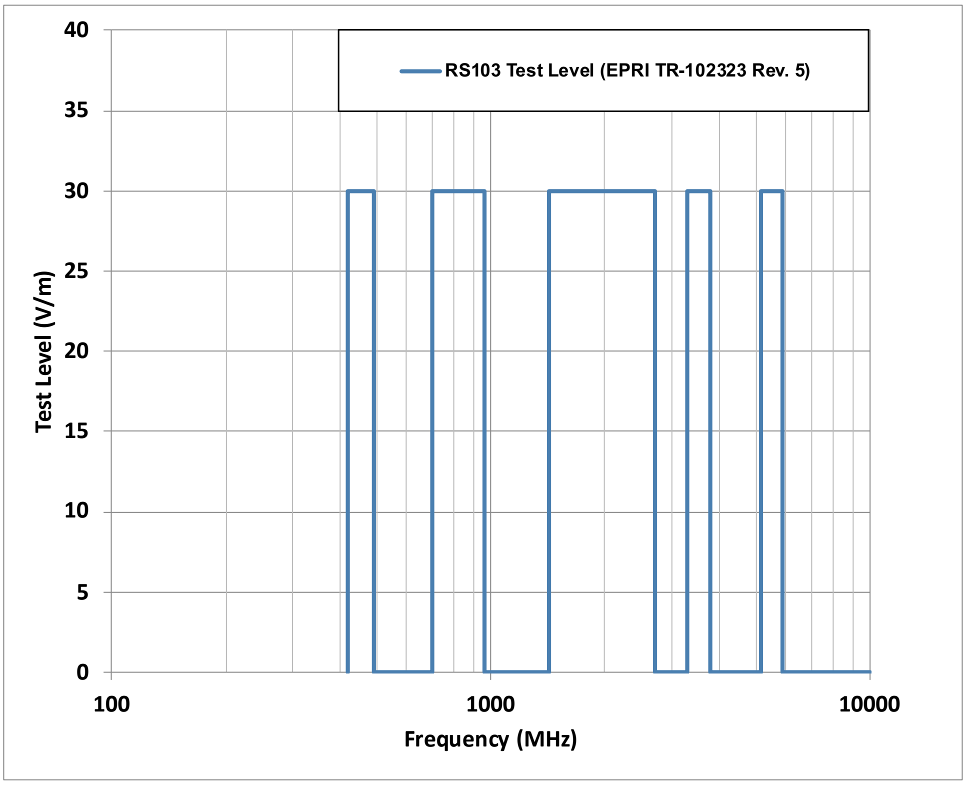

Figure 1 –- RS103 limit line covering wireless communication frequencies

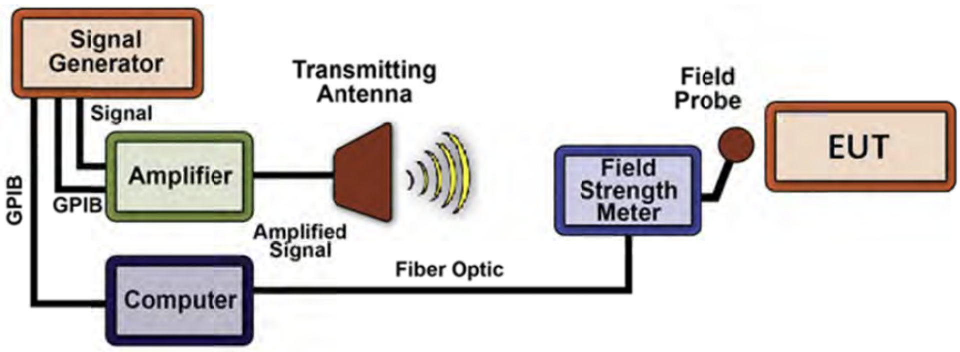

Figure 2 – Block diagram of the wireless immunity test system

Table 2 – Transmitting antenna types used during testing

Frequency Range	Antenna
420 MHz to 490 MHz	Log Periodic
698 MHz to 5.875 GHz	Double-Ridged, High Frequency Horn

3.2 TEST LOCATIONS

Upon arrival at the KSU facility, AMS worked with KSU and plant personnel to identify the representative list of equipment to test for immunity to RF signals. The test locations and associated ID#'s of the equipment, including their function, is provided in Table 3. This equipment list included three (3) cabinets and within each cabinet there were numerous modules which provide different functions. The modules in each cabinet that were tested are listed in Table 4. Figure 3 through Figure 11 are photographs of the various pieces of equipment that were tested.

Table 3 – Test locations and equipment identification

Test Location	ID	Function	Sensor
1	912K202	Differential Pressure	Yokogawa EJX110A
2	912K302	Flow Measurement	Yokogawa EJX910A
3	912K401	Level Measurement	ABB 265DS
4	921K301	Flow Measurement	Yokogawa EJX910A
	921K302	Flow Measurement	ABB 265DS
5	921K105	Pressure Measurement	ABB 265GS
	921K401	Level Measurement	ABB 265DS
6	921K403	Level Switch	Mobrey S01DB/84
	921K404	Level Switch	Mobrey S01DB/84
	921K405	Level Switch	Mobrey S01DB/84
7	921K502	Temperature Measurement	EPIC PT100 W-B-9K-D
	921V29	Valve	Fisher Fieldvue DVC2000
8	ZHD.102	Wiring Junction Box	N/A
9	THE.103	Equipment Cabinet	N/A
10	THE.104	Equipment Cabinet	N/A
11	THE.102	Equipment Cabinet	N/A

Table 4 – Modules within the Cabinets that were subjected to RF Testing

Cabinet ID	Modules	Function
THE.102	912K301 (QAIC201)	Flow Measurement (Value)
	912K402 (QAIC201)	Level Measurement (Value)
	912K301 (QAPL210)	Flow Measurement (Alarm Indication)
	912K402 (Givarfel)	Level Measurement (Alarm Indication)
THE.103	912K202 (QAIL201)	Differential Pressure Measurement
	912K302 (QAIC201)	Flow Measurement
	921K301 (QAIL201)	Flow Measurement
	921K502 (QAIL202)	Temperature Measurement
	912K401 (QAIL201)	Level Measurement
	921K401 (QAIL201)	Level Measurement
	921K504 (QAIL202)	Temperature Measurement
	921K105 (QAIL201)	Pressure Measurement
THE.104	912V36	Valve Position Indication
	912V36	Valve Regulator Deviation
	931K502 (QAIC201)	Temperature Measurement
	931K301 (QAIC201)	Flow Measurement (Value)
	931K301H1 (QAPL210)	Flow Measurement (High Alarm)
	931K301L1 (QAPL210)	Flow Measurement (Low Alarm)

Figure 3 - Test location 1 (Sensor 912K202) – Yokogawa EJX110A Differential Pressure Transmitter

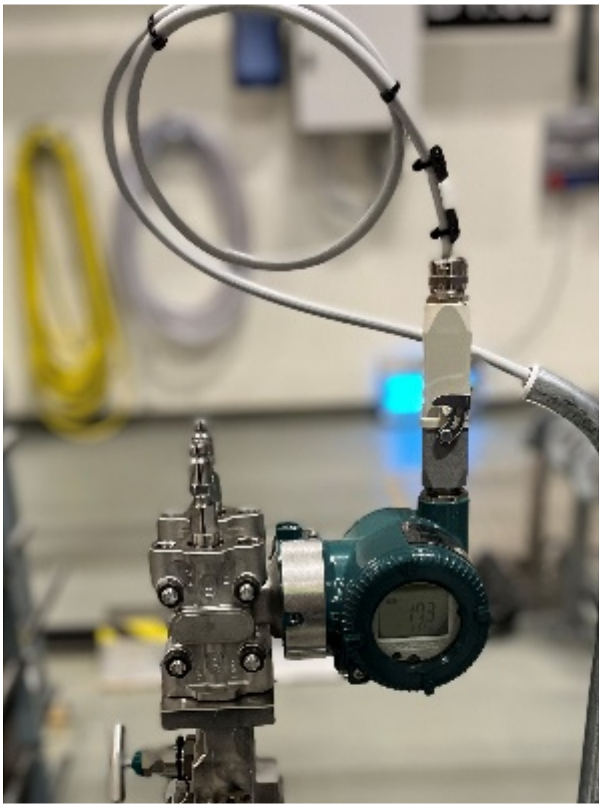

Figure 4 - Test location 2 (Sensor 912K302) – Yokogawa EJX910A Flow Transmitter

Figure 5 - Test location 3 (Sensor 912K401) – ABB 265DS Level Transmitter

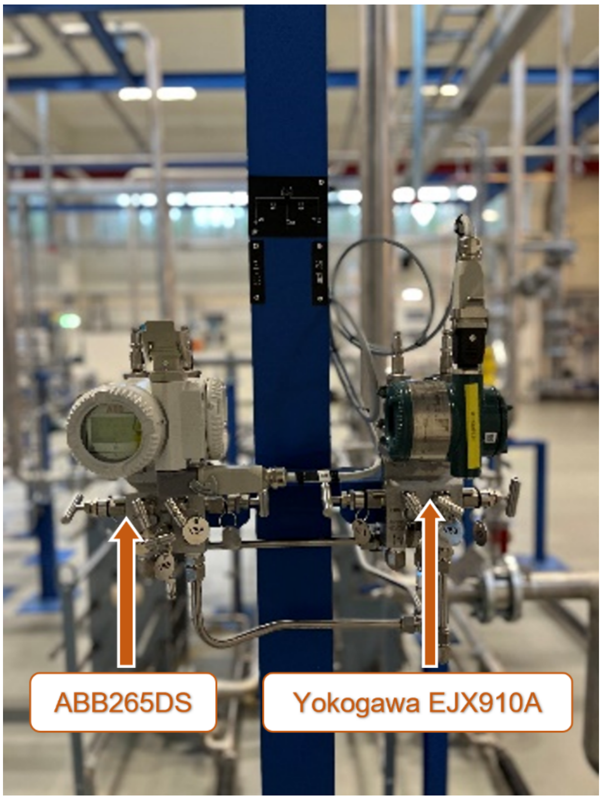

Figure 6 – Test location 4 – Yokogawa EJX910A Flow Transmitter (Sensor 921K301) and ABB 265DS Flow Transmitter (Sensor 921K302)

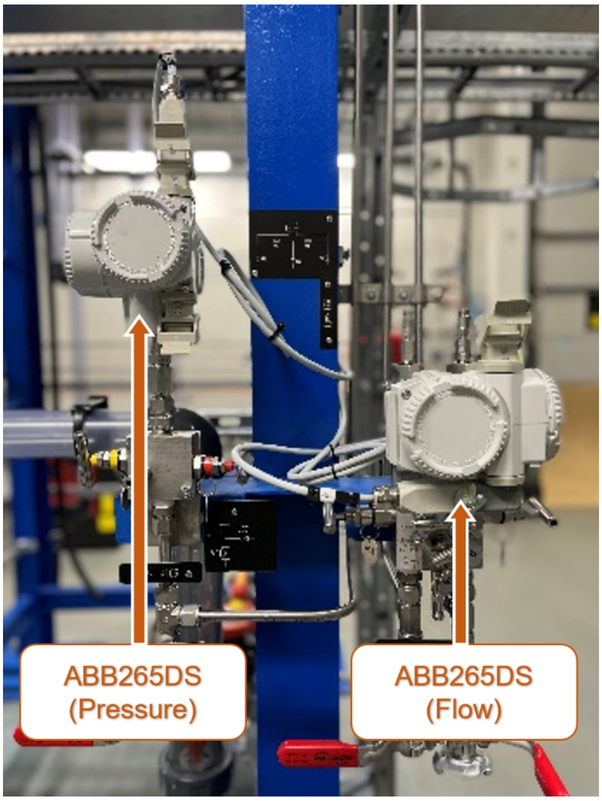

Figure 7 – Test location 5 – ABB 265DS Pressure Transmitter (Sensor 921K105) and ABB 265DS Level Transmitter (Sensor 921K401)

Figure 8 – Test Location 6 – Mobrey S01DB/84 Level Switch (Sensors 921K403, 921K404, and 921K405)

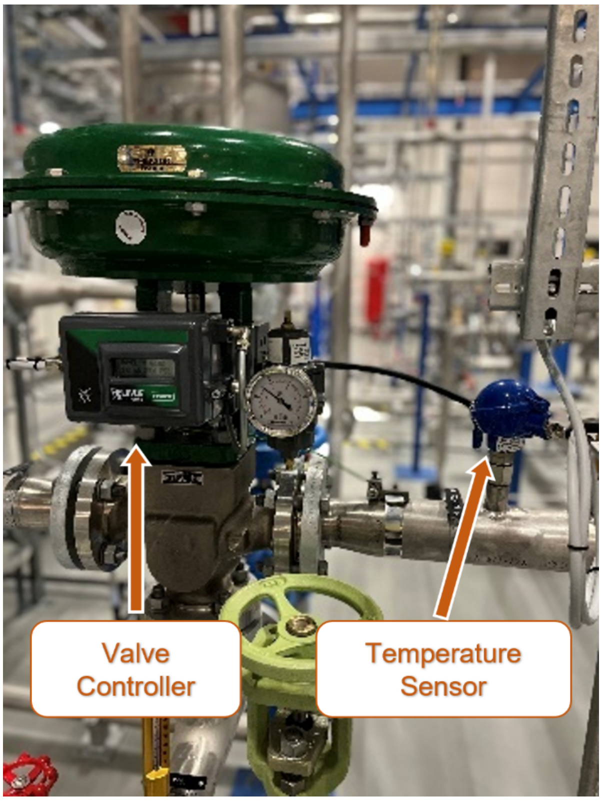

Figure 9 – Test Location 7 – EPIC PT100 W-B-9K-D Temperature Sensor (Sensor 921K502) and Fisher Fieldvue DVC2000 Valve Controller (Sensor 921V29)

Figure 10 – Test Location 8 – Wiring Junction Box (ZHD.102)

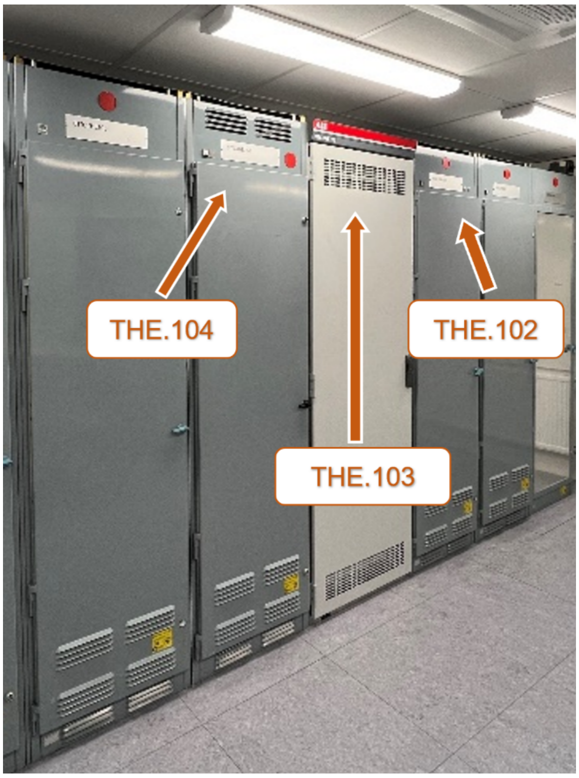

Figure 11 – Test Locations 9, 10, and 11 – I/O Equipment Cabinets (THE.102, THE.103, and THE.104)

3.3 EUT ACCEPTANCE CRITERIA

The equipment under test was monitored during testing to verify its performance remained within acceptable limits.

The general acceptance criteria for the systems that were tested were the following:

- No physical damage to the equipment.
- No loss of function during testing.
- No system alarms reported.
- All digital valued I/O shall not spuriously change state as a result of the testing.
- No actuation of any local or remote alarm.
- No nuisance of indicating lights or displays.
- No change of state of status or position of any component.
- All analog I/O shall not deviate from their nominal values by more than the specified values as defined by Energiforsk personnel during testing. If larger deviations were observed, the deviation values and frequency ranges were reported to Energiforsk personnel for immediate evaluation. Unacceptable levels of deviation were mitigated or dispositioned.

Monitoring data was collected by plant personnel for every piece of equipment that was tested using a digital recorder or digital multimeter. Most monitoring data was collected by connecting the monitoring equipment into test points within the control cabinets to record the indicated value of each piece of equipment. The control cabinets at the KSU facility, shown in Figure 12, contain the instrumentation and control equipment necessary for flow loop operation. The specific monitoring data recorded during testing for each piece of equipment that was tested is detailed in Section 4. There were two sensors, 921K302 and 921K105, that were not wired to the control cabinet. The local indication on these sensors were visually monitored during testing to verify there were no significant fluctuations.

Certain equipment (level switches, alarm indication cards, etc.) do not provide an analog output, and therefore, monitoring data values are not provided for this equipment. The monitoring that was performed consisted of verifying their indication did not change state during testing.

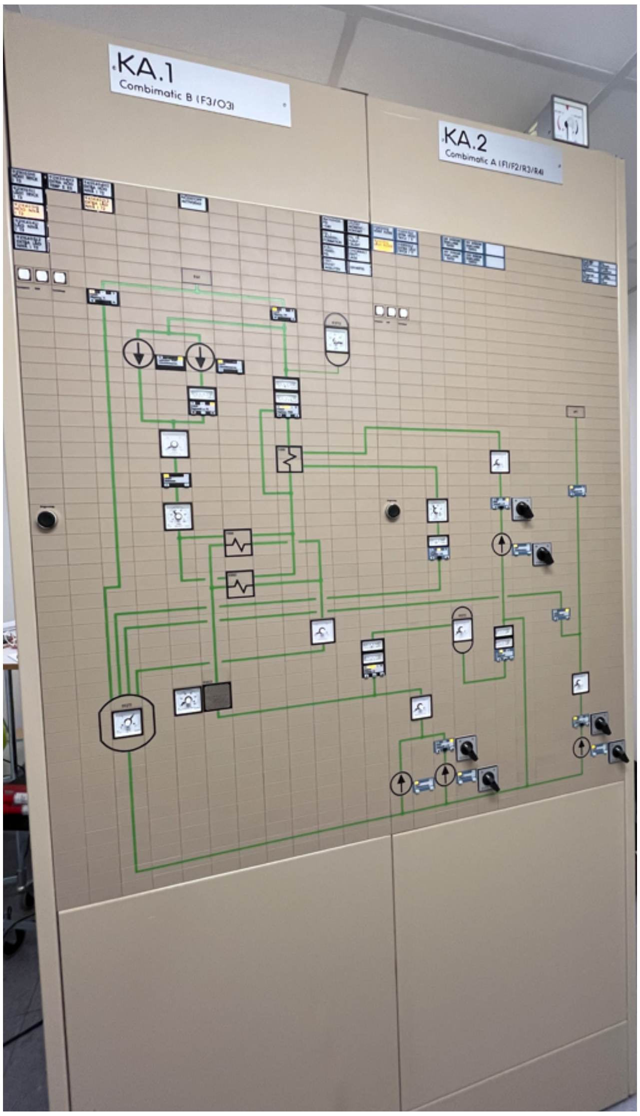

Figure 12 – Photograph of the Control Cabinets at the KSU Facility

3.4 TEST PLAN MODIFICATIONS

After arriving at the KSU facility and developing the specific list of equipment to test, several modifications were made to the test approach outlined in AMS test plan, EGF221101R0-T. These modifications were implemented in order to test as much equipment as possible within the allotted timeframe. Two main modifications were made to the RS103 test method as described below. A test signal with the following characteristics was used to decrease the test time at each location:

- The injected RS103 signal dwelled at each frequency point for 2 seconds instead of 3 seconds.
- Within each of the frequency bands, the signal was stepped by increments of 1% of the previous frequency rather than the smaller step sizes specified in MIL-STD-461G.

For MIL-STD-461G testing, a dwell time of 3 seconds is required to allow sufficient time for the system to respond to the interfering signal. However, some systems, such as those being tested at the KSU facility, likely would not require 3 seconds for them (or their output) to respond to the external stimulus. Therefore, the dwell time was reduced to 2 seconds. In addition, MIL-STD-461G specifies a frequency step size depending on the frequency range of test. In the frequency range of 30 MHz – 1 GHz, the maximum frequency step size is 0.5% of the previous frequency and this step size reduces to 0.25% in the frequency range of 1 GHz – 40 GHz. For the testing at KSU, AMS increased this step size to 1% for the entire frequency range.

The new signal characteristics adopted for the testing at the KSU facility are aligned with the testing approach contained within the International Electrotechnical Commission (IEC) 61000-4-3 standard. This IEC standard is the high frequency radiated immunity test equivalent of the RS103 test method. The IEC 61000-4-3 test uses a frequency step size of 1% of the previous frequency and allows for a dwell time of as low as 0.5 seconds. Because of the equivalency of the test methods, it was determined by AMS personnel that, in the interest of time, these modifications to the RS103 test method would not have a significant impact on the test results.

In addition to the modifications to the test signal, the equipment at KSU being subjected to the wireless immunity was slightly altered from the equipment specified in the test plan. The equipment list was reduced to account for the limited test time (1 week) at the facility. However, even though the equipment list was reduced, a representative sample of the equipment at the KSU facility was tested. Table 5 provides a list of the equipment that was not tested (based upon its ID) but notes the Equipment ID of similar equipment and installations that was subjected to the RF immunity testing. In the case of Equipment IDs 912K402, 921K504, 931K502, and 951K102, the installations of these sensors are almost identical to other equipment that was tested. Therefore, these sensors would likely have similar test results. In the case of sensors 912K301 and 931K301, their installation is similar to sensor 921K302, however, these sensors have a ground wire installed that attached the housing of the sensor to the grounded piping. This ground wire could potentially impact the susceptibility of the sensor thus affecting the extension of the test results of the 921K302 sensor to the 912K301 and 931K301 sensors.

Table 5 – Equipment in the KSU facility that was listed in the original test plan but was not tested

ID	Function	Sensor	Notes
912K301	Flow Measurement	Yokogawa EJX910A	Similar model and installation as 912K302, includes addition of a ground wire
912K402	Level Measurement	ABB 265DS	Similar model and installation as 921K302, different function
921K504	Temperature Measurement	EPIC PT100 W-B-9K-D	Similar model and installation as 921K502
931K301	Flow Measurement	Yokogawa EJX910A	Similar model and installation as 921K302, includes addition of a ground wire
931K502	Temperature Measurement	EPIC PT100 W-B-9K-D	Similar model and installation as 921K502
951K102	Pressure Measurement	ABB 265GS	Similar model and installation as 921K105

4 Test Results

The following sections contain the results of the RF immunity testing of equipment at the KSU facility. Testing the equipment within the KSU facility provided an opportunity to test equipment that is representative of nuclear power plant equipment without the associated risk of impacting plant operations. In the instances where vulnerabilities were identified in the equipment at the KSU facility, mitigation strategies were implemented such as shielding the equipment/cabling and/or establishing a threshold level at which the equipment was immune to the RF energy.

Since the installation of the equipment in the KSU facility may not exactly replicate the actual installation in a nuclear power plant environment, an evaluation should be performed to extend these results to existing plant equipment.

4.1 RF IMMUNITY TESTING

The RF immunity testing was performed according to the MIL-STD-461G RS103 test method with modifications as outlined in Section 3.4. The test method and procedures for the immunity testing are documented in AMS Test Plan, EGF221101R0-T, which is provided as Appendix C of this report. The specific test equipment used to generate, radiate, and measure the RF energy during testing is included in the datasheets provided in Appendix A. The KSU equipment under test was monitored by plant personnel as discussed in Section 3.3 of this report.

All equipment listed in Section 3.2 was subjected to an electric field strength of 30 V/m for the following five frequency ranges:

- 420 to 490 MHz
- 698 to 960 MHz
- 1428 to 2700 MHz
- 3300 to 3800 MHz

5150 to 5875 MHz

Figure 13 shows an example plot of the data recorded from the electric field strength probe during testing. This figure is from Test Location 1 (Sensor 912K202) with the transmitting antenna in the horizontal orientation. All five frequency ranges are shown on the graph including the specific field strength that was measured at each data point. Figure 14 shows an example plot where vulnerabilities were identified with sensor 912K302 and thresholding was performed. As seen in the plot, the sensor could withstand a field strength of 30 V/m for the two frequency bands below 1 GHz, but at frequencies above 1 GHz, the sensor could not withstand RF energy at a field strength of 30 V/m. The sensor could only withstand an electric field strength of 5 V/m in the frequency range of 1428 to 2700 MHz, a field strength of 10 V/m in the frequency range of 3300 to 3800 MHz, and a field strength of 15 V/m in the frequency range of 5150 to 5875 MHz. These test results were established with the transmitting antenna in the horizontal polarization. The plots of the field strength levels that each piece of equipment could withstand for all test locations, and for both polarizations of the transmitting antenna, are provided in Appendix B.

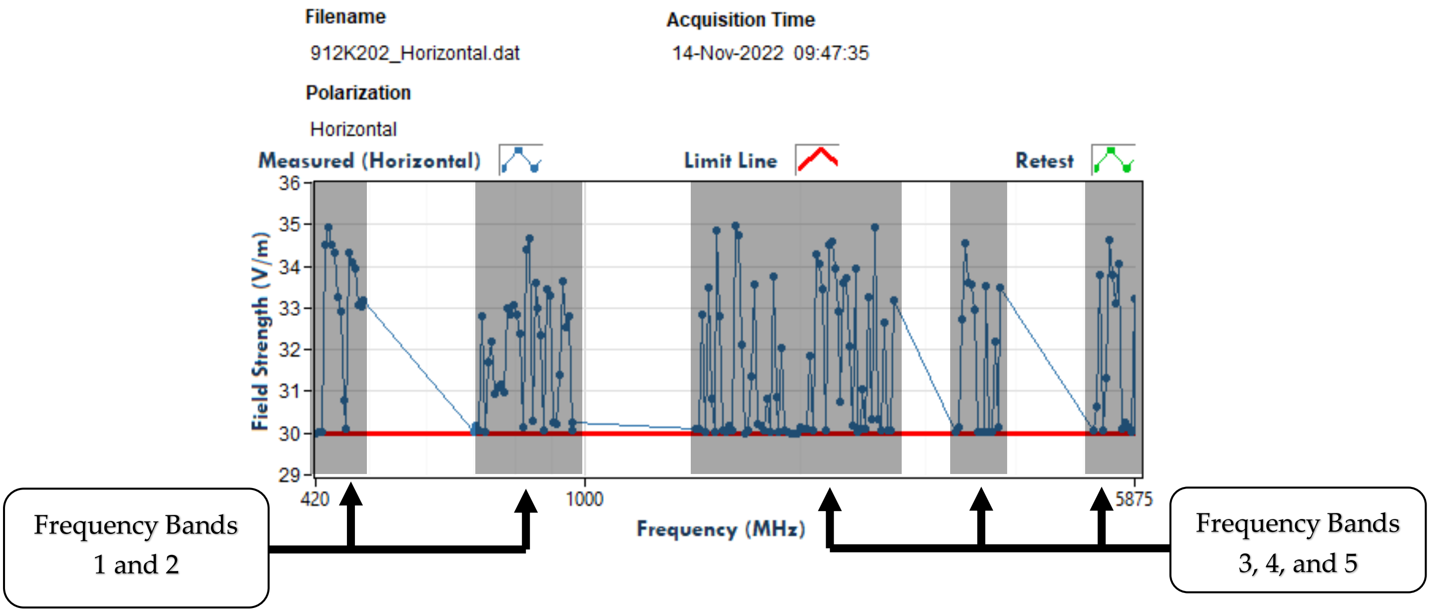

Figure 13 - Field strength level during RS103 testing on sensor 912K202 - horizontal polarization

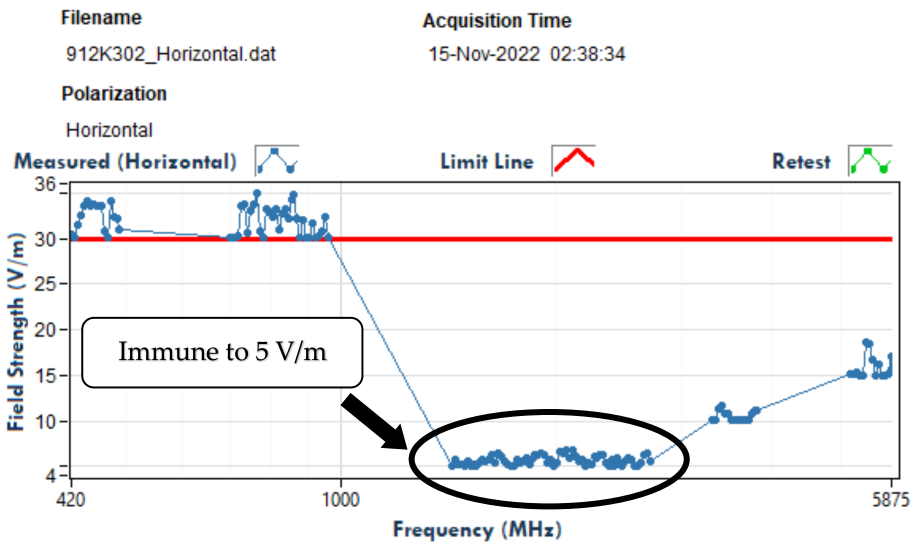

Figure 14 – Thresholding field strength levels during RS103 testing on sensor 912K302 - horizontal polarization

There were twelve different sensors, one panel, and three cabinets tested for vulnerabilities to RF energy. In some instances, because of the close proximity of the sensors to each other, multiple sensors were tested at the same test location simultaneously.

The results of the immunity testing for each piece of equipment are provided in Table 6. This table signifies if the equipment was immune to the signals (unaffected) or if the equipment was found to be susceptible to the RF energy. In the cases where the equipment was found to be susceptible, the table notes whether or not thresholding was performed to determine the RF level that the equipment could withstand without being affected or if other actions could be taken to improve the immunity of the equipment.

Table 6 – Results of the RF immunity testing

Test Location	Equipment Description	Equipment ID#	Result
1	Sensor	912K202	Immune
2	Sensor	912K302	Susceptible: Threshold Level Established down to 5 V/m
3	Sensor	912K401	Immune
4	Sensor	921K301	Susceptible[1]
	Sensor	921K302	Immune
5	Sensor	921K105	Immune
	Sensor	921K401	Susceptible: Threshold Level Established down to 10 V/m
6	Sensor	921K403	Immune
	Sensor	921K404	Immune
	Sensor	921K405	Immune
7	Sensor	921K502	Immune
	Sensor	921V29	Immune
8	Panel	ZHD.102	Immune
9	Cabinet	THE.103	Susceptible: Immune with Front Door Closed
10	Cabinet	THE.104	Susceptible: Immune with Panel Door Closed
11	Cabinet	THE.102	Susceptible: Immune with Front Door Closed

[1] Thresholding was not performed due to time constraints. Assuming the installation is the same, the thresholding results for this sensor would likely be similar to sensor 912K302 (Test Location 2).

The results of the testing for the individual pieces of equipment at the various test locations are contained within Table 7 through Table 19. These tables provide the test results for the specific frequency ranges (and associated transmitting antenna) and antenna polarizations (horizontal and vertical) at the target field strength. The tables also include the maximum and minimum values of the monitoring data for the given sensor during testing. The monitoring data was used by KSU and plant personnel to establish whether or not the equipment was immune to the RF energy.

Table 7 – Results for Test Location 1 (Sensor 912K202) – Yokogawa EJX110A Differential Pressure Sensor

Frequency Range (MHz)	Antenna	Polarization	Field Strength (V/m)	Result	Monitoring Data
420 to 490	Log Periodic	Horizontal	30	Immune	Minimum: 6.239 V
		Vertical		Immune	Maximum: 6.746 V
698 to 960	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	Minimum: 6.252 V
		Vertical		Immune	Maximum: 6.733 V
1428 to 2700	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	Minimum: 6.253 V
		Vertical		Immune	Maximum: 6.798 V
3300 to 3800	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	Minimum: 6.274 V
		Vertical		Immune	Maximum: 6.771 V
5150 to 5875	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	Minimum: 6.287 V
		Vertical		Immune	Maximum: 6.802 V

Table 8 – Results for Test Location 2 (Sensor 912K302) – Yokogawa EJX910A Flow Sensor

Frequency Range (MHz)	Antenna	Polarization	Field Strength (V/m)	Result	Monitoring Data
420 to 490	Log Periodic	Horizontal	30	Immune	Minimum: 5.930 V
		Vertical		Immune	Maximum: 6.031 V
698 to 960	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	Minimum: 5.918 V
		Vertical		Immune	Maximum: 6.037 V
1428 to 2700	Double-Ridged, High Frequency Horn	Horizontal	30	Susceptible	Minimum: 5.901 V
		Vertical		Susceptible	Maximum: 11.528 V[1]
3300 to 3800	Double-Ridged, High Frequency Horn	Horizontal	30	Susceptible	Minimum: 5.884 V
		Vertical		Susceptible	Maximum: 11.525 V[2]
5150 to 5875	Double-Ridged, High Frequency Horn	Horizontal	30	Susceptible	Minimum: 5.899 V
		Vertical		Susceptible	Maximum: 11.523 V[3]

[1] The maximum value recorded when tested at 5 V/m was 6.012 V.
[2] The maximum value recorded when tested at 10 V/m was 5.987 V.
[3] The maximum value recorded when tested at 15 V/m was 5.985 V.

Table 9 – Results for Test Location 3 (Sensor 912K401) – ABB 265DS Level Sensor

Frequency Range (MHz)	Antenna	Polarization	Field Strength (V/m)	Result	Monitoring Data
420 to 490	Log Periodic	Horizontal	30	Immune	Minimum: 6.654 V
		Vertical		Immune	Maximum: 6.688 V
698 to 960	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	Minimum: 6.628 V
		Vertical		Immune	Maximum: 6.685 V
1428 to 2700	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	Minimum: 6.637 V
		Vertical		Immune	Maximum: 6.680 V
3300 to 3800	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	Minimum: 6.632 V
		Vertical		Immune	Maximum: 6.671 V
5150 to 5875	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	Minimum: 6.626 V
		Vertical		Immune	Maximum: 6.664 V

Table 10 – Results for Test Location 4 (Sensor 921K301) – Yokogawa EJX910A Flow Sensor*

Frequency Range (MHz)	Antenna	Polarization	Field Strength (V/m)	Result	Monitoring Data
420 to 490	Log Periodic	Horizontal	30	Immune	Minimum: 5.461 V
		Vertical		Immune	Maximum: 5.549 V
698 to 960	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	Minimum: 5.468 V
		Vertical		Immune	Maximum: 5.544 V
1428 to 2700	Double-Ridged, High Frequency Horn	Horizontal	30	Susceptible	Minimum: 5.462 V
		Vertical		Susceptible	Maximum: 11.534 V
3300 to 3800	Double-Ridged, High Frequency Horn	Horizontal	30	Susceptible	Minimum: 5.464 V
		Vertical		Susceptible	Maximum: 11.535 V
5150 to 5875	Double-Ridged, High Frequency Horn	Horizontal	30	Susceptible	Minimum: 5.463 V
		Vertical		Susceptible	Maximum: 11.531 V

*Thresholding was not performed due to time constraints. Assuming the installation is the same, the thresholding results for this sensor would likely be similar to sensor 912K302 (Test Location 2).

Table 11 – Results for Test Location 4 (Sensor 921K302) – ABB 265DS Flow Sensor

Frequency Range (MHz)	Antenna	Polarization	Field Strength (V/m)	Result	Monitoring Data
420 to 490	Log Periodic	Horizontal	30	Immune	Minimum: 8.12 kg/s
		Vertical		Immune	Maximum: 8.31 kg/s
698 to 960	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	Minimum: 8.13 kg/s
		Vertical		Immune	Maximum: 8.33 kg/s
1428 to 2700	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	Minimum: 8.13 kg/s
		Vertical		Immune	Maximum: 8.31 kg/s
3300 to 3800	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	Minimum: 8.15 kg/s
		Vertical		Immune	Maximum: 8.31 kg/s
5150 to 5875	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	Minimum: 8.12 kg/s
		Vertical		Immune	Maximum: 8.33 kg/s

Table 12 – Results for Test Location 5 (Sensor 921K105) – ABB 265DS Pressure Sensor

Frequency Range (MHz)	Antenna	Polarization	Field Strength (V/m)	Result	Monitoring Data
420 to 490	Log Periodic	Horizontal	30	Immune	Minimum: 1.642 bar
		Vertical		Immune	Maximum: 1.672 bar
698 to 960	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	Minimum: 1.657 bar
		Vertical		Immune	Maximum: 1.676 bar
1428 to 2700	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	Minimum: 1.627 bar
		Vertical		Immune	Maximum: 1.677 bar
3300 to 3800	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	Minimum: 1.636 bar
		Vertical		Immune	Maximum: 1.645 bar
5150 to 5875	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	Minimum: 1.641 bar
		Vertical		Immune	Maximum: 1.647 bar

Table 13 – Results for Test Location 5 (Sensor 921K401) –ABB 265DS Level Sensor

Frequency Range (MHz)	Antenna	Polarization	Field Strength (V/m)	Result	Monitoring Data
420 to 490	Log Periodic	Horizontal	30	Immune	Minimum: 9.396 V
		Vertical		Immune	Maximum: 9.425 V
698 to 960	Double-Ridged, High Frequency Horn	Horizontal	30	Susceptible	Minimum: 7.784 V[1]
		Vertical		Susceptible	Maximum: 9.336 V
1428 to 2700	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	Minimum: 9.289 V
		Vertical		Immune	Maximum: 9.424 V
3300 to 3800	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	Minimum: 9.395 V
		Vertical		Immune	Maximum: 9.427 V
5150 to 5875	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	Minimum: 9.397 V
		Vertical		Immune	Maximum: 9.424 V

[1] The minimum value recorded when tested at 10 V/m was 9.12 V.

Table 14 – Results for Test Location 6 (Sensors 921K403, 921K404, and 921K405)- Mobrey S01DB/84 Level Switch

Frequency Range (MHz)	Antenna	Polarization	Field Strength (V/m)	Result	Monitoring Data
420 to 490	Log Periodic	Horizontal	30	Immune	Did Not Change State
		Vertical		Immune	
698 to 960	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	Did Not Change State
		Vertical		Immune	
1428 to 2700	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	Did Not Change State
		Vertical		Immune	
3300 to 3800	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	Did Not Change State
		Vertical		Immune	
5150 to 5875	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	Did Not Change State
		Vertical		Immune	

Table 15 – Results for Test Location 7 (Sensor 921K502) – EPIC PT100 W-B-9K-D Temperature Sensor

Frequency Range (MHz)	Antenna	Polarization	Field Strength (V/m)	Result	Monitoring Data
420 to 490	Log Periodic	Horizontal	30	Immune	Minimum: 3.752 V
		Vertical		Immune	Maximum: 3.785 V
698 to 960	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	Minimum: 3.778 V
		Vertical		Immune	Maximum: 3.810 V
1428 to 2700	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	Minimum: 3.804 V
		Vertical		Immune	Maximum: 3.870 V
3300 to 3800	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	Minimum: 3.865 V
		Vertical		Immune	Maximum: 3.887 V
5150 to 5875	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	Minimum: 3.880 V
		Vertical		Immune	Maximum: 3.904 V

Table 16 – Results for Test Location 8 - Wiring Junction Box (ZHD.102 – Sensors 912K202, 912K302, 921K301, and 921K502)

Frequency Range (MHz)	Antenna	Polarization	Field Strength (V/m)	Result	Monitoring Data
420 to 490	Log Periodic	Horizontal	30	Immune	No alarms
		Vertical		Immune	
698 to 960	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	No alarms
		Vertical		Immune	
1428 to 2700	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	No alarms
		Vertical		Immune	
3300 to 3800	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	No alarms
		Vertical		Immune	
5150 to 5875	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	No alarms
		Vertical		Immune	

Table 17 – Results for Test Location 9 (Cabinet THE.103) – I/O Equipment Cabinet

Frequency Range (MHz)	Antenna	Polarization	Field Strength (V/m)	Result	Monitoring Data
420 to 490	Log Periodic	Horizontal	30	Susceptible[1]	Alarms Occurred
		Vertical		Susceptible[1]	
698 to 960	Double-Ridged, High Frequency Horn	Horizontal	30	Susceptible[2]	Alarms Occurred
		Vertical		Susceptible[2]	
1428 to 2700	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	No alarms
		Vertical		Immune	
3300 to 3800	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	No alarms
		Vertical		Immune	
5150 to 5875	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	No alarms
		Vertical		Immune	

[1] The cabinet was immune to 30 V/m with the front door closed. With the panel door open, thresholding was performed at 10 V/m without producing alarms.

[2] The cabinet was immune to 30 V/m with the front door closed.

Table 18 – Results for Test Location 10 – I/O Equipment Cabinet (THE.104)

Frequency Range (MHz)	Antenna	Polarization	Field Strength (V/m)	Result	Monitoring Data
420 to 490	Log Periodic	Horizontal	30	Susceptible[1]	Alarms Occurred
		Vertical		Susceptible[1]	
698 to 960	Double-Ridged, High Frequency Horn	Horizontal	30	Susceptible[2]	Alarms Occurred
		Vertical		Susceptible[2]	
1428 to 2700	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	No alarms
		Vertical		Immune	
3300 to 3800	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	No alarms
		Vertical		Immune	
5150 to 5875	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	No alarms
		Vertical		Immune	

[1] The cabinet was immune to 30 V/m with the panel door closed. With the panel door open, thresholding was performed at 10 V/m without producing alarms.

[2] There were no alarms with the panel door closed. Thresholding was not performed for this frequency range.

Table 19 – Results for Test Location 11 – I/O Equipment Cabinet (THE.102)

Frequency Range (MHz)	Antenna	Polarization	Field Strength (V/m)	Result	Monitoring Data
420 to 490	Log Periodic	Horizontal	30	Susceptible[1]	Alarms Occurred
		Vertical		Susceptible[1]	
698 to 960	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	No alarms
		Vertical		Immune	
1428 to 2700	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	No alarms
		Vertical		Immune	
3300 to 3800	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	No alarms
		Vertical		Immune	
5150 to 5875	Double-Ridged, High Frequency Horn	Horizontal	30	Immune	No alarms
		Vertical		Immune	

[1] The cabinet was immune to 30 V/m with the front door closed.

4.2 MITIGATION OF EQUIPMENT VULNERABILITIES

In certain instances where vulnerabilities were identified (and time permitted), AMS attempted to mitigate the vulnerability of the equipment to an electric field strength of 30 V/m. In general, the mitigation strategy was to improve the shielding of the equipment to RF energy. The following sections provide a summary of the mitigation strategies that were performed for the selected equipment.

4.2.1 Sensor 912K302

Sensor 912K302 was identified as being vulnerable to frequencies above 1 GHz. A metallic blanket was wrapped over the entire sensor, as shown in Figure 15, representing a metallic structure shielding the sensor. With the shielding, the sensor was immune to an electric field strength of 30 V/m in the frequency ranges between 1428 to 5875 MHz. The practical application of this mitigation technique would consist of installing the sensor within a metallic enclosure. There was limited success with shielding just the cable connection to the sensor and/or the glass cover of the sensor. Further troubleshooting could identify the vulnerable portion of the sensor thus reducing the impact of the mitigation strategy on the plant installation.

Figure 15 – RF Shielding added to Sensor 912K302

4.2.2 Sensor 921K401

The 921K401 sensor was susceptible to an electric field strength of 30 V/m in the frequency range of 698 to 960 MHz. Two type 61 material ferrite beads (Fair-Rite Model# 461176451) were clamped around the input cable to the sensor and metallic tape was wrapped around the connector, as shown in Figure 16. Together, these mitigations resulted in the sensor being immune to a field strength of 30 V/m. These results indicate that there is poor RF shielding of the signal cable at this connection point.

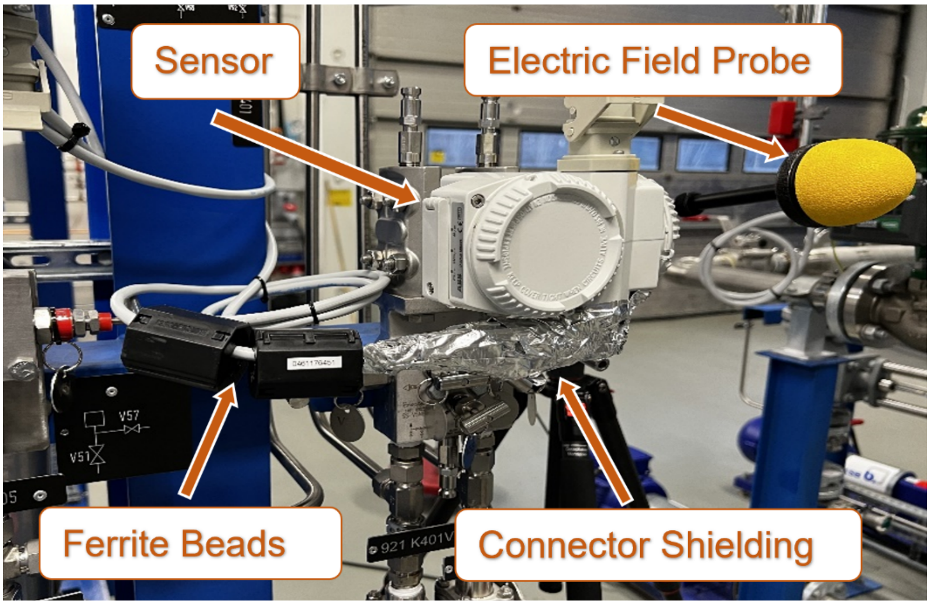

Figure 16 – RF Shielding and ferrite beads added to Sensor 921K401

4.2.3 Cabinets THE.102, THE.103, and THE.104

Vulnerabilities of the electronic modules within the three (3) different cabinets were identified at various frequency ranges. Testing of the cabinets were initially performed with the cabinet doors and internal panel doors open, as shown in Figure 17. If vulnerabilities were identified, then the field strength was reduced to determine the threshold level for immunity. In addition, the testing was performed with the internal panel door of the cabinet closed, as shown in Figure 18. In this configuration, the panel provided a level of shielding for the interior wiring of the cabinet. If the modules in the cabinet were still found to be vulnerable, then the testing would be repeated with the front door of the cabinet closed, as shown in Figure 19. With the front panel door closed, no vulnerabilities of the equipment were identified at a field strength of 30 V/m.

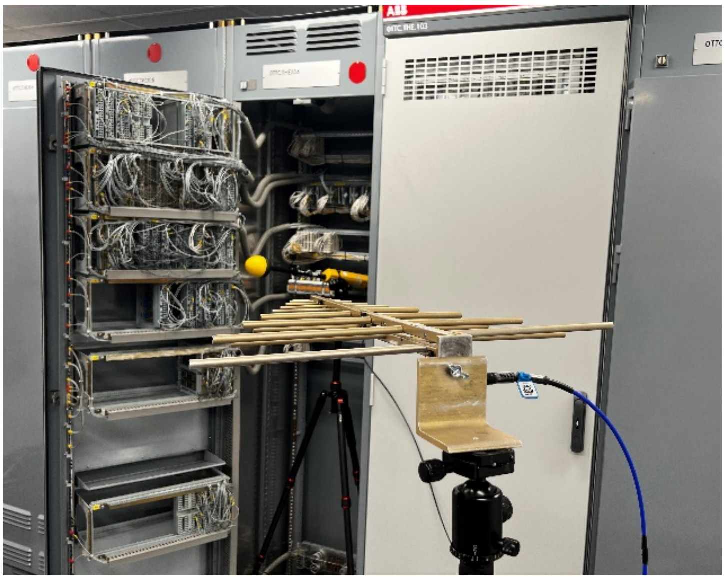

Figure 17 – Testing with the front door and internal panel door open (Cabinet THE.104)

Figure 18 - Testing with the internal panel door closed (Cabinet THE.103)

Figure 19 - Testing with the front door of the cabinet closed (Cabinet THE.102)

5 Walkdown of Forsmark Nuclear Power Plant

A walkdown of Forsmark Nuclear Plant was conducted to identify any differences between the equipment tested at the KSU facility and its installation at the Forsmark Nuclear Plant. Photographs of the plant equipment in Forsmark were not allowed and therefore, this section will contain graphics depicting equipment in the plant based upon the notes taken during the walkdown. The following sections provide observations that were noted of the sensors, their installation, and general wiring practices seen throughout the plant.

5.1 SENSOR MANUFACTURERS

There were several sensors seen in the plant which were the same make and models as those installed at the KSU facility, however, there were several examples of equipment which was not instrumented at KSU. Table 20 is a list of the manufacturers of pressure/level/flow transmitters which were identified at Forsmark but were not installed at the KSU facility. Additionally, several sensors installed in the plant had an additional AC to DC converter module mounted to the outside of the pressure/level/flow transmitter enclosure. This module, which was not installed on any of the sensors at KSU, provides power for the 4-20 mA loop of the sensor which could potentially be vulnerable to RF energy.

Table 20 – Sensors Identified at Formark and the KSU Facility

Sensor Manufacturers	Tested at KSU	Identified at Formark
Yokogawa	✓	✓
ABB	✓	✓
Contrans		✓
Schoppe & Faser		✓
Sauter		✓
Ashcroft		✓

5.2 SENSOR INSTALLATIONS

There were multiple differences between the installation of sensors at the KSU facility and at Forsmark. In this section, various installation practices such as exposed cable length, the use of quick connectors, and local indication of sensor values will be discussed. The effect that these differences could potentially have on the immunity test results will also be noted. A typical sensor installation at the KSU facility is shown in Figure 20.

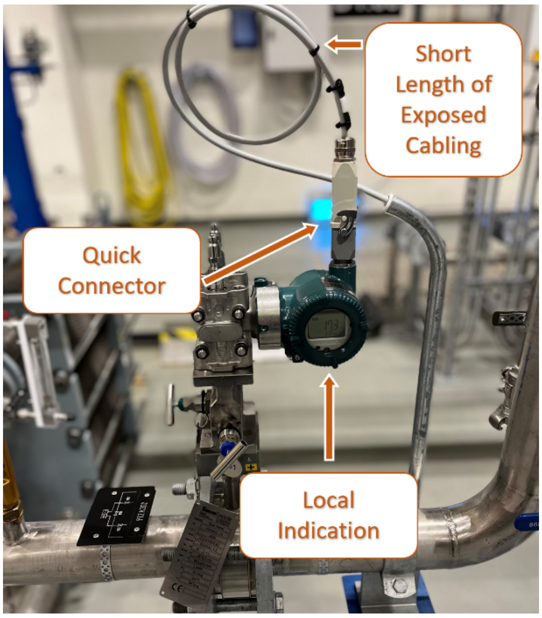

Figure 20 – Photograph of a typical installation of a sensor at the KSU facility showing the use of a quick connector, local indication, and a short section of exposed cabling

At the KSU facility, it was typical for the sensors to have a single loop of exposed cabling, approximately 0.5 meters long, between the sensor and the rigid conduit used to route the cable to the cable tray. Many of the sensors identified at Forsmark had long lengths of exposed cabling between the conduit and the sensor, up to and exceeding two meters in some cases. This configuration is demonstrated in Figure 21. The additional length of exposed cabling in the plant can allow for RF energy to couple to the cable and potentially cause interference with the sensor.

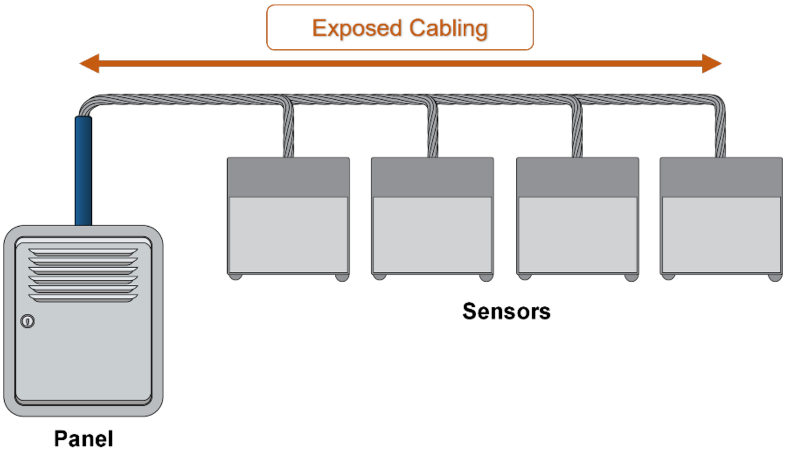

Figure 21 – Example depiction of sensor installation at Forsmark Nuclear Power Plant showing long lengths of exposed cabling between the sensors and rigid conduit

During the walkdown at Forsmark, it was noted that quick connectors were not always used to interface between the cabling and the sensor. In these cases, the cable was terminated within the sensor itself. At the KSU facility, quick connecters were used for all sensors, so therefore, the quick connector configuration was the only configuration tested for immunity to RF signals. For example, sensor 921K401, the quick connector was identified as the vulnerable component which allowed RF energy to couple into the sensor and cause interference. This vulnerability could be a result of the quick connector not maintaining a metallic connection between the shield of the cable and the outer casing of the sensor. Noise traveling along the shield of a cable, which is not terminated to the metallic case of the sensor (through the quick connector), could propagate into the sensor and cause interference.

For the sensors walkdown within the Forsmark facility, there were four basic installation practices. These practices consisted of the following:

1) Exposed cabling connected to the sensor using a quick connector
2) Exposed cabling wired directly into the sensor without flexible conduit
3) Flexible conduit connecting rigid conduit to the sensor without a ground wire
4) Flexible conduit connecting rigid conduit to the sensor with a ground wire routed parallel along the whole length

When considering the use of quick connectors, plant drawings and/or installation techniques at Forsmark should be compared with the techniques at the KSU facility. Ideally, the quick connector maintains a metallic connection between the shield of the cable and the sensor housing. For the other three installation practices, they were not replicated at the KSU facility and therefore their immunity to RF signals is unknown. Of the three practices, the use of flexible conduit with the parallel ground wire is expected to provide the best immunity performance. This configuration is demonstrated in Figure 22. If the flexible conduit does not make conductive contact to both the rigid conduit and to the sensor housing, then this break in the RF shielding could allow for RF energy to couple to the signal cable and potentially cause interference.

One other difference in installation that was noted at Forsmark was the lack of local indication on the sensors. The KSU facility had multiple sensors with local indication and some of these exhibited vulnerability to RF signals. The vulnerabilities could potentially be a result of the glass face plate over the local indication which is a break in the RF shielding of the sensor. For example, sensor 912K302, which has local indication, was found to be vulnerable to RF energy. The immunity of the sensor improved when the local indication cover was replaced with a solid metallic cover. The solid metallic cover allowed for continuous RF shielding around the entire sensor. Figure 23 shows the difference between a sensor with (left) and without (right) a local indication. The solid metallic cover configuration observed for the Forsmark sensors is expected to improve the immunity of the sensors to RF interference.

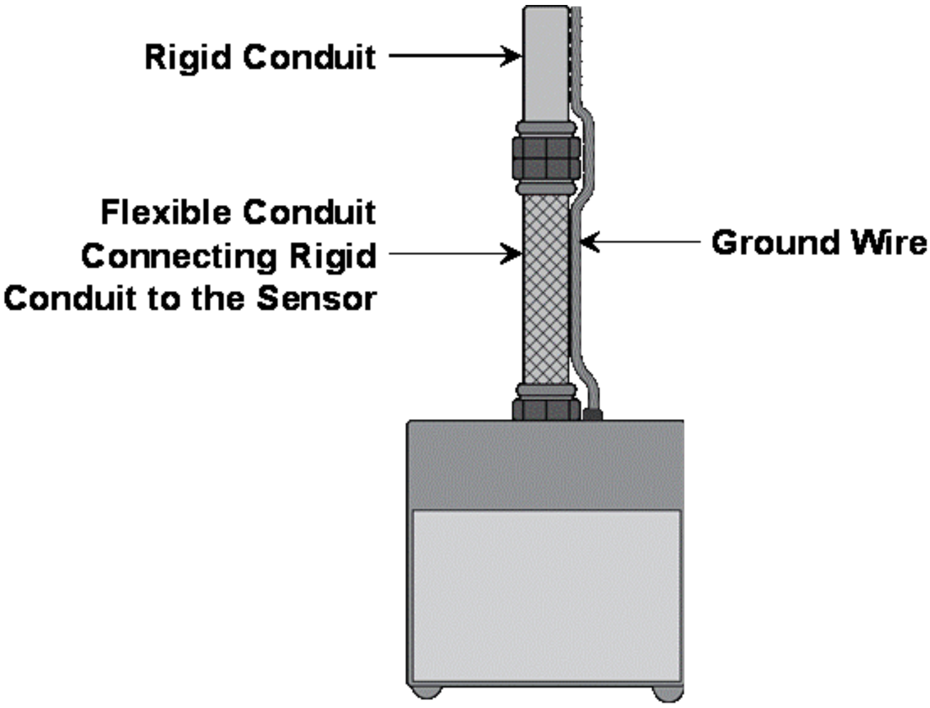

Figure 22 – Recommended installation practice showing ground wire routed in parallel with the entire length of flexible conduit

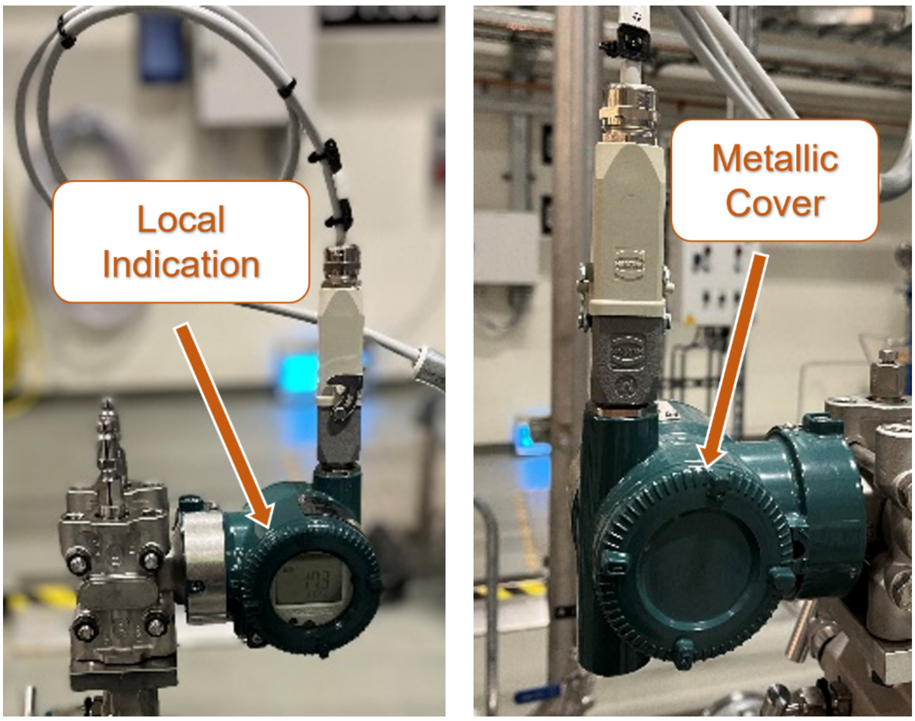

Figure 23 – Photograph of Yokogawa Sensors with (left) and without (right) local indication

5.3 POWER AND SIGNAL CABLING INSTALLATIONS

Within several of the cabinets in the Forsmark power plant, the power and signal cables are separated at the cabinet entry which is a very good EMC practice. This configuration minimizes noise from coupling between the power cables (typically noisy) and the signal cables (typically sensitive). There were however, differences noted between the KSU and Forsmark Nuclear Power Plant installations with the ground wires of the shields in the cabinets. At the KSU facility, the ground wire of the shield was routed directly to a ground bus bar improving the performance of the shield, and limiting the amount of RF energy that could couple to the signal wires. However, in the plant, the ground wires of the shields were longer and routed in parallel with the signal wires, thus potentially making them more vulnerable to energy flowing on the shields because of this extended path to ground. An example of the direct and indirect routing of the ground wire is shown in Figure 24.

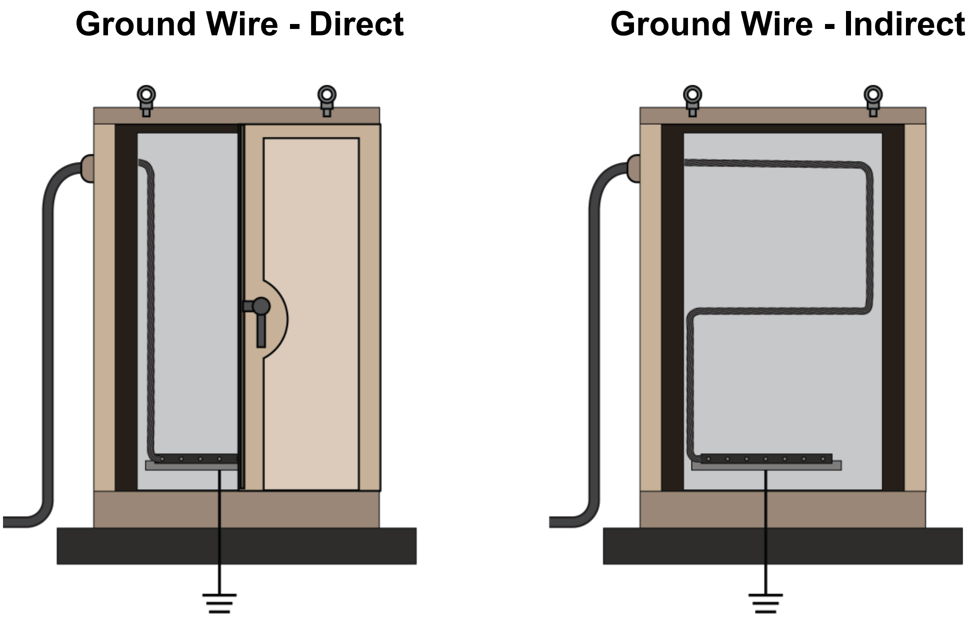

Figure 24 – Ground wire length located within the cabinets

5.4 CABLE TRAY GROUND WIRE

While not specific to any particular sensor, another EMC practice to note is the grounding of cable trays. When cables exit a cable tray and penetrate the wall or enter another cable tray, a ground wire should be used to maintain continuity of the ground reference plane of the cable between the two metallic structures. This will offer a low impedance path for noise to continue to flow and prevent it from coupling to sensitive plant cables. In addition, with respect to RF energy, the ground wire would provide a preferred coupling point for RF energy to couple to the ground wire rather than to the exposed plant wiring. Thus reducing the potential for interference.

Cable trays play an important role in routing cables from one place in the plant to another. Traditionally, in nuclear power plants, cable trays and all metallic structures are interconnected either through directly conductive contact or through the use of ground wires. An improperly grounded cable tray may inadvertently act as an antenna and transmit or receive RF energy and couple it to adjacent cables. Several instances were seen in the Forsmark plant where a cable left the cable tray, penetrated the wall, and a ground wire was not routed with the cable to connect the two metallic structures. In this instance, the exposed cabling can act as an antenna for any of the noise within the plant. A depiction of the cable tray grounding, as noted at Forsmark, is shown in Figure 25. While there is no reason to change this configuration in the plant, it is a vulnerability to consider as the plant looks to deploy wireless technology. With respect to Wi-Fi technology, the transmission frequency will not propagate efficiently on long runs of cable (or cable tray) and ground cable configuration should not be a concern.

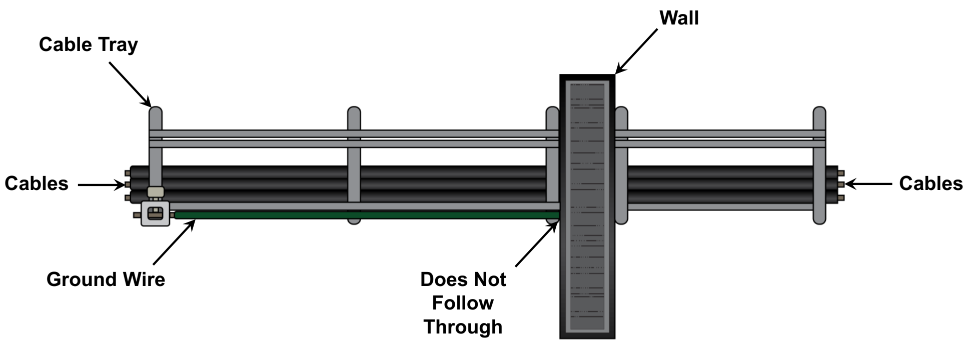

Figure 25 – Ground wire not penetrating the wall creating unintentional antenna

5.5 CONDUIT INSTALLATIONS

A common practice for the installation of cables within nuclear power plants is to use conduit as a method to protect the cable from damage and to provide a level of RF protection. Conduit can be either rigid or flexible, however, only metallic conduit will provide for shielding against RF energy. During the walkdown of the Forsmark plant, it was noted that in several cases, two sections of rigid conduit would be connected with flex conduit. In this application, if it can't be confirmed that the flexible conduit makes conductive contact with both sections of rigid conduit, then it could be beneficial to install a ground wire along the side of the flexible conduit connecting the sections of rigid conduit.

6 Conclusions

AMS performed wireless immunity testing at the KSU facility of several different types of equipment. There were several pieces of equipment, representative of those installed in Swedish nuclear power plants, which did not exhibit any vulnerabilities to RF energy (similar to the energy produced by cellular phones and other wireless devices). In instances where vulnerabilities were identified, AMS determined methods for mitigating the vulnerabilities and/or established a threshold level of RF energy that the equipment could withstand. Based upon the results of a walkdown performed at the Forsmark nuclear power plant, the equipment installations, while similar, do have some distinct differences, both in the installation practices and in the type of equipment, which would necessitate further evaluation and/or testing. However, based upon the results of the testing, and when used in conjunction with exclusion distance guidance contained within EPRI TR-102323 Revision 5, wireless devices could potentially be deployed in certain areas of Swedish nuclear power plants without posing a significant risk to plant operation.

The Yokogawa EJX910A pressure transmitter, sensors 912K302 and 921K301, exhibited susceptibility to the RS103 test in the frequency bands of 1428 to 2700 MHz, 3300 to 3800 MHz, and 5150 to 5875 MHz. The ABB 265DS pressure transmitter, sensor 921K401, exhibited vulnerabilities to the RS103 test in the frequency band of 698 to 960 MHz. The equipment was modified as described in Section 4.2 to achieve immunity to RF energy at the frequency bands of interest.

Modules in all three of the cabinets that were tested were susceptible to RF energy in the frequency range of 420 to 490 MHz. Modules in the THE.103 and THE.104 cabinets were also susceptible to the RS103 test in the 698 to 960 MHz range. However, in every case, the cabinets were not susceptible when the front door was closed.

In lieu of modifying the equipment and/or establishing administrative controls to maintain the panel doors closed, thresholding was performed to determine the field strength at which the equipment was immune. The field strength that each piece of equipment can withstand should be used to establish exclusion zones for the equipment based upon guidance in the EPRI TR-102323 Revision 5 document.

While a majority of the equipment that was tested demonstrated a general immunity to signal characteristics of wireless devices, it is impossible to test every device in every orientation relative to a wireless transmitter. Therefore, even if a device has been tested and found to have a general immunity to wireless signals, steps should still be taken to minimize the possibility of causing interference when using wireless devices around installed equipment. Such steps could include, but are not limited to:

1. Maintain an exclusion distance of one third of a meter (1/3 m) from all sensitive equipment as recommended by EPRI TR-102323 Revision 5, regardless of the level of immunity it demonstrated during testing.

2. Do not operate a wireless device within the boundaries of a panel, regardless of the level of immunity that the panel and associated equipment demonstrated during testing.

3. Turn off wireless capabilities when they are not needed.

All testing was performed in conformance with the Quality Assurance requirements specified in the project and the AMS Quality Assurance Program, as outlined in the AMS Quality Assurance Manual, QAM0101R12, as applicable. The Quality Assurance documentation for the testing activities is provided in Appendix C of this report.

7 References

EPRI TR-102323 Revision 5, Guidelines for Electromagnetic Compatibility Testing of Power Plant Equipment, Revision 5 to TR-102323. EPRI, Palo Alto, CA: 2019. 3002015757.

IEC 61000-4-3, Electromagnetic Compatibility (EMC) Part 4: Testing and Measurement Techniques – Section 3: Radiated, Radio-Frequency, Electromagnetic Field Immunity Test, International Electrotechnical Commission, Geneva, Switzerland: 2010.

MIL-STD-461G, Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment, US Department of Defense, December 11, 2015.

EGF221101R0-T, Wireless EMC Testing of Nuclear Power Plant Equipment for Energiforsk, Analysis and Measurement Services Corporation (AMS), November 2022.

APPENDIX A Datasheets

Available for program stakeholders.

APPENDIX B Test Data

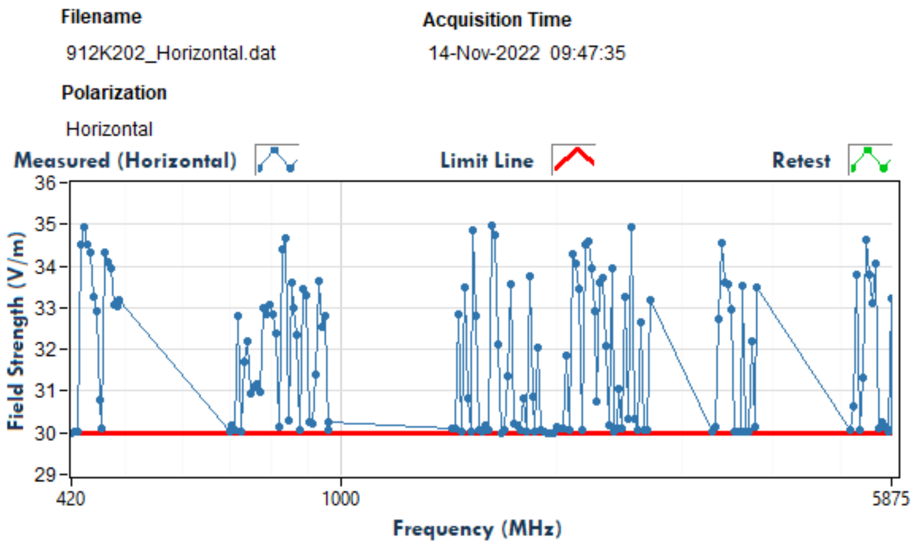

Figure B.1 – Field strength level during RS103 testing at test location 1 (912K202) - horizontal polarization

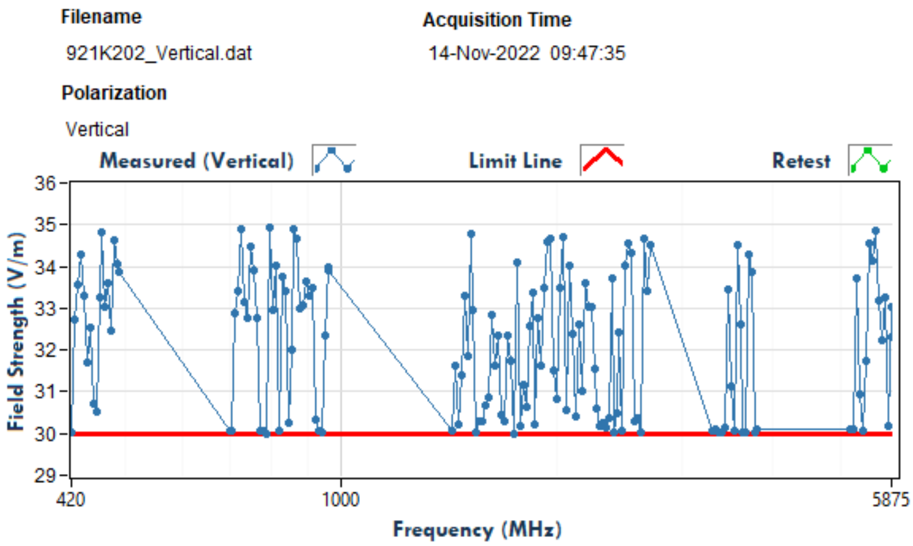

Figure B.2 – Field strength level during RS103 testing at test location 1 (912K202) - vertical polarization

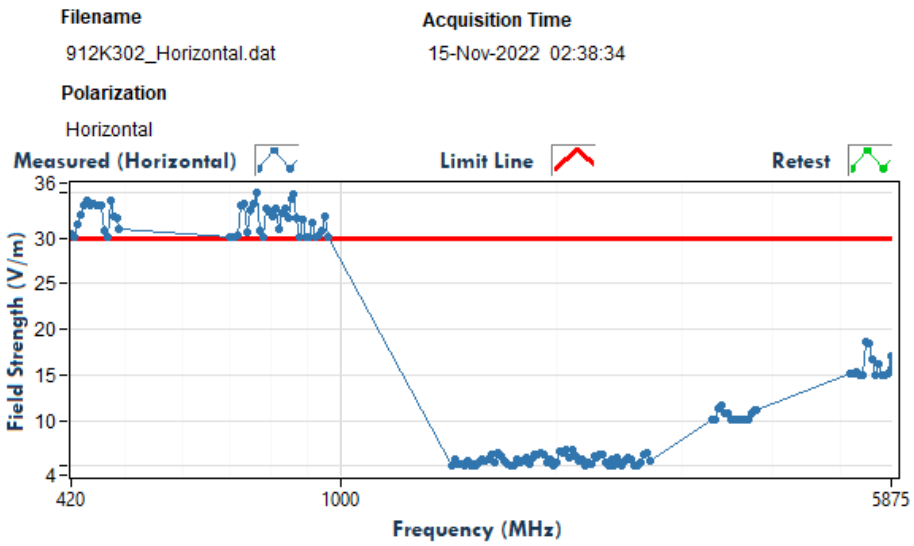

Figure B.3 – Field strength level during RS103 testing at test location 2 (912K302) - horizontal polarization

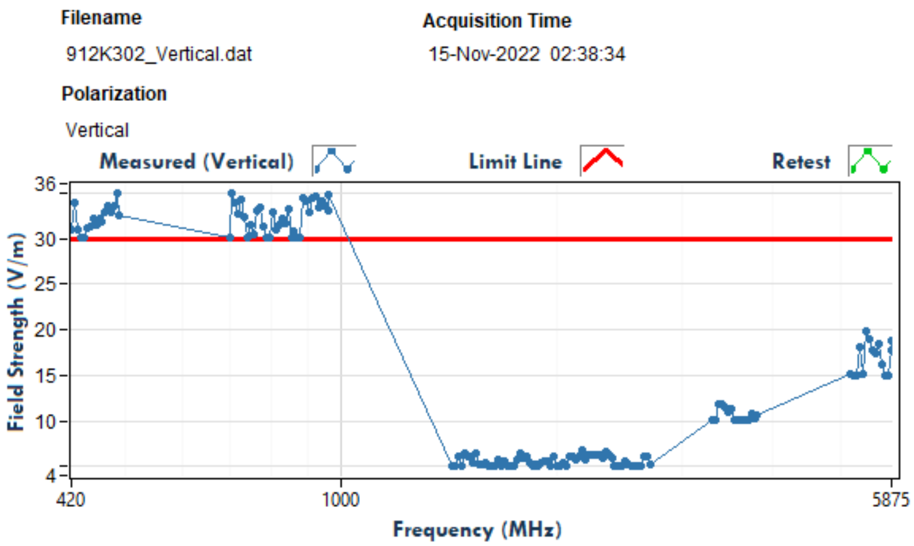

Figure B.4 – Field strength level during RS103 testing at test location 2 (912K302) - vertical polarization

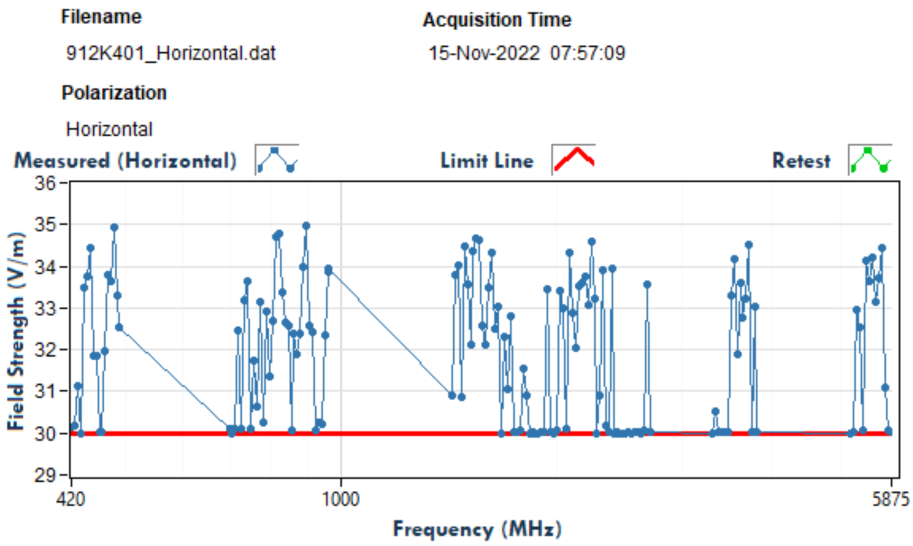

Figure B.5 – Field strength level during RS103 testing at test location 3 (912K401) - horizontal polarization

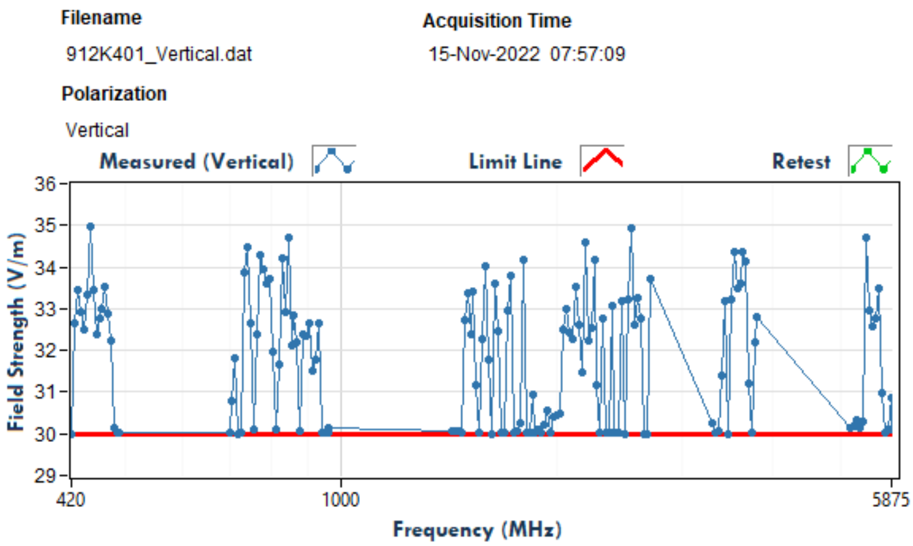

Figure B.6 – Field strength level during RS103 testing at test location 3 (912K401) - vertical polarization

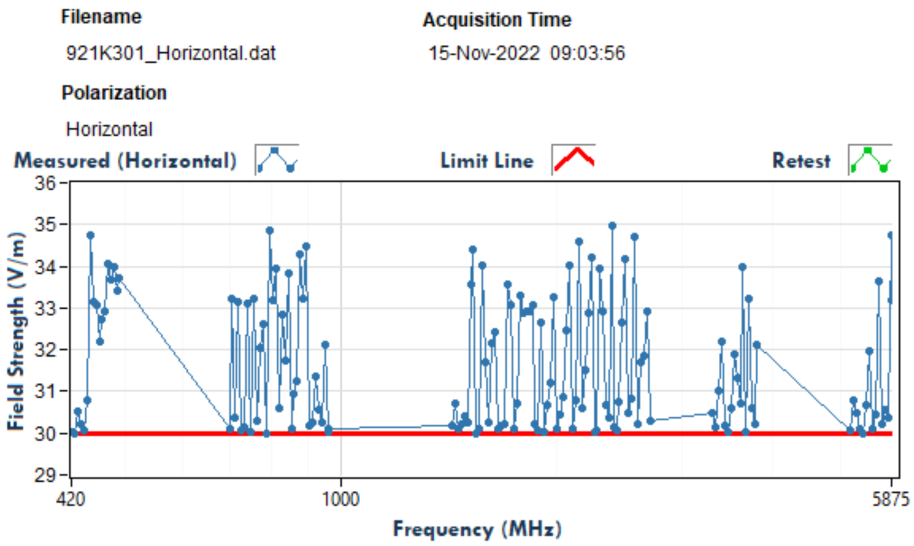

Figure B.7 – Field strength level during RS103 testing at test location 4 (921K301 and 921K302) - horizontal polarization

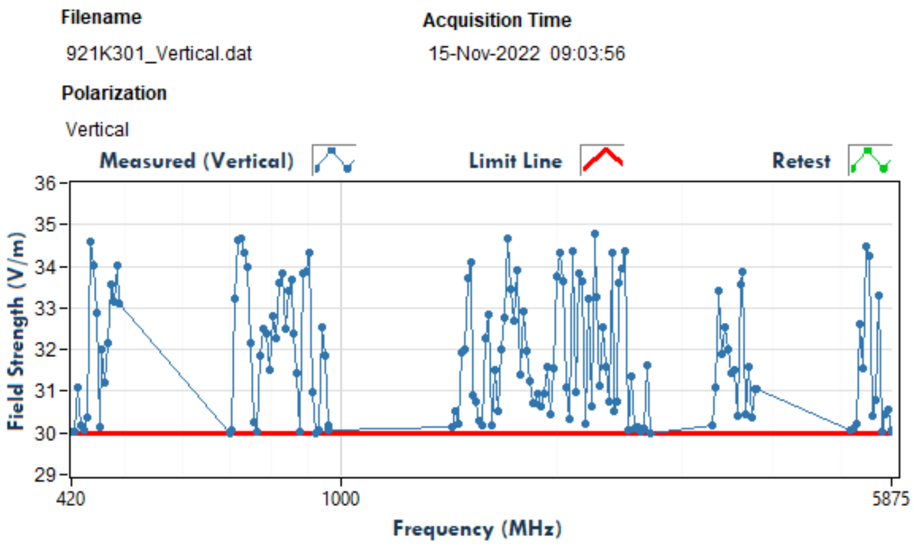

Figure B.8 – Field strength level during RS103 testing at test location 4 (921K301 and 921K302) - vertical polarization

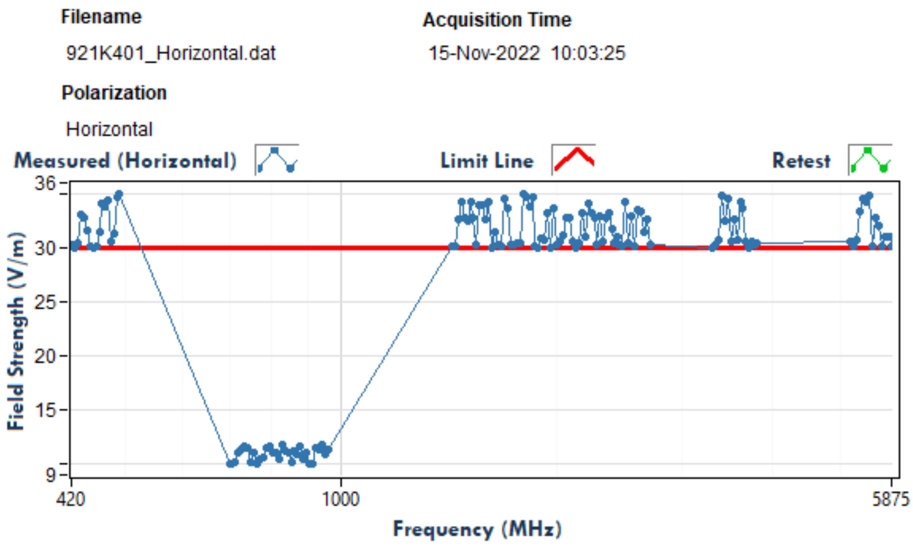

Figure B.9 – Field strength level during RS103 testing at test location 5 (921K105 and 921K401) - horizontal polarization

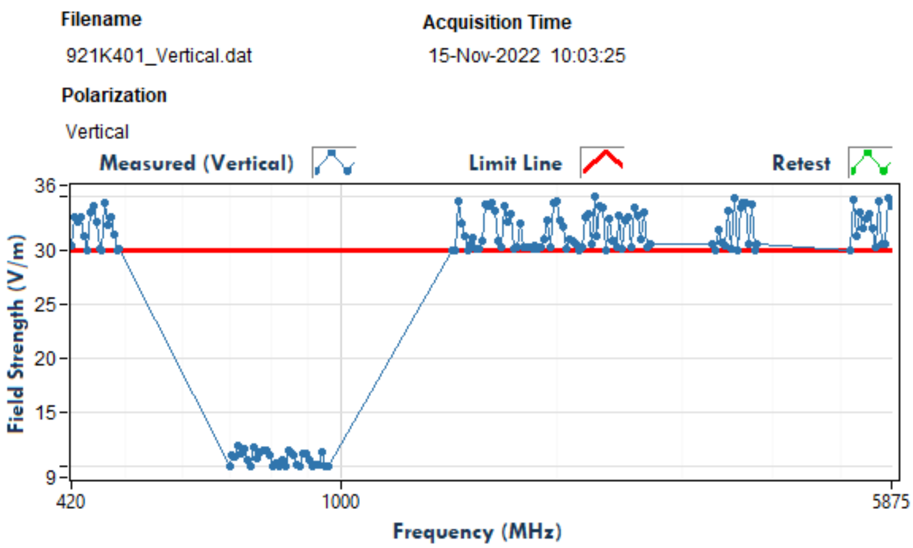

Figure B.10 – Field strength level during RS103 testing at test location 5 (921K105 and 921K401) - vertical polarization

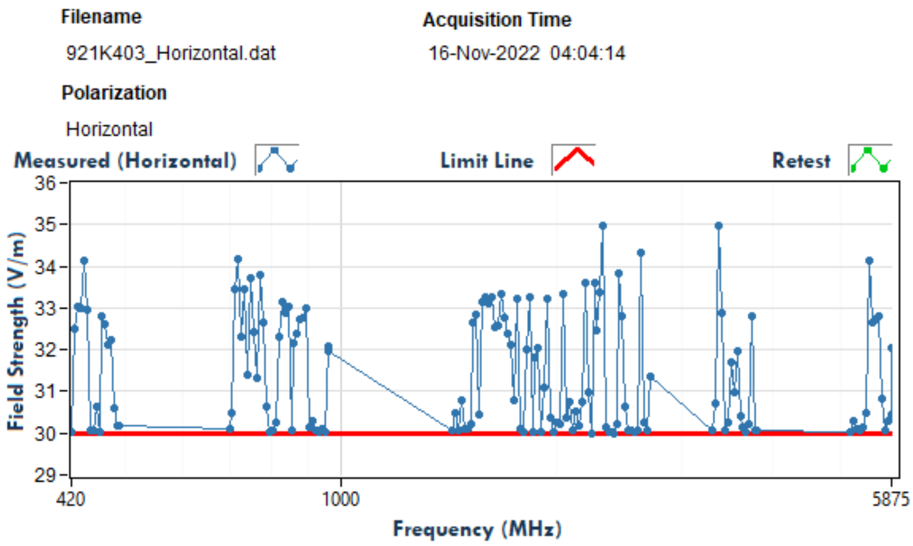

Figure B.11 – Field strength level during RS103 testing at test location 6 (921K403, 921K404, and 921K405) - horizontal polarization

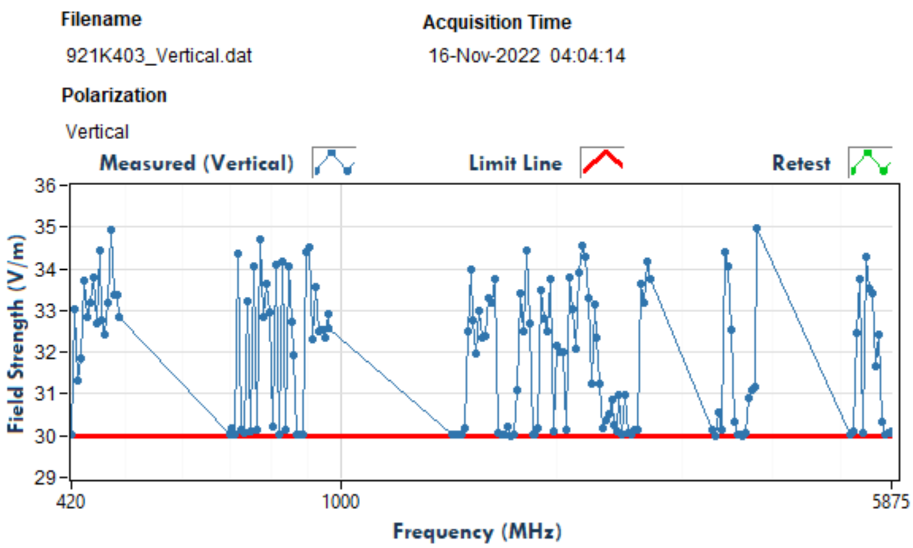

Figure B.12 – Field strength level during RS103 testing at test location 6 (921K403, 921K404, and 921K405) - vertical polarization

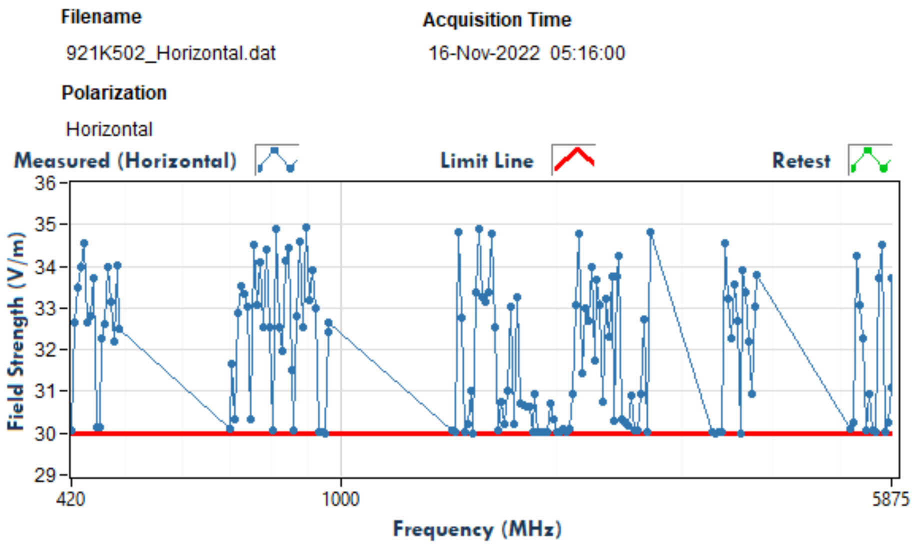

Figure B.13 – Field strength level during RS103 testing at test location 7 (921K502) - horizontal polarization

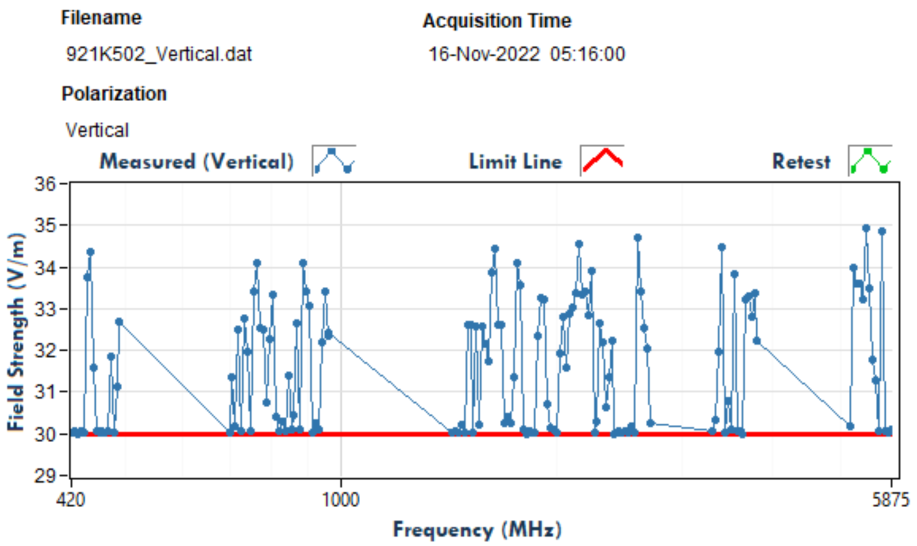

Figure B.14 – Field strength level during RS103 testing at test location 7 (921K502) - vertical polarization

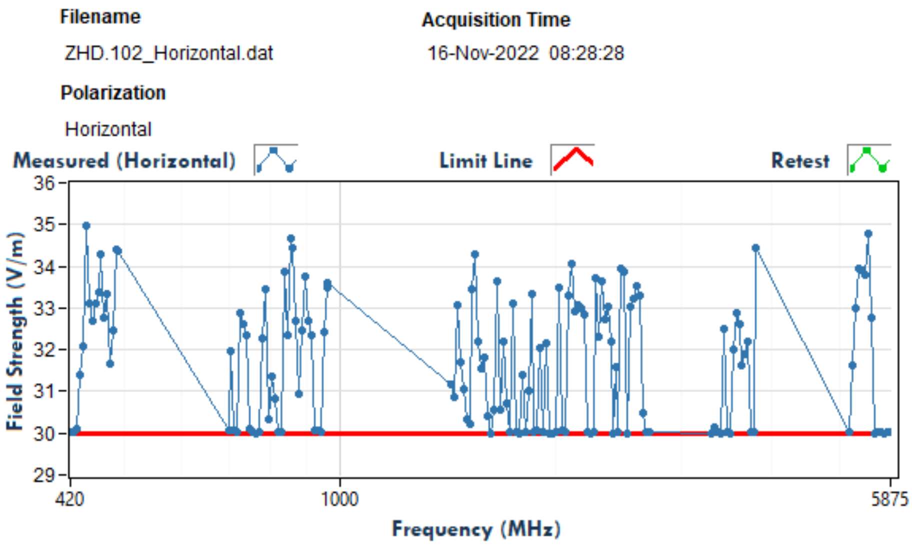

Figure B.15 – Field strength level during RS103 testing at test location 8 (ZHD.102) - horizontal polarization

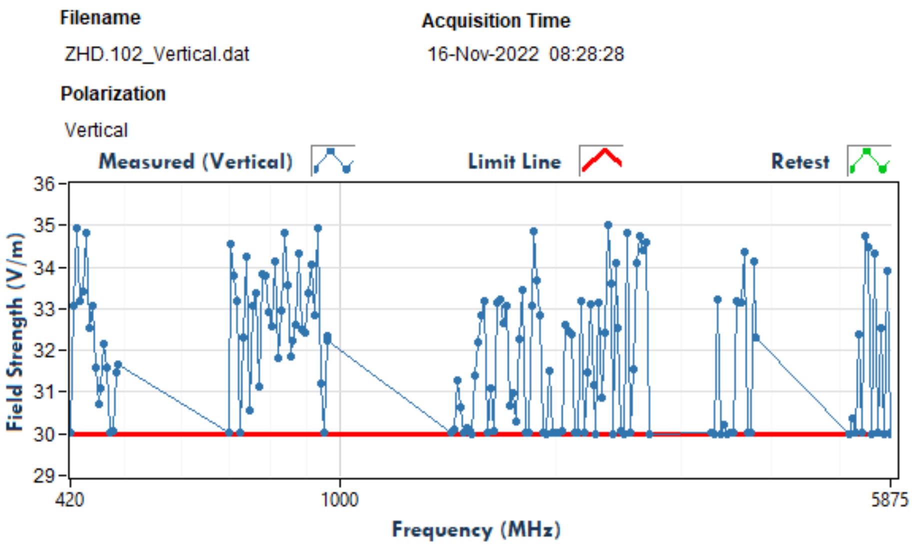

Figure B.16 – Field strength level during RS103 testing at test location 8 (ZHD.102) - vertical polarization

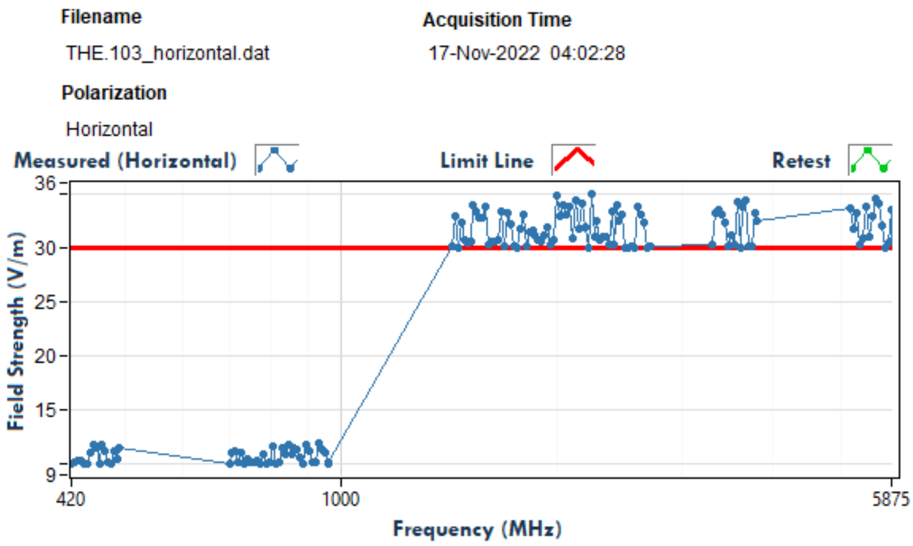

Figure B.17 – Field strength level during RS103 testing at test location 9 (THE.103) - horizontal polarization

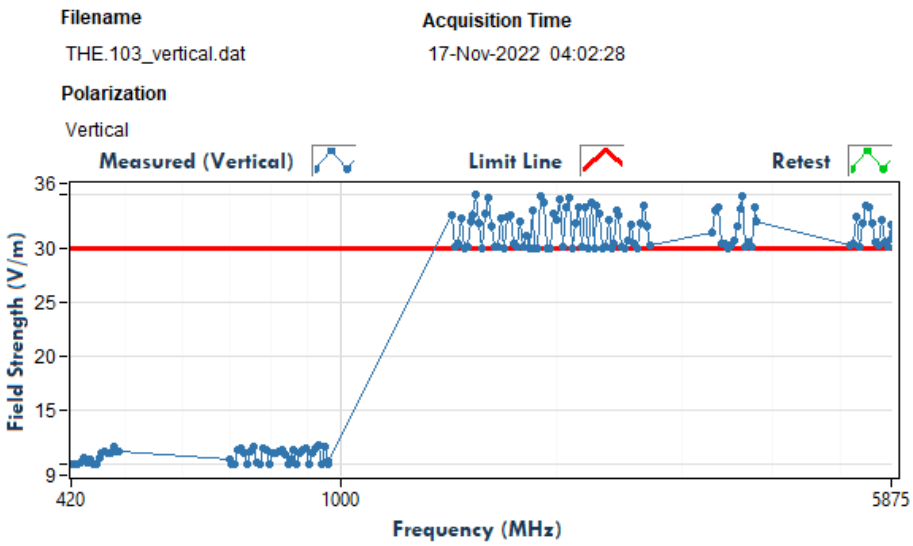

Figure B.18 – Field strength level during RS103 testing at test location 9 (THE.103) - vertical polarization

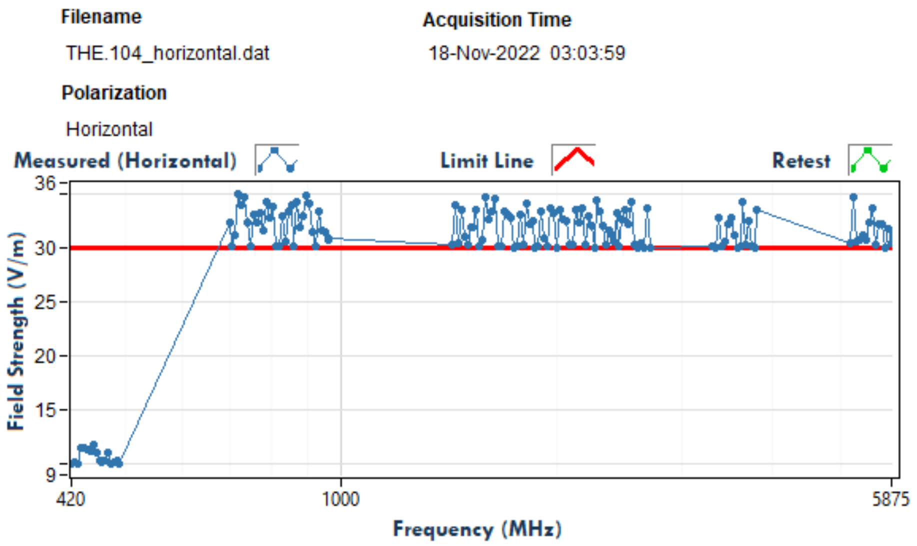

Figure B.19 – Field strength level during RS103 testing at test location 10 (THE.104) - horizontal polarization

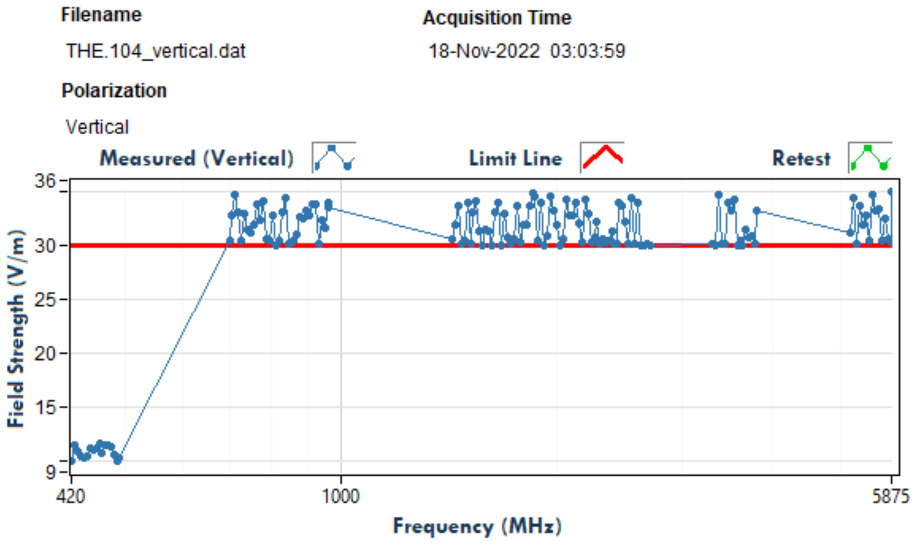

Figure B.20 – Field strength level during RS103 testing at test location 10 (THE.104) - vertical polarization

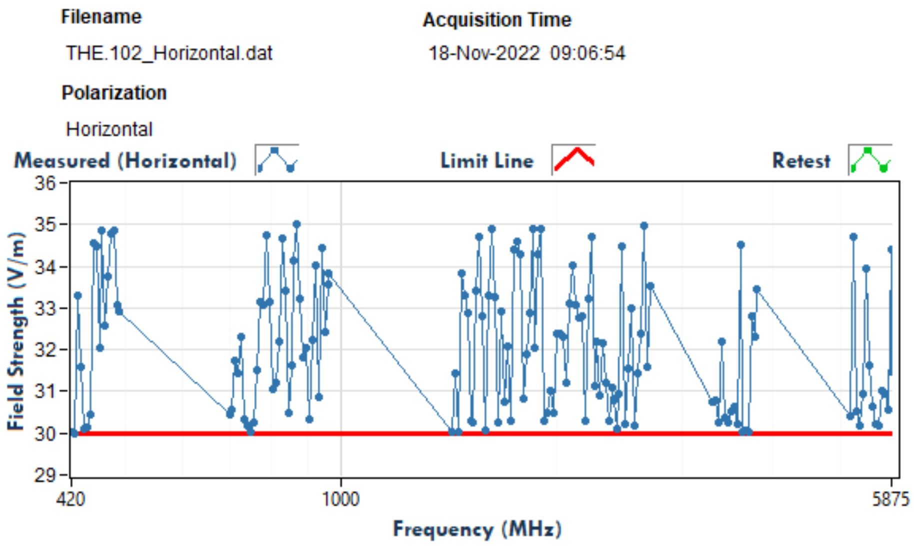

Figure B.21 – Field strength level during RS103 testing at test location 11 (THE.102) - horizontal polarization

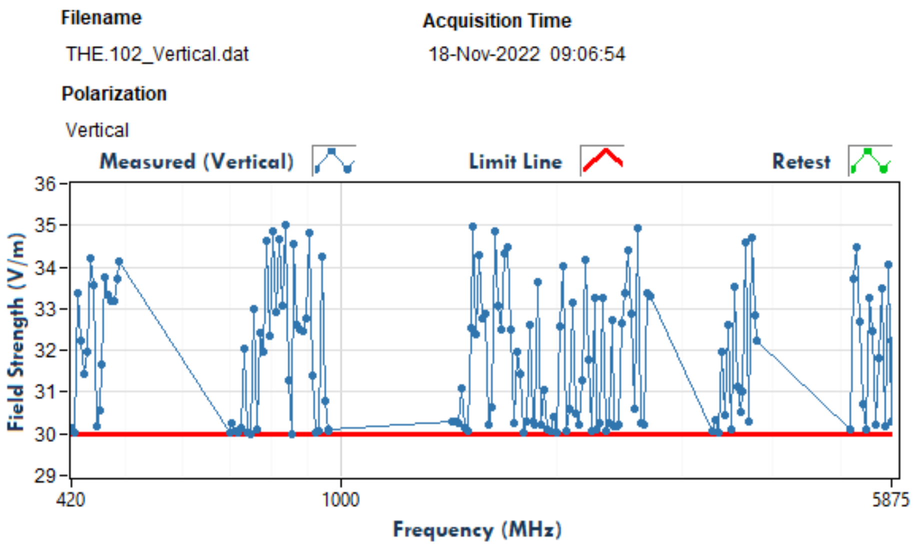

Figure B.22 – Field strength level during RS103 testing at test location 11 (THE.102) - vertical polarization

APPENDIX C Test Plan

Available for program stakeholders.

WIRELESS EMC TESTING OF NUCLEAR POWER PLANT EQUIPMENT FOR ENERGIFORSK

This report provides the final results and details of the radiated Electromagnetic Compatibility (EMC) susceptibility testing of Nuclear Power Plant (NPP) equipment located in the KSU training facility. Wireless technologies can provide many positive aspects for a nuclear facility, such as easier and faster ways to connect equipment and monitor plant and equipment status or provide a more cost-effective way to do test measurements or temporary installations compared to hardwired systems. One problem with wireless systems within nuclear power plants is that a large share of the existing equipment in the plant is developed and installed prior to many EMC standards and hence it is difficult to really know which equipment that can be affected by wireless networks and how this effect manifest into the equipment functionality. Also, many prior tests that has been performed have been against wireless or radio protocols and techniques that are no longer in use.

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