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AMS Whitepaper: Technical Approach for Enabling Widespread Use of Wireless Technologies in the Power Block of Nuclear Power Plants

1. INTRODUCTION

This whitepaper provides an overview of the technical approach employed by Analysis and Measurement Services Corporation (AMS) to enable widespread use of wireless technologies within the power block of nuclear power plants. AMS has worked with numerous utilities using the approach described herein including Diablo Canyon, Nine Mile Point, and the Krsko plant in Slovenia, among others. A summary of AMS qualifications in the area of wireless and EMC is provided in Attachment 1.

2. BARRIERS TO WIRELESS TECHNOLOGIES

Wireless technologies offer tremendous opportunities to nuclear power plants for improved safety, efficiency, and reliability by supporting equipment condition monitoring, voice and data communications, electronic work packages, and many other emerging technologies. Aside from cost and cyber security concerns, the primary challenge is that the majority of equipment installed in nuclear power plants was never tested for Electromagnetic Compatibility (EMC) with wireless devices. As a result, the ability of legacy equipment to reliably withstand wireless transmissions is not known. To manage this reality, utilities have used administrative controls to define distances from sensitive plant equipment where wireless cannot be used (i.e. separation distances or “exclusion zones”). In some instances, such as with cellular technologies, outright prohibition has also been implemented unless further technical evaluations are performed. AMS has demonstrated that although the concerns related to EMC for wireless technology implementation are valid, they are very manageable and can be addressed using a systematic approach that is described herein. The AMS approach helps objectively demonstrate that sensitive plant equipment will not be impacted by wireless technologies and thereby establish guidance for more free use throughout the plant. The AMS strategy for this work is the result of decades of experience in performing EMI/RFI measurements in nuclear power plants as well several million dollars in research and development projects carried out for the Department of Energy as described in Attachment 1.

3. GOING BEYOND EXCLUSION ZONES AND/OR PROHIBITIONS

Exclusion zones, which are calculated by using the power output of the wireless devices, are based on guidance provided by the Nuclear Regulatory Commission (NRC) and the Electric Power Research

Institute (EPRI). In a study performed by AMS, it was determined that exclusion distances in almost all nuclear power plants are overly conservative and thereby severely limit the use of wireless devices in most areas of the plant. This is evident in the data shown in Table 1 where exclusion zones as calculated for a nuclear power plant are compared for some of the commonly used wireless devices. AMS has demonstrated that many exclusion zones could be reduced significantly with the approach described in this white paper. Further, justification to remove prohibitions of unknown mobile technologies such as cellular can also be developed.

Table 1. Examples of Exclusion Distances in Nuclear Power Plants*Note***

Wireless Device	Distance (Feet)
iPad 4	8
iPad Mini	6
Cell Phone	9
Laptop Computer	3
Dosimeter	1
Wireless Vibration Sensor	2
Walkie Talkie	13

It should also be pointed out that exclusion zones in nuclear power plants are defined based on the power output of wireless signals and do not account for the effect of frequency. In fact, AMS has demonstrated through in-plant and laboratory work that the vulnerability of plant equipment to wireless signals diminishes significantly at higher frequencies as illustrated in Figure 1. This implies that the higher frequencies from devices using Wi-Fi and Bluetooth (e.g. 2.4 GHz) may not pose a significant risk to power plant equipment even when they are very close to the equipment.

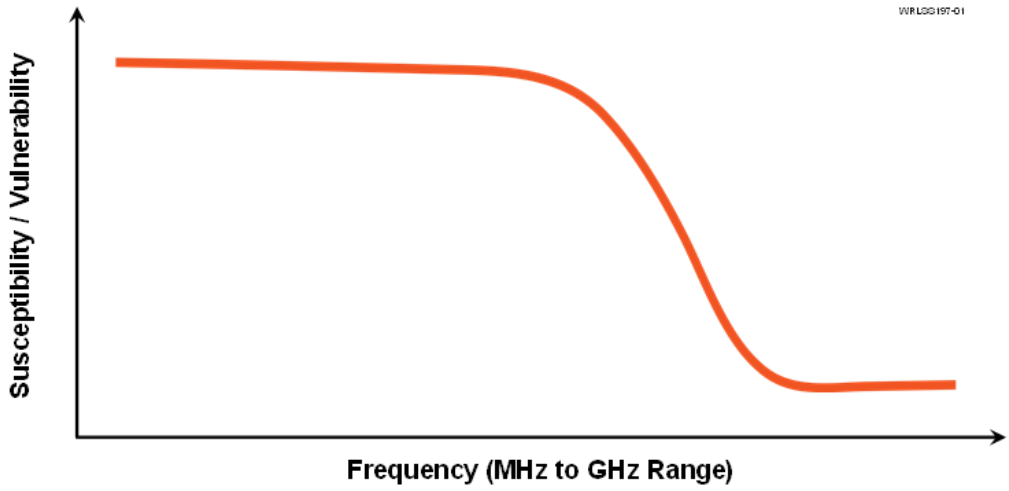


Figure 1. Illustration of Vulnerability of Plant Equipment to Wireless Signals Versus Frequency

4. METHODOLOGY FOR ENABLING WIRELESS IN THE POWER BLOCK

The general approach employed by AMS for evaluating the use of wireless technologies involves the following steps:

1. Site Walkdown with EMC Consultation Services. The purpose of the site walkdowns is to identify areas of concern for implementation of wireless technologies, identify areas in the plant where there would not be concern with using wireless, and to define the recommended scope of work for performing future Electromagnetic and Radio Frequency Interference (EMI/RFI) site surveys.
2. On-site Testing through EMI/RFI Site Surveys. AMS has developed a specialized EMI/RFI site survey program for the nuclear industry to specifically address wireless EMC. The results of the testing provide objective data for justifying widespread use of wireless technology throughout the power block.

These activities are described in more detail in the following sections.

5. SITE WALKDOWNS AND EMC EVALUATIONS

To establish the basis for expansion of wireless technologies in a nuclear power plant, an EMC engineering consultation visit and site walkdown is first performed to fully understand plant-specific considerations. The walkdown will tour different areas of the plant, with specific emphasis on I&C systems that might be vulnerable to wireless signals. Examples include main turbine control cabinets, electronic/digital relays, digital recorders, area radiation monitors, pressure, level, and flow transmitters, instrument panels, annunciator systems, digital displays, supply breakers, protection system components, among others. This on-site work is used to define the recommended scope of work for performing future EMI/RFI site surveys and to align stakeholders on the use of wireless throughout the power block.

During the site visit and prior to performing the walkdown, AMS engineers will meet face-to-face with plant stakeholders to determine areas where wireless technology would ideally be used, identify potentially sensitive plant equipment within these areas, and review previous EMI/RFI experiences and issues. Prior to coming on-site, AMS will also review engineering drawings, current use of wireless exclusion zones, and other applicable documentation.

Based upon the results of on-site meetings and off-site evaluations, areas of the plant will be selected for a walkdown. The walkdown will be used to identify sensitive I&C equipment in the applicable areas as well as the potential for interference from wireless technologies. AMS will also identify any observed deviations from ideal EMC practices such as inadequate grounding, missing shielding, cable tray discontinuity, etc. Standards and guidelines such as EPRI TR-102323 Revision 4, EPRI TR-102400 Volume 2, IEEE 1050, IEEE 603, as well as AMS experience are used to help identify equipment that may have either vulnerable installations, be critical to plant operation or safety, have a history of malfunction in the presence of wireless devices, or could cause nuisance alarms for plant operators.

The deliverable of the walkdown is a comprehensive EMI/RFI site survey plan which details a listing of equipment and plant areas recommended for testing as described in Section 6.0.

6. EMI/RFI SITE SURVEYS AS DEFINED BY PLANT WALKDOWN(S)

AMS has developed a specialized EMI/RFI site survey program for the nuclear industry with associated equipment and technology to specifically address wireless EMC. This test program helps to evaluate the ability of existing plant equipment to withstand wireless transmission. To do this, AMS will make use of specialized software, spectrum analyzers, antennas, amplifiers, and, as needed, a newly developed Cognitive Radio System (CRS), a field testing device used to perform on-site wireless testing in nuclear power plants. This approach is described below.

Traditional EMI/RFI Site Surveys – Passive Emissions Mapping: This relates to the performance of passive wireless EMI/RFI site surveys to 1) locate and identify signal sources and frequencies that may compete with wireless devices and/or 2) indicate potential vulnerabilities of the equipment identified during the site walkdown. Numerous utilities use EMI/RFI site surveys to support site-wide implementation of wireless devices. Site surveys use passive antennas to capture and characterize the Electromagnetic Environment (EME) in a certain area and are performed while the plant is operating. For the frequencies of interest regarding wireless devices, the EME can be made up of intentional transmitters from devices such as radios and cell towers as well as unintentional sources such as clock frequencies, arcing, etc. which may radiate from plant components or cables. Overall, it is important to understand the EME of the plant prior to installing new digital equipment such as wireless technology. Example data from passive emissions mapping in a nuclear power plant is shown in Figure 2.

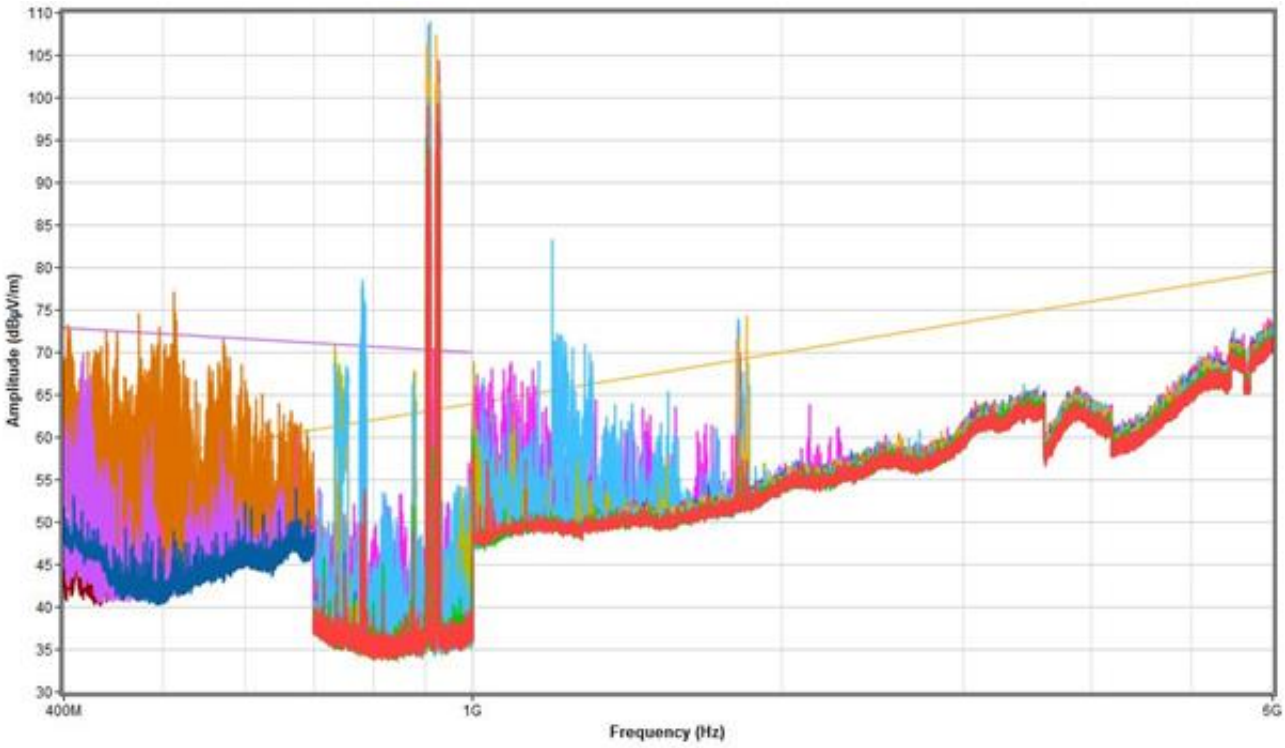


Figure 2. Traditional EMI/RFI Site Survey Data for a Nuclear Power Plant (400 MHz – 6 GHz)

For the passive emissions mapping, AMS provides experienced EMC Test Engineers on-site to perform the work. EMC testing is conducted in accordance with EPRI TR-102323 Rev. 4 and/or NRC Reg. Guide 1.180 Rev. 1 using guidance from the Mil-Std 461 RE102 test method entitled, "High Frequency Radiated Emissions". Testing will be performed for the common wireless frequency bands between 400 MHz - 6 GHz to cover the full spectrum of wireless devices. The work will be performed using a spectrum analyzer and antenna(s) coupled with specialized AMS software and/or the AMS CRS tool.

Testing is be performed during plant operation; therefore, all testing is performed using non-intrusive, non-transmitting probes and antennas. Should high levels of emissions be identified during any part of the site emissions survey, AMS attempts to locate the source of the emissions to provide any recommendations for mitigation.

1. Specialized EMI/RFI Site Surveys – In-Situ Immunity Testing of Selected Equipment: The purpose of this testing is to provide evidence of whether or not equipment is susceptible to signals from wireless devices and thereby establish objective and less conservative exclusion distances (or remove outright prohibitions) thereby enabling more widespread use of the technology all throughout the plant. This testing is done on-site and is referred to as "in-situ immunity testing." The immunity testing is performed by generating non-destructive Radio Frequency (RF) energy at the same frequencies as wireless devices and radiating it onto equipment and cables. The testing is done using AMS equipment and guidance from the Mil-Std RS103 test method entitled, "High Frequency Radiated Susceptibility." The AMS CRS tool may also be used to further quantify plant equipment immunity levels (see Figure 3). The CRS is designed to transmit and receive wireless signals such as Wi-Fi or cellular to establish distances at which existing plant equipment will not be affected. All testing is carefully coordinated with site personnel to evaluate the best methods for performing the work. Testing is typically performed during a plant outage, in the plant simulator, in plant training centers, or "on the bench" where equipment can be staged. To help facilitate testing in the plant, AMS has also developed a number of methods to contain the RF energy to the equipment under test so as to protect nearby sensitive equipment (Figure 4). The exact list of equipment to be tested in the plant would be defined as part of the site walkdowns summarized in Section 5.0.

Figure 3. Block Diagram of AMS Cognitive Radio System (CRS Tool)

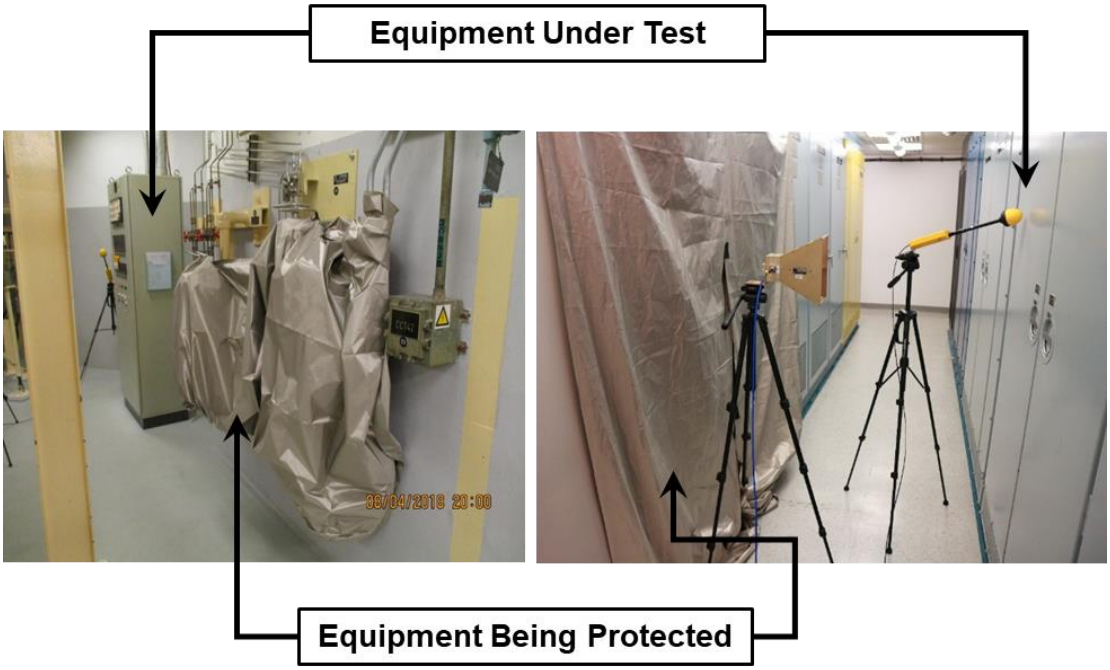


Figure 4. In-Situ Immunity Testing in a Nuclear Power Plant with Nearby Equipment Protected through Lightweight EMI Shielding Fabric

For the specialized EMI/RFI site surveys, AMS provides experienced EMC Test Engineers on-site to perform the work. EMC immunity testing will be conducted in accordance with EPRI TR-102323 Rev. 5 and/or NRC Reg. Guide 1.180 Rev. 2, using guidance from the Mil-Std 461 RS103 test method. Testing is performed over the frequency bands between 400 MHz – 6 GHz to cover the full spectrum of common wireless devices. The specialized AMS CRS tool can also generate Wi-Fi, cellular, and other common wireless signals using signal generators designed for the purpose. To provide a level of margin, the testing will be performed for power levels at or above the worst-case scenario for the wireless devices intended for installation in the plant. Figure 5 shows an example of AMS performing this testing inside the control room of a nuclear power plant.

AMS will coordinate with plant personnel to determine whether or not the systems tested are susceptible to the frequencies generated by the CRS tool. This could involve monitoring plant computer data points, meters and indicators in the cabinets, or additional test equipment attached to the equipment under test. If the equipment is found to be immune to the RF energy, then no further investigation is necessary. However, if the equipment is found to be susceptible, further measures should be taken to identify the threshold of susceptibility, mitigate the susceptibility by making modifications to the equipment or cabling, or establish the wireless device exclusion distance that must be maintained to prevent malfunction. AMS has experience in both noise mitigation and the determination of exclusion distances and will be prepared to perform these activities on-the-fly/during the on-site work. Figure 6 provides an example of equipment found to be vulnerable to wireless signals as a result of in-plant testing. In this example, the equipment vulnerabilities were mitigated by adding temporary shielding around the non-metallic flexible conduit connected to the equipment housing.

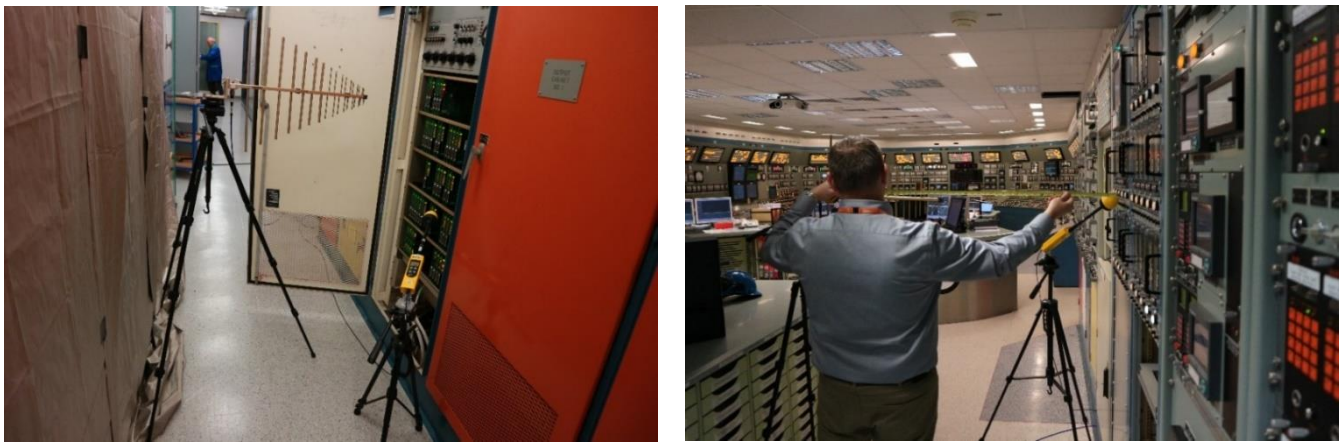


Figure 5. In-Situ Immunity Testing Performed Inside the Control Room of a Nuclear Power Plant

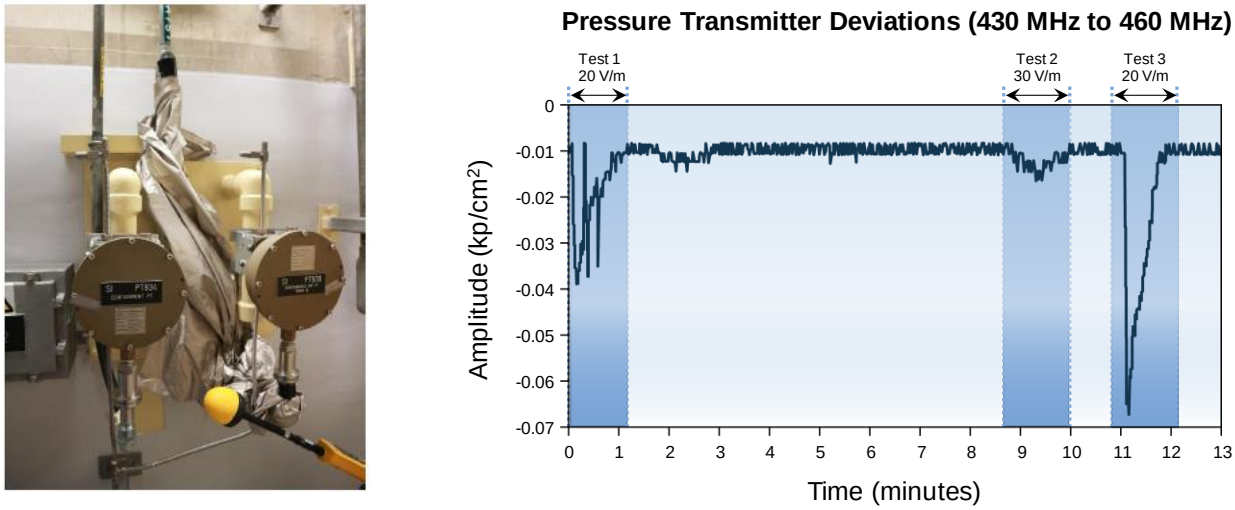


Figure 6. Example of Equipment Modifications Made to Mitigate Vulnerabilities Identified During In-Situ Wireless Immunity Testing (Note Temporary Shielding Material in Picture)

7. CONCLUSION

Extensive research and development and site operating experience have shown that the combination of site walkdowns, EMC evaluations, and an EMI/RFI site survey testing program is an effective way to enable wireless technology within the power block of a nuclear power plant. The work allows a site to have confidence, based on real test data, that wireless technology implementation will not affect existing sensitive equipment. The results provide guidance that can be used for many years of future plant operation. This is illustrated in Table 2, which provides a sample result of a nuclear plant component tested for immunity to wireless signals.

Table 2. Summary of Indicator Meter Testing for Immunity to Wireless Signals

Wireless Test Frequency	Test Level	Test Result
430 MHz – 460 MHz	20 V/m	Immune
698 MHz – 960 MHz	15 V/m	Immune
1428 MHz – 2200 MHz	15 V/m	Immune
2400 MHz – 2700 MHz	20 V/m	Immune
3400 MHz – 3600 MHz	15 V/m	Immune
5150 MHz – 5350 MHz	20 V/m	Immune
5470 MHz – 5875 MHz	20 V/m	Immune

REFERENCES/AMS PUBLICATIONS

[1] Kiger, C.J., "Empowering the Nuclear Industry's Mobile Workforce: Are Exclusion Zones Enough?," Analysis and Measurement Services (AMS) Corporation (June 2013).

[2] Kiger, C.J., Hashemian, H.M., Moarefy, A., "Wireless Technology." *Nuclear Plant Journal*, Volume 33, No. 2, pp 26-27, 42 (March-April 2015).

[3] Kiger, C.J., Lowe, C.L., "Strategy for Implementation of Wireless Technologies in the Electromagnetic Environment of Nuclear Power Plants." Presented at the American Nuclear Society 9th International Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technologies (NPIC & HMIT), Charlotte, NC (February 23-26, 2015).

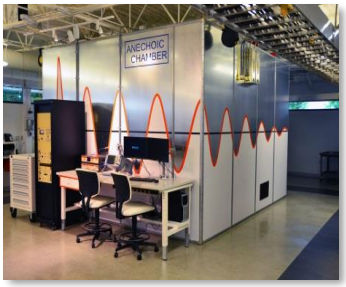
[4] Kiger, C.J., Grganic, H., "In-Situ Electromagnetic and Radio Frequency Interference Testing of Equipment in the Main Control Room of Krško Nuclear Power Plant." Presented at the American Nuclear Society 11th International Topical Meeting on Nuclear Plant Instrumentation, Control and Human Machine Interface Technologies (NPIC & HMIT), Orlando, FL (February 9-14, 2019).

Attachment 1

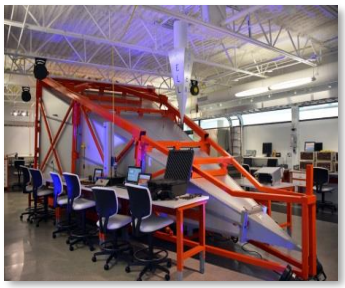
Qualifications of AMS: Wireless and EMC

Qualifications of AMS: Wireless and EMC

Figure 1. AMS EMC Laboratory



Anechoic Chamber



GTEM Cell

New EMC Expansion (3-Meter Chamber)

AMS has served the nuclear power industry for over 40 years in instrumentation and control (I&C) system testing, diagnostics and prognostics, electromagnetic capability (EMC) measurements, EMI/RFI troubleshooting, wireless technology deployment, cable and connector testing, predictive maintenance of equipment and processes, and automated test equipment development.

AMS has been a major supplier of EMC qualification testing, EMI/RFI troubleshooting, and cable condition monitoring for over 20 years. Our infrastructure, employees, procedures, and quality assurance (QA) program are all tailored to meet the unique needs of the nuclear power industry. In fact, AMS has just completed the construction of a third building, representing a major expansion to its main technology campus. This new $5 million testing and research and development (R&D) facility adds 15,000 square feet of new office and laboratory space to AMS' existing headquarters, including a $1 million 3-meter EMC chamber. The new chamber contains nearly 10,000 cubic feet for MIL-STD and IEC testing to meet the EMC requirements of the NRC and EPRI and is designed to accommodate equipment with weights up to 5,000 pounds. As such, AMS is familiar with and regularly employs the use of the relevant standards for nuclear EMC qualification testing such as EPRI TR-102323, "Guidelines for Electromagnetic Interference Testing of Power Plant Equipment," U.S. NRC Regulatory Guide

1.180, “Guidelines for Evaluating Electromagnetic and Radio-Frequency Interference in Safety-Related Instrumentation and Control Systems,” Department of Defense Interface Standard MIL-STD 461, “Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment,” IEC Standard and European Norm (EN) 61000, EMC – Part 4, “Testing and Measurement Techniques,” and others.

Field Testing in Diablo Canyon

AMS’ infrastructure for EMC testing in the nuclear power industry also includes a 1-meter semi-anechoic RF chamber and a Gigahertz Transverse Electromagnetic (GTEM) cell. AMS boasts one of the finest laboratories for EMC qualification and research in the United States (Figure 1) and provides a significant amount of EMC qualification testing of analog and digital I&C components for nuclear power plants. The laboratory allows for EMC testing and research from 30 Hz to 18 GHz. Our state-of-the-art EMC test facility is accredited to ISO/IEC 17025, “General requirements for the competence of testing and calibration laboratories,” by the American Association for Laboratory Accreditation (A2LA) under AMS’ A2LA certificate number 3483.01.

In addition to performing EMC qualification testing of nuclear plant equipment and wireless devices in the laboratory, AMS has also been involved in mapping the electromagnetic environment at dozens of nuclear power plants in the U.S., performing passive site surveys as well as specialized on-site immunity testing to provide objective data regarding the potential impact of wireless signals on existing plant equipment. We have also developed and deployed wireless condition monitoring systems in nuclear power plants.

For example, AMS has completed a project with the Diablo Canyon Nuclear Power Plant consisting of plant walkdowns, site surveys, laboratory testing, and on-site immunity testing of plant equipment to verify that cell phones, tablets, and other wireless devices will not pose a significant impact to the operation of existing plant equipment. AMS performed a similar project at the Nine Mile Point Nuclear Power Station as they implement cellular devices on a site-wide Distributed Antenna System (DAS). The project with Nine Mile Point has also involved the laboratory testing of a Samsung Galaxy S8+ cell phone using AT&T service and an Apple iPad Pro tablet using Verizon service to quantify its near-field and far-field emissions and establish their associated exclusion distances. In 2018, AMS also performed a comprehensive EMI/RFI evaluation and testing project at the Krško Nuclear Power Plant in Slovenia to support the widespread use of wireless technologies and to facilitate future digital upgrades at the plant.

Testing Performed in AMS' Anechoic Chamber

Examples of installations of AMS wireless condition monitoring equipment in nuclear facilities include the High Flux Isotope Reactor at Oak Ridge National Laboratory, Comanche Peak Nuclear Power Plant in Texas, and Arkansas Nuclear One (ANO). These implementations culminated in the installation of a wireless system in the containment building of ANO Units 1 and 2 to monitor the vibration of containment cooling fan motors and control element drive mechanisms (CEDMs). The ANO system has provided reliable and consistent data daily since October 2011.

AMS Participation in National and International Guidance and Standards

The following listing provides examples of the different areas where AMS is involved in helping to develop national and international standards and guidance on the use of wireless technologies in the nuclear power industry.

1. In May 2009, the IEC SC 45A Technical Working Group on Nuclear Power Plant Control and Instrumentation held a meeting which resulted in the recommendation to develop a technical report addressing the applicability of incorporating wireless technology throughout nuclear power plant systems. The focus of the report was on non-safety applications with future work and investigations identified as necessary to overcome the barriers of using wireless for control and safety applications. The report was issued in July 2014 as IEC/TR 62918 ed. 1.0. The technical report was meant as a precursor to an IEC standard on the same topic. The IEC 62988 standard, "Nuclear Power Plants – Instrumentation and Control Important to Safety – Selection and Use of Wireless Devices," was published in 2018. AMS was one of the principal authors of the report and is serving as a co-chair for the standard development.

   In addition to the wireless standard, AMS is also the chair of the revision to IEC 62003, "Nuclear Power Plants – Instrumentation, Control, and Electrical Systems Important to Safety - Requirements for Electromagnetic Compatibility Testing." A major emphasis on the revision of this standard is to address the implementation of wireless devices in nuclear power plants. This standard is expected to be released in 2020.

2. In 2014, the Nuclear Power Engineering Section of the Division of Nuclear Power at the International Atomic Energy Agency (IAEA) conducted a project on, "Application of Wireless Technologies in Nuclear Power Plant Instrumentation and Control Systems." The goal of the project was to develop and demonstrate techniques for advanced wireless communication in instrumentation and control systems at nuclear power plants that can be applied for transferring process and diagnostic information as alternatives to wired technologies. AMS participated as a Chief Scientific Investigator (CSI) for the project and a technical report was published in 2019.

3. In June 2016, the IEEE Standards Association approved the development of an RF Site Survey Standard, “Recommended Practice for an Electromagnetic Site Survey (10kHz to 40GHz).” AMS is serving as the chair of the Working Group that is developing the standard through the IEEE EMC society. In conjunction with the IEEE site survey standard, AMS is also participating in the development of an “In-situ EMC Immunity Test Standard” being developed by the American National Standards Institute, ANSI C63.24.

   IEEE is also developing their own nuclear EMC standard, P2425, “Standard for Electromagnetic Compatibility Testing of Electrical and Instrumentation and Control Equipment at Nuclear Power Generating Stations and Other Nuclear Facilities”. AMS serves as a working group member on this standard which is expected to take several years to complete.

4. The EMC Working Group of the Electric Power Research Institute (EPRI) is developing guidance on the use of wireless technologies as it relates to EMI/RFI. For example, this group developed a new appendix on the use of wireless technologies for the guidance stipulated in EPRI TR-102323 Revision 4. AMS, through its CHAR Services division, has participated in the working group since the mid-1990s and was one of the principal authors of EPRI TR-102323.

5. AMS has been the major contributing author on a number of EPRI Technical Reports related to the use of wireless technologies including:

   a. *Implementation Guideline for Wireless Networks and Wireless Equipment Condition Monitoring,* EPRI, Palo Alto, CA: 2009. 1019186. This report includes guidance for the implementation of a wireless network within a nuclear power plant and also covers the use of wireless sensors for asset condition monitoring.

   b. *Wireless Sensor Survey and General Specification*, EPRI, Palo Alto, CA: 2018. 3002011818. This report presents the various wireless sensor technologies that are commercially available; an overview of EMI/RFI concerns for wireless sensor technology, including laboratory test results for numerous sensors; guidance for specifying and procuring wireless sensor technology to meet a particular equipment condition monitoring application; and the suggested responsibilities of various departments within the power plant during the implementation of wireless technology. The results of this report can be used by a utility to assist in the deployment of wireless technology within a nuclear power plant environment.

   c. *Wireless Technology Assessment*, EPRI, Palo Alto, CA: 2018. 3002012707. The purpose of this project was to perform laboratory EMI/RFI testing of modern and currently prevalent wireless devices to identify the typical distances that smartphones, tablets, and laptop devices exceed recommend EMI/RFI emissions and susceptibility limits. The results of the work were used to support the fifth revision to EPRI TR-102323 that includes license guidance for the use of portable wireless communications devices in commercial nuclear facilities. The fifth revision was published in December 2019.

6. Since 2009, AMS has been awarded over $6M in R&D projects by the U.S. Department of Energy that focus on the use of wireless technologies in the nuclear power industry. The project titles are as follows:

    - *Wireless Sensors for Equipment Health and Condition Monitoring in Nuclear Power Plants.* Major developments include deployment of wireless sensor networks for use in nuclear power plants. This included installation of a new, first-of-a-kind wireless system to monitor cooling fan vibration inside the containment of a nuclear power plant.

    - *Wireless Sensors for Predictive Maintenance of Rotating Equipment in DOE's Research Reactors.* Major developments include wireless sensor networks for process measurements in DOE's research reactors.

    - *Strategy for Implementation of Fixed and Mobile Wireless Technologies in Crowded and Confined EMI Environments of Nuclear Power Plants.* This project focuses on development of new equipment and techniques to resolve wireless EMC and coexistence issues and facilitate widespread use of wireless technology in nuclear facilities. The result of the work has allowed nuclear power plants to use on-site immunity testing to reduce or eliminate exclusion zones for wireless transmitters.

    - *Distributed Antenna System for Wireless Data Communication in Nuclear Power Plants*. The goals of this project are to build upon industry experience with the Distributed Antenna Systems for voice and data communications in nuclear power plants by identifying and addressing implementation concerns as well as identifying/developing sensors capable of using the new communication capabilities.

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