CASE HISTORIES AND LESSONS LEARNED FROM THE DESIGN, DEVELOPMENT, PLANNING AND IMPLEMENTATION OF NEW I&C SYSTEMS, INCLUDING EFFECTIVE INTEGRATION WITH EXISTING SYSTEMS AND PROCESSES

D. Greene, R. Greene
Greene R&D International Inc., USA

Email address of main author: David.Greene@grdi.com

Abstract.
This paper is based on practical, wide ranging and in-depth experience of many aspects of power plant design and operation. The authors have decades of experience working in the nuclear industry, as well as other high technology fields. This includes leading teams on development, design and implementation of plant diagnostic and monitoring equipment; fundamental technology and R&D investigations; and integration of advanced technologies and processes into nuclear energy, space reactors, and other industries. The paper will draw from this experience and describe the lessons learned when implementing systems 'from-womb-to-tomb', The paper is in two parts. We will use practical experiences to suggest project development best practices in Part 1; and illustrate lessons learned during I&C system installation, testing and validation in Part 2,

Damage to a steam generator from a sodium-water reaction can be extensive if not mitigated by a rapid detection system. A strong economic case can be made to develop a reliable detection system with very low false alarm rate (typically one false alarm in thirty years). A passive acoustic tomography leak detection system was invented and fully developed (the BatScan system). BatScan, in effect, has many tens of thousands of virtual microphones within the vessel, and can independently measure the noise field at each virtual microphone. BatScan's software then produces a three dimensional image of the absolute sound field within the volume, indicating the size and location of a tube leak.The project to develop this detection system was extensive, covering analyses, laboratory tests, and installation and integration with large test facility and Nuclear Power Plant Instrumentation and control systems. Analytical and experimental investigations covered a wide range of fields, from Sodium-water reaction phenomena, acoustic technology, to sensors and state of the art electronics. Best practices and lessons learned from the project are described.

Part One: Best practices used in I&C project – Development

1. Introduction: Steam Generator Water/Steam Leak Detection System

Liquid metal cooled fast reactors use sodium to transfer reactor thermal energy into an intermediate heat exchanger. The secondary sodium circuit uses another heat exchanger to produce steam, the steam generator (SG). The water/steam loop of the steam generator operates at high pressures to drive turbines and produce electrical power. The steam generator is designed with tube bundles containing water/steam, with sodium flowing on the shell side. Great care is taken to design and fabricate high integrity steam generators, but operating experience from test facilities and operating power plants indicated there is a finite chance that a leak will appear in the SG. Rupture disks, venting systems and reaction product dump tanks assure the integrity of the power plant for large leaks (simultaneous rupture of multiple water tubes) [Ref 1].

If the steam generator tube leaks, the high pressure water/steam is injected into the sodium. A very vigorous reaction produces H_2 (hydrogen gas), Na_2O (sodium oxide), NaOH (sodium hydroxide) and NaH (sodium hydride) and heat. A small water leak from a tube (milligrams/second) could initiate failure of nearby tubes in the heat exchanger in time-scales of ~5-seconds to 30-minutes. Detection systems were developed for reaction products, but the detection timescales were unacceptably long compared to timescales associated with damage propagation. The long detection times were due to transit times from the leak site, and the dispersal and dilution of the reaction products in the sodium

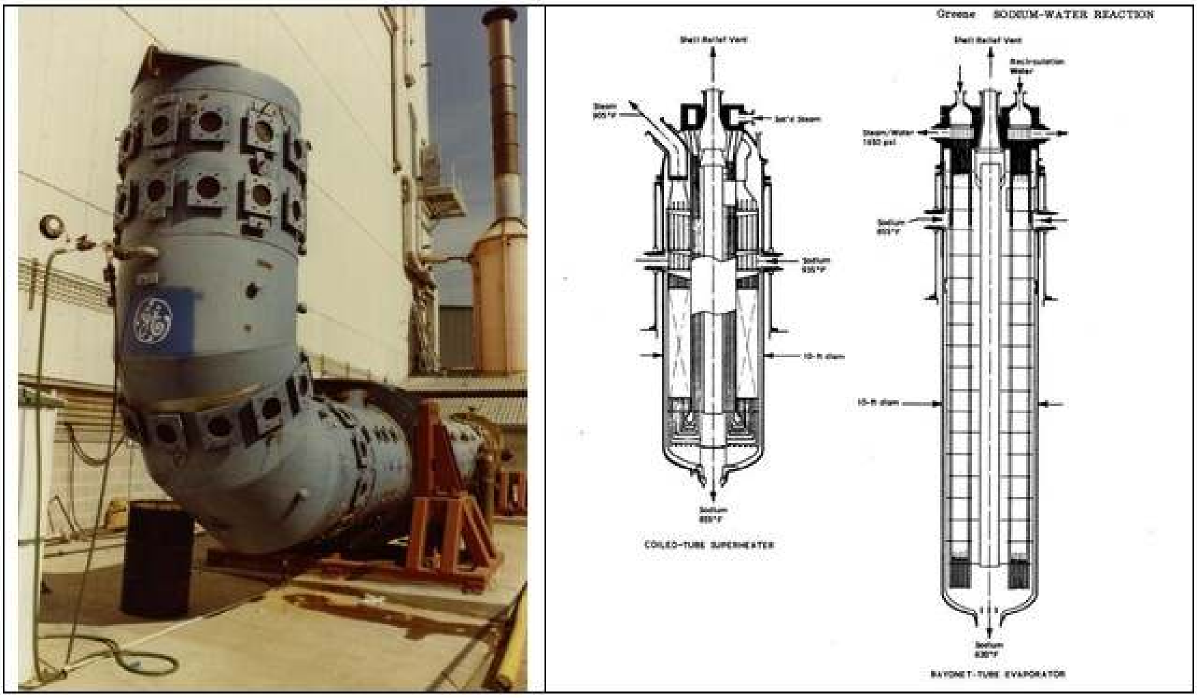

FIG. 1. Steam Generator Designs, and Hockey Stick Model used for developing BatScan System

and cover gas. BatScan, a passive acoustic tomography system that rapidly detects small and intermediate leaks and their sodium-water reactions was developed to protect NPP capital investment. Figure 1 shows two steam generator designs, a helical coil unit, and a bayonet tube unit. The unit on the left was a full size model of a 'hockey stick' design steam generator used to provide a realistic test bed for the BatScan system. It was also used for thermal hydaulic tests; during which steam generator background noise due to fluid flow was also measured (the vessel was mounted vertically for the thermal hydraulic tests, but horizontally for BatScan development to reduce support structure costs).

Damage from a sodium-water reaction can be extensive if not mitigated by a detection system. Repairs, investigations of the event, plus associated plant unavailability costs are extremely high. The main purpose for installing a water-into-sodium leak protection system is to protect the capital investment in the plant and to increase plant availability. A cost to benefit analysis showed substantial financial benefits if the detection system mitigated the damage associated with just one small or intermediate sized leak. This aspect of the problem attracted several strong champions with the power or influence to demand the project be completed.

The authors will use the BatScan plant condition monitoring system as a foundation for suggesting best practices. It was developed and tested for use in nuclear plant monitoring; specifically for protecting steam generators. This system uses passive acoustic tomography monitoring techniques to identify and locate anomalous sounds within plant components. When used to protect process plant, it uses externally mounted sensors to monitor the three dimensional acoustic field in the internal volume of a large vessel (i.e. a steam generator), and indicates when an internal defect or fault condition exceeds a threshold intensity. BatScan provides both the absolute sound intensity and its exact location within the internals of the plant component. The BatScan system detects and precisely locates the fault. This paper will follow the BatScan system from idea conception and proof of principle testing, through system development, design, installation, operator acceptance as an I&C subsystem, and performance experience on operating steam generators.

2. Projects need to have all required components to succeed

Some projects take on a life of their own; they survive budget cuts, changes of management and even occasional bad performance. Others projects seem to flash in and out like a firework, a short time of brilliance followed by the darkness of oblivion. The first type of project requires three equally strong major components; technical, human and organizational. Failure to implement or balance these components produces the second type of project. We have been responsible for projects that are part of a larger program, and have been able to continue the project long after the original program has been halted. This is because the project was directly responsive to a well defined need that was not yet satisfied, so a new home (and funding) was found by supporters and sponsors.

Most Engineers and Scientists find it relatively easy to define and implement the technical component part of an instrumentation based project. The technical component of the BatScan project defined and solved the analytical and practical problems in developing a tube leak rapid detection system. However, giving all of the effort to this technical component will not satisfy the overall goal of the BatScan project; this cannot be defined by the technical component alone. It requires identifying and implementation of at least two further component parts of the project, the human and organizational components.

> *It is an essential best practice to ensure a project has three main components; human or community involvement component, technical component, and an organization or operations control component.*

The three project components will be developed and described individually, although in practice they are not isolated and overlap and interact. Each of these component parts of the project will include best practices that may also be applicable to other project components.

2.1.Human Component: Project Stakeholders, Champions, Communities

Complete tube rupture is a very low probability event; a small leak is a far higher possibility. It is not a plant safety problem, but one of protecting capital investment in the power plant. There were strong economical incentives for a leak detection project to limit damage; allow controlled plant shutdown, and minimize thermal shock to plant components. The identities of the stakeholders in the BatScan project were unknown at the start of the programme, and they may not even have been aware of the existence or potential impact of the project. The human stakeholders must be identified and educated about the project scope; especially since they have the most to gain or lose. The stakeholders generally have the strongest input when setting project goals. The acoustic leak detection system stakeholders included the Nuclear Power Plan (NPP) owner (Association of Utility Owners who provided partial funding), Government Agencies (who controlled or apportioned federal or state funding), the plant operator (the actual user of the system), and possible technical contributors (National Labs, Academic, subject matter experts in companies). Control room operators, their management as well as external regulatory agencies need to be totally satisfied that the installed system will not compromise the integrity or safety of the plant. Regulatory agencies generally require demonstrated proof that all reasonably practical precautions are taken to ensure safety. These also form part of our involved community.

This loose consortium of stakeholders must ‘buy in’ to the technical part of the project, and they may require significant changes to the technical community’s original project plan. The stakeholder needs must be addressed close to project initiation and regularly updated; then given due credit for their contribution. The project leader’s responsibility includes identifying project champions in the stakeholder groups; then ensure they remain cognisant of project results, both positive and negative.

The Nuclear Power Plant owner/operator must be satisfied that improvements or updating the NPP is economically viable. This applies to retrofitting or updating as well as new installations. Just as important, the NPP community, especially plant owners and regulatory agencies, must ‘buy-in’ to all aspects of the outcome of the development, design, testing, validation and implementation of the system. Without this consensus building, the system may be severely crippled in its acceptance and support by the user community. Design, development, proof testing and installation efforts can only be justified by comparison with expected economic benefits; quantitative strength is added by cost-to-benefit ratio investigations.

Let’s introduce a fundamental idea on how to achieve consensus within this community. It is communication using the ***‘Principle of No Surprises’***. Operate with 360 degrees of information exchange. The concept is not to surprise your management, your colleagues, your peers and supporters, and make it plain you do not expect to be on the receiving end of any surprises. Do not hide bad news; ask for help, suggestions and reviews. Do not try to be omniscient; stay open. Build a cohesive community, not a fence. A diversified, informed group results in strong practical project support, and minimizes adversarial relationships or conflicts.

2.2. Organizational Component of Project, Protectors, Archivists and Resurrection

The third component of the project is operations management and organizational support. This is often viewed by the technical component as a burden. In reality they are the technical team’s best friend: they help prevent or mitigate mistakes. They provide the customer with an assurance of quality of product, process, and procedure. They help to define design standards and verification needs; they impartially check and report on activities or progress. The third component assures system quality, protects the investment in the project by requiring adequate documentation, archiving, fabrication records, data and manuals that allow reconstruction of the project. In one sense, it is the most important component since it maintains the intellectual foundation for all future growth.

> *A best practice approach to optimizing organizational support is to define the level of quality assurance checks required for each task in the project, typically three or four levels of overview of the project. This is a negotiation that takes place at the start of the project.*

The most intensive and rigid level is defined for items that are critical to health and safety, including defining regulatory codes and standards, and tasks considered as essential to success. The lowest level is routine checks to ensure company or project defined reporting or documenting requirements are being met.

Many times I have made the following speech at the start of a project; "When we get to this task we have to check and document exactly as we have just specified. I will probably be stressed and under pressure and try to persuade you by any means to skip or change the task. Do not do it. This is an important task and it must be done as specified". This speech has saved me many times from making mistakes or losing important data. For example, the Quality Engineer insisted we soak the electronics at 75 degrees C for 24 hours as specified. Our subcontractor complied and found the nylon tie wrap did not expand, but the plastic coated cable bundle did, and shorted many cables. Performing this task despite the slight delay in deliverables ensured that the resulting product was fully functional. Another important best practice is to negotiate appropriate levels for each task or subtask. Not every part of the project requires the assurance level of the most important task.

2.3.Technical Component of Project, Scientists and Engineers

The technical component of the project produces the definition of the problem being solved, and the actions that will be taken to obtain answers, develop and test solutions, and generate lots of data, documents, reports and plans. This component often carries the major burden of the whole project in terms of volume of effort. Many people with a technology based foundation are convinced logic, analyses and tests and detailed application are all a project really needs. This approach leads to the darkness and oblivion mentioned earlier. The technical component has to be integrated and work together with the other project components. This means taking time to explain, educate and support we lesser mortals so that the project becomes a team effort. Always apply the Principle of ***'State the Obvious'***; what might be obvious to one person can be a complete mystery to another. If Einstein can explain the motion of the universe with simple equations, surely the technical community can derive simple explanations for what they are doing.

> *It is a best practice to generate easily understandable and consistent explanations for all project technical concepts.*

2.4.Proof of Principle Investigation of Acoustic Detection System

The detection concept seems very simple. Almost every school chemistry teacher will demonstrate that the reaction between sodium and water produces a bang. So why not use a listening device to quickly detect a leak? The concept was simple; the implementation turned out to be very complex. The chemistry of the reaction was fairly clear, but the noise generation and damage propagation mechanisms were not well defined. Many questions arose; Was it possible to listen from the outside of the shell, or would in-sodium sound sensors be required? Did the reaction noise consist of a sequence of explosions, or was the noise generated by the formation of gas bubbles? Did the reaction noise have any distinctive spectral signature? How intense and what was the character of the background noise, and how did it compare with leak reaction sound? How did sodium water reactions cause damage? Getting answers to these and other questions required an extensive and extended series of experimental and analytical investigations.

A review of available information and some opportunistic measurements on test rigs gave insights into the problems of acoustic detection. The background noise in steam generators was relatively intense compared to leak reaction noise intensity. For most operating conditions the leak noise was totally masked by the background noise. The leak noise was similar to noise from gas injections into liquids, but the spectral patterns were not identical. No evidence suggested the leak sound had a unique characteristic, it was just noise. Monitoring with internal sensors was extremely difficult, and expensive. Sensors mounted externally on the shell were the preference.

To progress from a good idea to an instrumentation subsystem suitable for monitoring operation and protection of a critical component power plant such as a steam generator is not a straight forward process. It has many stages, and each must be addressed totally in order to enhance the power plant’s life or improve efficiency.

The experiential database will be described from idea conception and proof of principle testing through system development, design, installation, operator acceptance of I&C subsystem, and performance experience on operating steam generators. It will show how the BatScan System is readily adaptable to other balance of plant systems, and to non NPP applications.

3. Passive Acoustic Tomography

A new monitoring approach was invented to detect the acoustic noise generated by the leaking tube. It was based on the concept that the leak was uniquely positioned within the steam generator. If this position was known, then the leak was detected. A successful proof of principle test was completed using gas injected into water to simulate a leaking tube. The concept was given the name of passive acoustic tomography. When used to protect process plant, it uses externally mounted sensors to monitor the internal volume of a large vessel (i.e. a steam generator), and indicates when an internal defect or fault condition exceeds a threshold intensity. This approach provides both the absolute sound intensity and its exact location within the internals of the plant component. *It simultaneously and precisely locates and detects the fault.* The development program for the leak detection and location management system included the following tasks:

- characterization of sodium water reactions [2][7]
- steam generator tube failure, and damage propagation due to sodium-water reaction [3]
- sensor development
- noise generated by sodium water reactions[3]

- noise generated by fluids flowing through the steam generator [6]
- data acquisition system to stream the data from the sensor arrays to dedicated data analysis computer
- acoustic leak detection system test [4][6]
- acoustic leak detection system validation. [5]

The passive acoustic tomography system is an engineered system. It can be designed using established and validated equations, specifications and detection criteria. A simple relationship connects detection sensitivity, the sensor array geometry and system cost. Cost estimates for both chemical and acoustic detection systems at that time indicated the acoustic system had similar costs to a chemical system. (The acoustic system costs are now substantially lower; computer and electronic system costs then were very high but have now decreased by orders of magnitude).

4. Needs Definition and Setting Realistic Expectations

All three project components of the project respond to the same overall needs, not necessarily for the same reasons or in the same manner. Valid, strong, realistic needs must be defined and discussed, then clearly define the expectations for meeting the needs.

> *An essential best principle is to make a strong, well organized and researched project needs assessment and expected outcome/s of meeting the defined need.*

The best approach for completing this assessment is a 'needs definition list'; then develop the goals based on the list for 'buy in' by the support community.

4.1.Defining Needs

Instrument system definition requires very precise, well bounded characterization of its need. Successful implementation of new or retrofitted instrumentation will be difficult if not impossible if this definition is not comprehensive. Bounding a problem includes in-depth knowledge of physics, chemistry, and properties of matter that are associated with the monitored or controlled system and its local and global environments. Finally, technologies, development programs instruments and sensors do not exist in isolation; they must include proof that the monitoring system will:

- meet defined and agreed to list of needs
- be safely and effectively integrated into the plant I&C system
- be easily isolated from the plant I&C system for upgrade and repairs
- not significantly impose on normal routines of control room staff
- fit into the monitoring and control culture of the staff and plant operators.
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This leads to the issue of how to define what is needed. All project components must agree on a definite list of the goal needs and expected outcomes. This list will be the foundation for agreements between each project component. The first and most important definition criterion is ***'do what is needed, not what you can do'***; the second criterion is to ***'always remember why it is being done'.*** Together, these criteria define the ultimate goal of the proposed project. Together, they allow definition of the expected and required project scope and optimize the characteristics of the proposed detection system. A supplementary benefit is that it provides a baseline to characterize and then minimize unjustified project scope creep over time.

Leak detection systems were essential to monitor the steam generator to prevent sodium-water reaction damage propagation, and significantly reduce economic impacts of repair and recovery. Identifying the strong economical incentives to develop a tube leak rapid detection system (BatScan) helped gain strong support from the entire NPP community, including active participation in need development and goal setting.

4.2.Subsystem Requirements: Passive Acoustic Tomography Condition Monitoring System

The very first stage is to decide upon the subsystem requirements. The principle is ***always define a required action***. This is a more powerful requirement than defining a list of I&C system expected sensitivity and performance operating parameters. A required action is typically independent; it is not linked directly to another action requirement. Further definition of the action sets limits or ranges of monitoring parameters based on data or analyses.

> *A best practice is to state a need as a required action, then quantitatively modify needs by setting range or limits over which the desired action takes place.*

This principle is applied below to define acoustic leak detection needs.

4.2.1. What does the monitoring subsystem have to do?

Most plant component failure modes have a precursor condition that precedes serious or catastrophic failure. The major design objective of a monitor is to detect this incipient or initial condition and allow a timely and controlled movement of the plant to a safe mode of operation. For the acoustic monitor the action requirement became:

> ***The monitor shall detect an incipient predefined fault level within a predefined time for all operating modes.***

Note, the detection criteria is not a sensitivity requirement, it is a *required protection action*. This required action is conditioned by limits. These limits reflect data obtained from the sodium-water reaction damage program. The monitor shall detect the intensity of water/steam leak acoustic noise when totally masked by background noise:

- at a signal to noise ratio (S/N) of **-5dB** the detection time shall be within **0.5 seconds** at part load and with **full power** operation,
- at a signal to noise ratio (S/N) of **-25 dB** the detection time shall be within **5** seconds during **standby operation** of the steam generator.

4.2.2. What does the Utility operator need?

The cost of a power plant 'SCRAM' is not only the loss of revenue from selling power. This loss of revenue can become almost negligible compared to the cost of persuading regulatory bodies the cause of the shutdown is known with certainty and the NPP can then safely return to full power operation. Every reactor SCRAM also impacts the remaining lifetime of the plant due to the thermal shocking, etc. of components. Proving an alarm is false can be quite difficult, and may require extensive analyses and diagnostic investigations. The second action requirement is responsive to these factors.

The monitor shall reliable detect fault condition with very low false alarm rate. Further definition sets limits that will not reduce the plant lifetime:

- The acoustic monitor system shall operate with **less than one false alarm in thirty years.**
-

4.2.3. What are the engineering staff concerns?

Most I&C systems are not self contained. They have to be installed into an existing physical structure, and often have to be physically attached, pass through, or be fused to the walls and piping of critical structures. Meeting all of the safety, installing and operating requirements are usually a mandatory condition of installation. This requires that every I&C component or part, system features, and every expected operation mode (both planned and unexpected) must be considered for potential problems. Regulatory design limits (e.g. NRC regulation, ASME code, etc) have to be met. Supplementary investigations were often needed to confirm there would not be problems generated by incorporating the acoustic monitor into the plant I&C system.

> ***Installation and operation of acoustic monitoring system shall not degrade the physical plant or it's I&C systems.***

Again, it is required actions that govern the monitoring system detailed design. There are still the issues of installing the monitor into the plant I&C, and then integrating its operation into overall operating procedures. After installing a monitoring system, the next step, and in the author's opinion the most difficult, is to gain plant management and plant operator acceptance of the system. This is not a trivial problem. It requires very deliberate efforts to build operator confidence in the system.

4.2.4. What does the power plant operations management need?

The main objective of plant operators and their management is to keep the plant online. The operators want a monitoring system that will have an insignificant impact on day-to-day operations. They have only peripheral interest in non-critical monitoring instruments. This is especially true if the instrument is looking for a low possibility event. One does not expect a steam generator to have regular water leak events; it is most likely to be a very unusual condition. A critical integration factor is to educate and train both management and operators on all aspects of the monitor, including its operating concept/technology, design, features, operation and the potential results from a leak event.

> ***Make the system reliable, its use intuitive, and only provide data needed by the operator.***

The goal is to achieve 100% operator confidence in the system. If they have any doubts about its efficacy, they may have a tendency to doubt its performance, and thereby limit the functionality of the monitor. The immediate instrument/monitor operational management problems include:

- Getting operator “eyeball space”, especially if looking at very long term data trending. Maintaining operators understanding of the monitors use, operation, and expected responses. (action requirement: Operator understanding and knowledge reinforcement)
- The acoustic monitor described in this paper has integrated health and fault operation diagnostics. Regular performance reports are provided to operators and management.

4.2.5. How can the instrument designer maintain operator interest in the monitoring system from womb-to-tomb?

Relatively sophisticated features are incorporated into the BatScan acoustic monitoring subsystem. The design requirements actions include:

> ***Interactive monitoring system, integrated operator training and interactive knowledge bases.***

The software has a “built-in” capacity to provide off-line plant operator training in reacting to alarms. It can be used by management to check operator performance by simulating different levels of fault condition. Success is achieved when the operator requires the subsystem to be on-line during plant operation, indicating that they have taken ownership of the monitor.

4.2.6. What is system’s added value to operating staff?

The instrumentation subsystem includes integral thermal/hydraulic modeling of the system being monitored (e.g. steam generator and secondary loop).

> ***Make the system an interactive design tool with modularity that encourages upgrading the capabilities of the subsystem.***

This allows "what if" scenarios and system design analyses by engineering staff when considering different age management possibilities. This interactive capability was used to confirm that the use of neural networks and fuzzy logic system enhancements improved operator interfacing, and increased monitor detection performance.

Part Two: Lessons learned from I&C project - Installation and Test

5. Validation Testing of BatScan System

FIG. 2 256 Channel BatScan System installed at SCTI (USA);8 Channel BatScan at Hengelo (NL)

A Prototype Steam Generator was constructed to provide design validation for the Clinch River Breeder Reactor steam generator. It was tested in the Sodium Component Test Installation at the Energy Technology Engineering Center (SCTI/ETEC). The steam generator was a hockey stick shaped design, approximately 1.22 meters (4 ft.) diameter by 21.64 meters (71 ft.) long. The wall thickness of the shell was 7.5 cm (3 in.). The test facility generated up to 76 MW thermal power for transfer to the sodium through a heater, and removed the heat from the water side through coolers. It allowed testing of the steam generator at simulated normal and off-normal test article operating conditions, with both steady state and transient conditions. A test of the acoustic detection system was added to the planned test program scheduled for the facility.[5] The primary objective of the SCTI leak detection program was to demonstrate practicality of installing and operating a GE-ALDS system for power plant use, and to then validate its performance with a demonstration test. Approximately 170 BatScan acoustic leak detection system accelerometers were installed on the outer surface of the vessel to monitor the total vessel. These were attached to the BatScan system electronics and mini-computers through a complex multiplexer system for selecting individual or arrays of transducers under computer program control. The electronics and multiplexers were located in the steam generator cell and three mini-computers in the control room. Figure 2 shows one of two cabinets (2 metres high) containing the BatScan System Electronics at SCTI about 15 years ago. The test program lasted about two years. The steam generator with three recessed accelerometer assemblies is at the left of the photograph. The photographs on the right were taken in the Control Room of the 50MW test facility in Hengelo, Holland about thirty years ago.

Lessons Learned: The acoustic leak detection system was added to an existing steam generator in an existing facility. Sensor installation was onto the surface of an ASME code designed pressure vessel. Sensors, cabling and electronic subsystems were integrated into the facility existing instrumentation and control system. Every stage or step of the procedures for installation of the acoustic detection systems was not automatically approved. Every procedural step was checked by a review team. If any concern was raised, it became the responsibility of the test requester to provide data or information to allay the concern. In many instances, supplementary testing or analyses were made to get approval from the facility management, staff, and control room operators. About a dozen test facilities were fabricated to generate answers to their questions. Even after physical installation was completed, operating and test plans receive the same in-depth scrutiny before approval was given. Expect all monitoring systems to be under facility control and operated by facility staff. Expect to provide operator training. Similar experiences were found when installing BatScan on a steam generator at EBRII and the Hengelo 50 MW test facility.

6. Operating experience with BatScan System

The BatScan acoustic leak demonstration test detected/located simulated leaks and provided detailed measurement information on background noise characteristics and distribution along the steam generator. The other main objective was to demonstrate BatScan's day-to-day performance characteristics, validation of leak detection criteria, and especially it's robustness for operation without false alarms. These objectives were successfully met. A full program of thermal hydraulic and endurance runs were completed, and provided ancillary test data for BatScan, such as background noise generation data.

Beside internal background noise generated by fluid flows, various external noise source were also present. External sources included operation of valves and other process plant equipment, construction of a subsurface chamber about 15 meters away (using explosives to shatter the bedrock and then drilling with a 1 meter auger), full power testing of shuttle engines at an adjacent test site that caused earthquake like ground tremors lasting tens of minutes, and local site auto and truck traffic. Since external noise sources are rejected by the BatScan monitoring system, no false alarms were generated. The system performance at SCTI was verified and validated by simulation of a small leak within the heat exchanger.

After an initial test period, the system was totally incorporated into the plant protection system and handed over to the plant operations staff. (What actually happened was that the operation room staff took control of the system after BatScan indicated there was water seepage to the atmosphere from the steam flange at the top of the vessel. This was equivalent to about 4 millilitres per day. The Operations staff also used individual sensor outputs to listen to noises, such as sodium filling of the vessel. Eventually they refused to allow us to 'play' with ***their*** leak detection system!) The result of the BatScan system's performance was that it had almost immediate operator acceptance. The BatScan system monitored the heat exchanger for a period of two years without false alarms. (During the same period false alarms were generated by the chemical monitors).

Lessons Learned: Schedules for tests are set by the operations staff, and if equipment is not ready for ‘prime time’, you may not get a second chance. I&C systems are very low on the totem pole compared to maintaining the regular plant operation schedules. Your test will invariably start at least 24 hours later than the original schedule. All tests are done to detailed procedures; don’t expect to make on-the-fly changes. Operators are very supportive and helpful, but their primary responsibility is keeping the system on-line. If they don’t feel comfortable with the test, it will be aborted. It is the requester’s responsibility to educate and train the operations staff on your test operation and expected outcomes.[8]

7. Defining an I&C Subsystem to monitor for tube leakage in steam generators

From its inception, the BatScan system was designed with the assumption that hardware, software, requirements and users of the system would change. The system’s original name was GE-ALDS. When the US nuclear program was severely cut back, the authors formed a company, GRDI, and continued development of the BatScan acoustic leak detection system, initially in partnership with GE. BatScan has successfully accommodated orders of magnitude changes in hardware systems, and several computer operating systems and languages. The basic process plant BatScan system has been extended to include neural network detection system algorithms (pattern detection); a zoom system to precisely examine a small region in the volume; and fuzzy logic algorithms. Corrective actions to be taken by an operator are enhanced by a second fuzzy logic (expert) interface controller. Patents protect this technology. The enhanced BatScan system has been used in other non-nuclear fields and applications, including monitoring the condition of rotating machinery (ship propulsion system) and investigating three dimensional jet engine noise generation characteristics. The experience gained from the BatScan passive acoustic tomography plant condition monitoring system showed it is possible to design, document, and “keep young”, systems throughout decades of technology change.

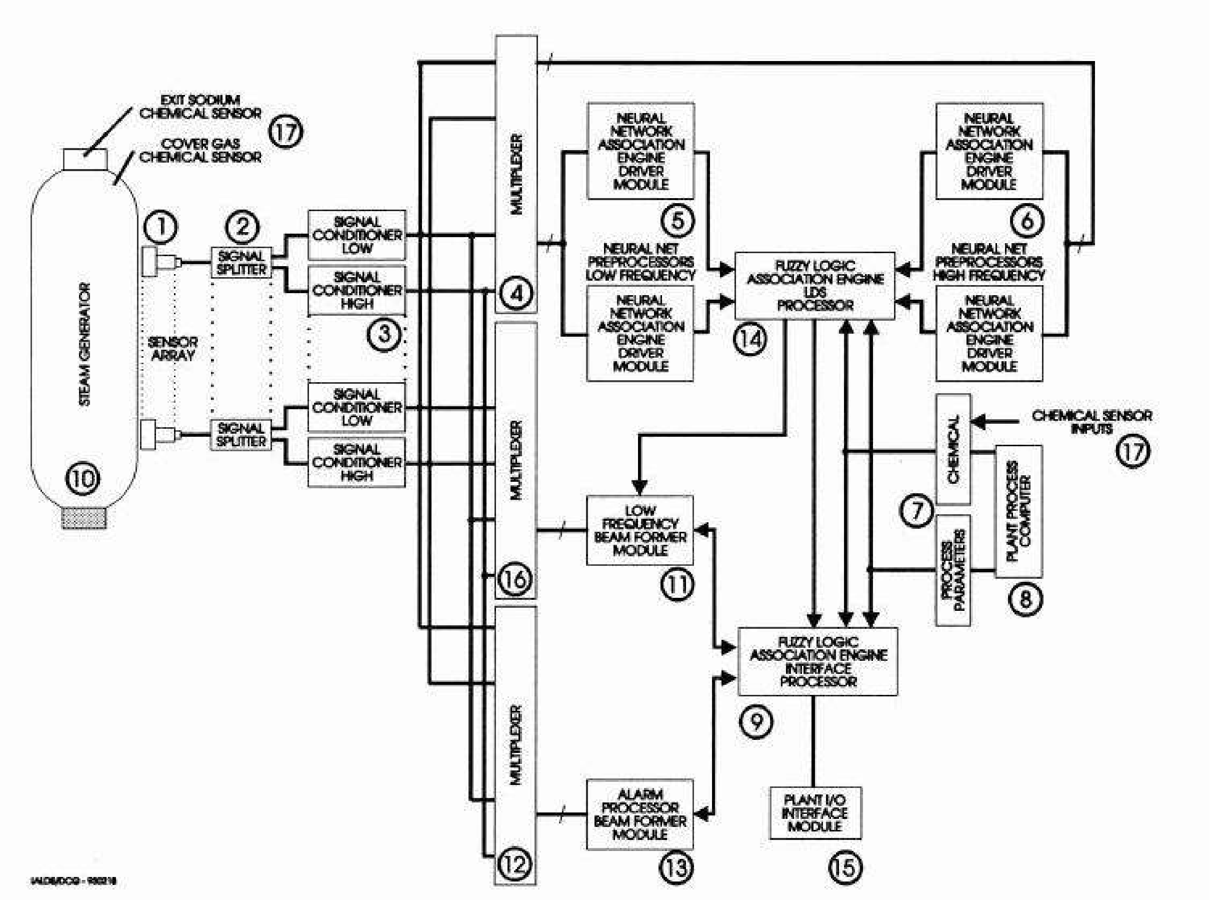

FIG. 3. BatScan Integrated Leak Detection System (with neural network and expert fuzzy logic)

8. Additional applications: Jet Engine Noise monitoring

The current BatScan system was used to monitor aerodynamic noise generation in wind tunnels and anechoic chambers containing models of structures or jets. The acoustic field is traditionally monitored by placing microphones at various locations, taking a measurement, then moving the microphones to a different location and taking further data. This technique provides limited coverage of the noise field, and draws strongly on empirical or semi-analytical models to define the field at other locations. Microphones must often be placed within the near field noise, and their presence can cause distortion of the field. The BatScan array of microphones was mounted to form a volume containing the jet nozzle; the array is outside of the expected noise cone. The scanning system maps the location and absolute intensity of the three-dimensional acoustic noise field within this volume, approximately 60,000 values. For subsonic operation an expanding, toroid shaped cone of intense noise existed with a relatively quiet region along the jet axis. The angle of this cone is about 45 degrees about the axis. Secondly, this cone starts to develop some distance from the mouth of the nozzle. A distinct change in noise pattern was measured for supersonic jets, a series of 'noise cells' were found. The first series of tests were made using an anechoic chamber to minimize reverberant noise, the second with a metal box surrounding the nozzle and microphone array to provide highly reverberant conditions. Identical noise profiles were measured with and without the anechoic chamber.[10]

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