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# Extended In-Situ and Real-Time Monitoring
## Task 2: Instrumentation for Monitoring Severe Accident Conditions

**Argonne National Laboratory**

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## Task 2: Instrumentation for Monitoring Severe Accident Conditions

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# SUMMARY

We have described a strategy and assortment of devices for a data acquisition system that can operate during a station blackout involving complete loss of power to the main I&C systems. This proposed backup system, denoted the “secondary DAS”, consists of a wireless sensor network that is completely separate from the plant’s conventional equipment (Fig. 1). Each instrument has its own sensor, communications hardware, and power supply. Power for the devices may be drawn from batteries, energy harvesting, or a hybrid of the two. Sensor readings are collected at one or more remote work stations such as battery-operated laptops running communications and data acquisition software that are, like the hardware, entirely independent of the plant’s conventional systems.

The proposed secondary DAS would refrain from using any preexisting sensors of the main I&C system. Though this approach forgoes some advantages associated with using existing equipment, it yields a number of benefits: with no hardwired connections between the secondary DAS and the main I&C system, the reliability of the old system remains unaffected by the new one. Installation of a completely separate system is expected to be less expensive than one linked to the main I&C system as there would be no need to integrate new technology with old. This strategy frees one to choose devices that are best suited for the task without the need to consider compatibility with the existing I&C system.

**Task 2 – Instrumentation for Monitoring Severe Accident Conditions**

## 1. SCOPE OF STUDY

This document reports on a scoping study to assess monitoring techniques that can be used for the prevention and mitigation of severe accidents. The NRC staff determined that a number of post-9/11 plant improvements undertaken to improve security could also be effective in preventing core damage for non-security related severe accidents. The NRC recognized that both the reliability and effectiveness of this new equipment might be improved with the aid of advanced instrumentation and monitoring technologies. This study considers the application of such hardware in the context of a particular severe accident scenario selected by the NRC.

The complete spectrum of severe accident scenarios encompasses a wide variety of physical phenomena. In many cases specialized instrumentation and measurement techniques have been developed to study the more extreme phenomena in a laboratory setting. The scope of this report, however, is limited to consideration of a plant in the aftermath of an emergency shutdown and loss of all power to the instrument and control (I&C) systems, including backup DC power supplies. Control room links to hardwired sensors and control systems will be considered inoperable. This scenario corresponds to an especially low probability event such as sabotage, or an extremely severe earthquake. The term “severe accident” typically refers to an event causing core damage, but it will be used here in a broader sense that includes this particular plant blackout scenario.

We examine monitoring techniques that can be used to prevent core damage and bring the plant to a stable state without access to the plant’s main I&C systems. Instruments may feature a local display so that they can be used to guide actions such as adjusting a nearby valve or actuating a pump. We consider also communications and power supplies as these are basic elements of any data acquisition system. Much of this report is dedicated to power systems as they are critical in a monitoring system that can function independent of the main plant systems. Most attention will be devoted to commercially available hardware and technologies on the verge of commercialization, but a number of more experimental techniques and devices are also discussed.

There are a great number and variety of sensors in a nuclear power plant and it is not self-evident which of them might be critical in managing a severe accident. However, through a series of studies and expert meetings, specialists in the field have identified the main parameters one should know to successfully manage an accident. A portion of this report briefly touches on these parameters so that we can limit the amount of backup monitoring equipment.

The scope of this study is distinct from that of broad technology reviews such as NUREG/CR-6992 by Korsah et al., which treats emerging I&C technologies that could be of general use in future power plants. This study considers only technology solutions specific to the blacked-out plant scenario with a reactor scram followed by an otherwise uneventful cold shutdown. If reactor damage were to occur, instrument availability could be impaired through releases of steam and radioactivity. Instrument survivability is beyond the scope of this report as it depends upon the accident scenario and plant design (see, for example, Arcieri and Hanson, 1991 and 1992). Plant automation systems are also not addressed as it is assumed that power for control devices is unavailable. In short, this report is restricted to considering instrumentation that can function during a total loss of conventional and backup power.

This study was well underway when the Fukushima accident occurred. Though the original scope did not extend to scenarios entailing core damage, there is understandable interest in using this material to address observed I&C weaknesses at Fukushima. For extended periods during the accident, some very basic pressure, temperature, and flow measurements were unavailable, making the situation more difficult to manage and analyze. Much of the material here can be applied directly to the Fukushima situation since the intent is to propose a basic measurement system for use in the absence of plant power and even an abandoned control room. Extending wireless sensing capabilities to adverse environmental conditions is considered future work and is discussed in the closing section of this report.

## 1.1 STRATEGY FOR PLANT MONITORING

Under the complete power loss scenario, plant monitoring and control might be achieved, in part, by manipulating equipment by hand while referring to local indicators and self-powered sensor systems. This must be supplemented, however, by an autonomous data acquisition system that collects and transmits enough information to provide operators at some central location with an overview of the state of the plant. Though control may be manual and localized, it is necessary to have a comprehensive picture of the state of the plant to implement appropriate accident management procedures and instruct personnel at stations where action must be taken. Many or all of the sensors in the backup system should have the ability to relay data to a network for collection and use by a program that monitors global plant status. Taking action without such a global view risks doing more harm than good.

The sensor and communications network supporting plant control under the above described blackout conditions will be designated here as the "secondary DAS" (data acquisition system) as it will not have control functions. The amount of power required for equipment control is orders of magnitude beyond that of the secondary DAS and so plant control during the blackout is presumed to be manual. The proposed secondary DAS would be a relatively small network of sensors of high reliability with just enough accuracy to be useful for accident management. A conceptual picture of the ideal system is shown in Fig. 1. Devices might be powered by onboard batteries, or energy could be harvested from sources such as ambient lighting, mechanical motion, or waste heat. Long-lived power supplies such as those based on radioisotopes are also a conceivable solution for a system that should remain largely maintenance free for years or even decades.

We propose that the secondary DAS interface as little as possible with systems used for daily plant operation, including preexistent sensors. This conflicts with the notion that one should not introduce new instruments solely for accident management. Though there is a natural preference for accident management instruments to be equipment that operators regularly use, there are benefits of a strategy that introduces completely new hardware:

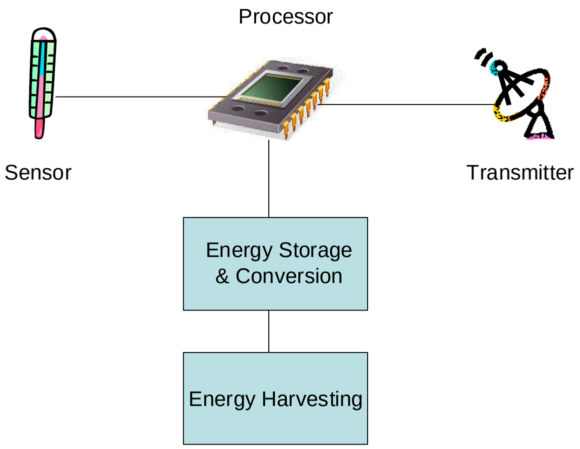

Fig. 1. The main elements of an autonomous monitoring

- Independence. Loss of the main control and sensing systems should have absolutely no effect on the secondary DAS. This is best assured by complete separation of sensors, communications, and power sources.

- Ease of implementation. Introducing an entirely independent sensor and communications network is likely to be less difficult than trying to integrate one with existing systems. This sidesteps the issue of how to interface a new data acquisition system with an old one. Development could proceed without the need for a complete understanding of the workings of the main I&C systems.

- Reliability. It is tempting to try to use existing sensors, taking advantage of instruments that have been installed at considerable cost, but they would then have to be hardwired to the secondary DAS for data transfers and/or auxiliary power. In addition to the difficulty of tapping into in-service sensors, hardwired links with the secondary DAS could introduce new uncertainties in the reliability and accuracy of the preexisting I&C equipment.

- Minimal impact on normal operations. Much of the development and testing of the new system could be conducted independently of the existing plant I&C systems. Accuracy of the secondary DAS could be checked by comparisons with the plant's main systems without shutdowns or unusual operations. Sensors for the secondary system could be added piecemeal and at times that prove least inconvenient, such as during routine maintenance periods. Sensors requiring pipe penetrations and hardware modifications would be avoided as much as possible so that normal plant maintenance and outage schedules could be maintained.

- Lower cost. A completely independent secondary DAS is expected to cost less than one partially integrated into the existing sensor network because it would be easier to implement and would have less impact on normal operations.

- A development tool for young staff members. Technical staff generally have great interest in the latest technologies, and young members are likely to have experience with contemporary hardware rather than the legacy equipment found in a typical nuclear power plant. The proposed system would include some of the latest wireless sensing and communications technologies while consisting entirely of commercial hardware and software so that a modest system could be planned and implemented largely by plant staff, with minimal involvement from vendors. Along with its appeal to young staff, the project would provide experience that could prove useful in the many I&C modernization programs being considered for aging plants.

The secondary DAS would be a network of completely autonomous sensors with far less complexity than the main plant system. Sensors need not meet conventional accuracy standards and, where possible, accuracy would be traded for simplicity, ease of installation, and cost savings. As an independent network, the secondary DAS could grow as resources and schedules allow with minimal impact on normal facility operations.

## 1.2 STRUCTURE OF REPORT

The next section introduces the process parameters one must know in order to manage the plant. They have been suggested by others in previous work on information needs for severe accidents and serve as a basis for considering sensor and instrument candidates. In this report, the term sensor refers to the basic sensing element such as a strain gauge or a thermocouple, while the term instrument includes peripherals such as microprocessors, communications hardware, and power supplies. Thus devices with varying peripherals are considered different instruments even if they use the same sensor. This distinction is made because virtually all of the intriguing possibilities for the secondary DAS lie with recent advances in peripheral hardware. There are few, if any, revolutionary sensors on the horizon for use in nuclear plants. This report is therefore concerned largely with innovative instruments, i.e., sensors with innovative peripherals, rather than the sensors themselves.

Section two is devoted to commercial self-powered instruments that could be put to use immediately. Remote sensing and wireless communications technologies have advanced to the point where off-the-shelf hardware may be adequate for many of the plant’s process monitoring needs. The section also includes several proposed unconventional flow measurement techniques that have some advantages over commercial products. Installation issues are often paramount when backfitting a nuclear plant, and in some cases an unconventional instrument, even if less accurate, may be preferable for severe accident monitoring if installation is far less onerous. Flow meters can be particularly troublesome since they often require changes to the process piping.

The remainder of the report is devoted mostly to instruments and peripherals technologies for advanced sensor networks. Technologies to support autonomous sensing are developing rapidly and some could be of use for the plant blackout application. While commercial wireless instruments often operate on batteries, advances in microelectronics and energy harvesting techniques are paving the way for large-scale autonomous sensor networks that draw energy from the environment. With self-powered instruments, one can operate enormous sensor networks indefinitely with little or no maintenance. These emerging technologies have much appeal not only for the plant blackout application, but also in the context of general plant monitoring. An extensive network of self-powered wireless instruments could be used to monitor the state of the plant to a degree that will never be feasible with conventional wired instrumentation.

The report concludes with a summary and brief discussion of further work the NRC might pursue in this area.

## 1.3 IDENTIFYING PARAMETERS TO MONITOR

Severe accident management is akin to normal plant operation in the sense that its chief concern is core cooling. If the core is damaged, plant systems must stabilize it within the reactor vessel or quench and immobilize lost core debris within the containment. Severe accidents pose, in principle, special difficulties for control and monitoring systems because of the wide range of potential phenomena. Normal plant operations involve a much narrower range of phenomena than severe accidents or even design basis accidents (see Wahba 1993). It follows that a rather extensive and diverse array of instruments must be in place to characterize the full range of potential severe accidents.

Fortunately, utilities are required to manage and arrest severe accidents rather than study them and so monitoring requirements can be limited to what is necessary to successfully manage an event. Despite the wide range of potential severe accident phenomena, it is generally agreed that a relatively small collection of instruments can be used to manage such accidents. For example, key parameters for severe accident management at the Tihange plant in Belgium were limited to the following [De Boeck, 2003]:

1. Core exit temperature
2. primary circuit pressure
3. steam generator water level
4. containment pressure
5. containment sump level
6. radiation level at various locations

Other important parameters have been noted, such as flow status, relief and isolation valve positions, control rod position, boron concentration, and containment hydrogen and oxygen levels (see Hanson et al., 1993, Karwat 1989, and IAEA Guidebook 1999). This report examines pressure, temperature, and flow instrumentation, which are widely available and serve to illustrate the nature of the peripheral hardware needed for the secondary DAS. This same hardware (e.g., power supply, communications) is also suitable for less common sensors such as hydrogen and radiation detectors and so there is no need to consider them separately.

## 2. COMMERCIAL INSTRUMENTS

Process measurements in nuclear plants are much the same as those of other large industrial enterprises. Pressure, temperature, level, flow, pH, etc., are all very common control parameters, and associated sensing technologies are quite mature. Sensor developments are now mostly confined to incremental improvements in accuracy, stability, and reliability. As a result, there are no revolutionary sensors to be recruited for severe accident management. Instead, conventional sensors can be combined with advanced peripherals to create instruments with many or all of the properties proposed above. As we will see below, there are commercially available instruments that are quite capable of providing many standard process measurements in the absence of hardwired power. This section is an introduction to the sort of standard commercial hardware that could be employed for process monitoring during the blackout. There are also suggestions for unconventional flow measurement methods that minimize or avoid piping modifications. More esoteric technologies associated with the notion of large-scale self-powered sensor networks are reserved for sections 3 and 4. As we progress through these sections, it will become apparent that some capabilities of the more experimental devices have already made their way into commercial instruments. The division into “commercial” and “esoteric” hardware is somewhat arbitrary, but it is useful in separating immediately deployable technologies from those that are confined to laboratory test benches.

### 2.1 Pressure, temperature, and level

Industrial pressure transmitters are available for nearly any imaginable process conditions and so there are no fundamental difficulties associated with measurements during a blackout other than the need for power. This is fortunate since pressure transmitters can also be used to determine level and flow rate. If it is deemed acceptable to share process taps with the main I&C transmitters, the backup instruments can be installed without cutting or welding of the main process piping.

Stand-alone, solar powered pressure transmitters are commercially available from companies such as Weiss Instruments. These devices are equipped with local LED displays and can operate at light levels below 10 lux (typical office lighting is ~400 lux). If emergency lighting is nonfunctional or ambient lighting too low, one can shine a flashlight on the face of the device and within seconds it will resume operation. This device is therefore fully capable of providing data to an operator during a complete power outage. Similarly, solar powered thermometers are commercially available from companies like Dwyer Instruments. These instruments could be kept isolated from the main I&C system by replacing single junction thermocouples with multijunction units and wiring one sensor to each system. For the price of a new thermocouple one would eliminate the need for a new pipe penetration to accommodate the backup probe.

Accuracy of both the pressure transmitters and temperature sensors is more than sufficient for accident management purposes. The expected service life of the solar cells and associated circuitry is unknown.

These solar powered instruments meet the key requirements of autonomy and local display, but lack wireless transmission capability. The solar powered temperature sensor is limited to a local display while the pressure transmitter is capable also of 4-20 mA output. The current output could be sent to supplementary data acquisition hardware that is itself capable of wireless transmission.

Self-powered transmitters with wireless communications and substantial processing power are commercially available, but at the cost of swapping solar cells for batteries. Battery-powered wireless pressure and temperature transmitters are available from companies like Rosemount/Emerson Process Management. Devices have local displays for reading process variables and can link to a portable communications unit that uses standard industry communications protocols. The local link can be used to confirm that the device is operating properly and to re-range it if necessary. Batteries are non-rechargeable lithium-thionyl chloride with an estimated service life of 10 years at a data rate of one transmission/minute. Note that particularly cold or hot ambient temperatures can reduce battery life and so the service environment will be of interest. Still, the battery for the Rosemount unit is expected to drop less than 20% for continuous exposure to ambient temperatures near the transmitter operating limits of $-40^{o}$C and $85^{o}$C. Effective range is hundreds of meters when in line-of-sight of a wireless gateway, and can be more when signals are routed through neighboring transmitters on the network. The wireless communication ability of these devices may have enough appeal to offset their need for batteries.

Level measurements are often made with differential pressure transmitters, but other technologies are also common: radar, time domain reflectometry, conductivity, fiber optics, ultrasonic, and radiometric. All but the latter require probe access to the process. The radiometric method is based on gamma attenuation and, being noninvasive, is an appealing alternative. However, the technique is rather involved and expensive and is typically reserved for special situations such as those with corrosive media or extremely high temperatures. In contrast, pressure transmitters are simple, relatively inexpensive, and can be easily added wherever one is already operating on behalf of the main I&C system. Except for special cases, pressure transmitters are likely to be the best option for level measurements during a blackout.

Note that wireless temperature sensing for office environments is already rather common. Vendors offer battery-free, wireless temperature and humidity sensors along with motion detectors and switches. Solar cells generate power from ordinary office lighting. Transmitter range is tens of meters within buildings and hundreds of meters line of sight. But this equipment is light duty and unsuitable for a power plant, and so it is not discussed in detail. Still, this is a preview of one avenue of development in wireless sensing: an effort to eliminate batteries entirely by harvesting energy from ambient energy sources. Eventually commercial offerings of the more heavy duty industrial instruments will match these capabilities. As devices become more efficient at both using and harvesting energy, they will be able to support additional functionality and provide more of the features required of a nuclear plant. Developments in this area are discussed in sections 3 & 4. Additional vendor and product information can be found from the Enocean Alliance, which promotes self-powered wireless monitoring of buildings.

## 2.2 Flow rate

Flow rate is among the most difficult of process parameters to measure. Instrument selection usually involves tradeoffs among characteristics such as accuracy, cost, installation needs, stability, and maintenance requirements. A typical plant has a wide variety of flow instruments, each selected to suit the needs of a particular measurement station. Flow rates among various stations may differ by orders of magnitude, and process conditions can lie anywhere between ambient conditions and very high temperatures and pressures. The process fluid could be a gas, a liquid, or a two phase mixture. As a result, there is generally far more variety among the flow devices of a plant than, for example, temperature and pressure transmitters.

A lengthy consideration of flow measurement techniques and devices would not be constructive here. Our interest is confined to technical solutions that can provide flow rates in the absence of plant power. Though an existing plant flow meter could function under these conditions if provided its own backup power supply, one of the self-imposed guidelines for the secondary DAS is to refrain from electrical links with the main systems. Therefore the secondary DAS should have its own set of flow meters. Unfortunately, many commercial instruments are incorporated into the piping itself as a spool piece/insert, which is undesirable since it would require significant modifications to plant piping. These restrictions circumscribe the pool of flow metering candidates.

This section presents several conventional and unconventional flow metering solutions. The conventional ones utilize standard commercial equipment. The unconventional solutions are a mix of devices and measurement techniques that are familiar, but not commonly used, largely because of accuracy and range limits. The common theme among these flow solutions is ease of installation and independence from the main I&C system. Bear in mind that process conditions vary greatly across a plant and this section does not address the particular needs at any one measurement station. Instead, flow metering for blackout conditions is considered in a general sense and the needs of a particular station must be decided on a case by case basis, just as they are for the main I&C system.

### *2.2.1 Conventional devices*

Many plant flow meters are based on measurements of differential pressure, for example venturis and orifice flow meters. These need electrical power only for a pressure transmitter and so they could supply data without plant power using one of the self-powered transmitters described above. Such a transmitter could be added alongside the conventional unit that is linked to the plant's main I&C system. This extra transmitter would differ from the conventional unit in that it would be self-powered, equipped with a local display, and linked to the secondary DAS through a wireless communications network. The two transmitters would share some of the impulse piping between themselves and the hardware producing the pressure drop. This type of backup is not strictly independent of the primary flow measurement as it shares the flow sensor, but it otherwise operates completely independently of the main I&C system and its power supplies. Still, there could be concern that sharing the impulse piping reduces reliability of the primary measurement, perhaps via leaks through the additional valves or extra opportunities to trap noncondensable gases in the impulse piping. It is unlikely that this would be a serious issue, but it illustrates why preferred solutions are those that are incapable of perturbing the main I&C system.

Pitot tubes are also devices based on differential pressure measurements and they are appealing in their simplicity. A pitot tube is little more than a pair of capillaries or light duty tubing suspended within the flow. As with a venturi, power is required only for the pressure transmitter. Small diameter tubing can be used to keep the pressure drop low and so these devices could be used with minimal impact on the process. Coupled with high quality pressure transmitters, pitot tubes are able to provide accurate measurements over a considerable flow range. But pressures are measured through rather small holes in the tube, which are susceptible to plugging, and this severely restricts reliability over long time intervals. While not widely used for liquid flows in industrial settings, pitot tubes are fairly common for gas flow, especially in large ducts and stacks operating at atmospheric pressure. Pitot tubes are an appealing solution in principle, but much less so in practice for liquid flow in a nuclear plant. There are analogous but more robust instruments based on the same principle, the Rosemount Annubar flowmeter, for example. The probe, which is inserted into the process, has a diameter ranging from 15 to 50 mm and so the pressure drop would be higher than that of a small Pitot tube. Still, the Annubar flow meter is a commercial product that can be fitted with a battery operated wireless transmitter. The installation of insert probes is often less involved than that of spool pieces, and so this device could be of interest in locations where the pressure drop can be tolerated.

Ultrasonic flow meters are a relatively recent addition to flow metering technologies. A typical instrument uses two transducers that each act as both a signal transmitter and a receiver. The configuration shown in Fig. 2 determines flow velocity by measuring the time of flight of ultrasound moving with and against the flow. The difference in time of flight increases with flow velocity. These devices are often referred to as transit time flow meters (as opposed to cross correlation meters, which will be discussed next). The most accurate of them have the transducers built into a spool piece, but others use clamp-on transducers that can be put into service without piping modifications. At least one vendor, Shenitech LLC, offers a solar powered wireless unit. This type of device fits our main specifications: no links to sensors used by the main I&C system, no process pipe modifications, wireless communications, and self-powered. Note also that portable units are available so one could install a flow meter on some vital line after a blackout. Though pipe insulation must be removed to attach transducers to bare pipe, clamp-on ultrasonic flow meters are well-suited for improvised measurements, even on high pressure lines.

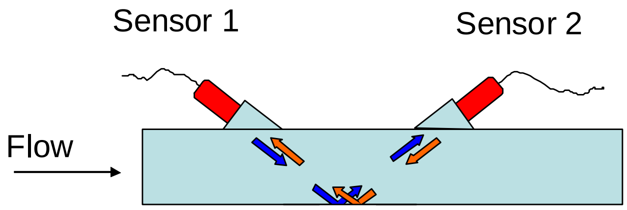

Fig. 2. Principle of time-of-flight ultrasonic flow measurement.

### *2.1.2 Unconventional alternatives*

Flow rate may be measured with less sophisticated instruments if one accepts a considerable increase in measurement uncertainty. One approach is to gauge flow rate by measuring differential pressures across ordinary system flow restrictions such as valves or pipe area reductions. This does not differ in principle from the venturi or orifice flow meters, but avoids piping modifications by utilizing pressure drops already existing within the system. Accuracy is likely to be rather low where pressure drops are small or inconsistent. Depending on the configuration, e.g., choice of restriction and transmitter, this technique might only provide indications of high, medium, low, and reverse flow. Though certainly not accurate enough for normal daily use in the main I&C system, this arrangement might in some instances provide just enough data to monitor and manage flow after shutdown. It would involve nothing more than the installation of a pressure transmitter while avoiding piping linked to sensors devoted to the main I&C system.

In cases where higher resolution and accuracy are required, flow measurement through cross correlation of process signals is a technique with much potential. The basic principle is illustrated in Fig. 3, which shows two temperature sensors within a pipe separated by a distance D. Fluid flow is often accompanied by local fluctuations in temperature, though they may be quite small. Fluctuations registered by sensor 1 will be transported downstream to sensor 2. Signals from the two sensors are cross-correlated by shifting them in time. The correlation function exhibits a peak for a time delay equal to the fluid transit time between sensors. The transit time and distance between sensors indicates the average fluid velocity between sensor locations, which is then used to calculate the flow rate [Beck and Plaskowski, 1987].

The cross-correlation technique can utilize a wide variety of signals, e.g., void, pressure, ultrasound, and radiation. Perhaps its primary advantage for our application is the ability to use simple sensors such as thermocouples, which are inexpensive and far easier to install than a conventional flow meter. These simple sensors are also comparatively resistant to harsh process conditions such as high temperature, corrosive fluids, and radiation. For these reasons the technique has received consideration for use in nuclear plants [Roverso and Ruan 2004, Moazzeni 2010].

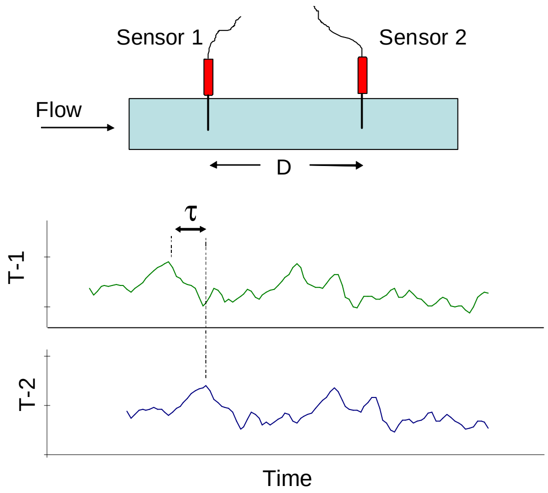

Fig. 3. Principle of cross correlation flow measurement

Despite the advantages of the cross-correlation technique, it is not commonly used in flow metering because of generally low accuracy and dynamic range (often referred to as “turndown”). Configurations are optimized for a particular flow range through selection of sensor spacing and response time. In high-speed flows, for example, spacing is relatively large to produce a discernible delay between signals (though this can be addressed in part with high-speed signal acquisition). But such a configuration is not well-adapted to low flow rates as temperature fluctuations tend to decay and distort during the relatively long transit time. As a result, the cross-correlation function will be unable to generate a single clear peak indicating the correct transit time. Hence cross-correlation flow measurement has both a rather limited dynamic range along with accuracy that degrades quickly outside the optimized range. Still, this technique merits special attention because its main weakness, low accuracy, is of limited concern for severe accident management. And dynamic range can be extended with additional sensors at varying separation distances.

The major vendors do not offer cross correlation flow meters as part of their standard product line. One can generally find a suitable device among the wide range of other options, which includes coriolis, vortex, and magnetic flow meters, though these are in-line devices that are part of the process piping. Two notable exceptions are systems developed by WH Technologies and Advanced Analysis and Measurement Group, Inc. with Westinghouse. The latter developed a device called CROSSFLOW, which was tested in cooperation with the NRC and is in operation at a number of nuclear plants. It appears that detailed technical data is proprietary and so we do not know whether the CROSSFLOW is integrated into a spool piece or nonintrusive with clamp-on transducers. The WH Technologies system is nonintrusive. In any event, ultrasonic cross correlation flow meters exist. It may be possible to outfit these units with batteries or solar power like the Shenitech system.

Also of interest is an alternative cross correlation system based on gamma attenuation. A pair of radiation sources is placed on one side of a pipe and detectors on the opposite side. Small bubbles in the flow modulate radiation levels at the detectors. The upstream and downstream detector signals are correlated to obtain flow rate [Jung et al., 2009]. Though this is a more complex system than those based on thermocouples or conductivity probes, it is of interest because it requires no pipe penetrations. In addition, these devices have the potential to meter two-phase flows with void fractions that are too high for ultrasonic flow meters.

The review of flow metering technologies suggests that clamp-on ultrasonic devices are likely to be the leading candidate for most metering needs. They can be installed without pipe modifications, are available with solar powered and wireless options, and are sufficiently accurate for this application. Differential pressure based flow measurements are also feasible using solar or battery powered pressure transmitters. Transmitters could be linked to existing sensors such as venturis or, for low resolution and accuracy measurements, configured to detect low level flow losses in existing process piping. Cross correlation flow metering offers alternatives for special cases, but the technique is not widely used in industry. However, it is of interest in the context of large-scale self-powered sensor networks, where sensing devices must operate on very little power. This suggests thermocouples and conductivity probes, which do not consume the power of, say, an ultrasonic transducer.

### 2.3 Miscellaneous instruments

A variety of other instruments are commonly employed in plants, including pH and conductivity meters, valve and switch position indicators, hydrogen sensors, and radiation detectors. The market for such devices is not as extensive as those discussed above and so they are less commonly found with advanced peripherals such as wireless transmission. Still, Rosemount, for example, offers battery-powered wireless transmitters for tasks such as acoustic event monitoring and switch position indication.

In practice, most conventional sensors can now be rather easily incorporated into a battery-operated module that provides power for the sensor, analog to digital conversion, and wireless communications. Such modules are now quite prevalent, with some able to operate for years on a single battery if the data rates are low, say several transmissions per minute. Battery life is extended by running the device mostly in a low power sleep mode, waking only briefly to energize the sensor, make a measurement, and transmit data. Therefore turnkey wireless devices may not be available for some process measurements, but it is likely that a suitable device can be readily made from a small collection of commercial hardware.

In summary, wireless, self-powered devices for the secondary DAS are available to make most, if not all, of the required process measurements. With a prudent selection of sensing techniques, instruments could be added with little alteration of process piping. Data transmission would occur independently of the primary I&C system and data acquisition would be carried out using commercial software. With a well-conceived network layout, data could even be transmitted outside the plant for monitoring in cases where the control room has been abandoned.

The need for batteries in these devices is a significant shortcoming. Battery life is not only finite, but decreases as transmission rates grow. Conflicts may arise between the need for data rates high enough to control the plant and the desire to preserve battery life. And battery replacement can be difficult if sensors are in hard to reach or hazardous locations. Ideally, a device would be installed and never need service to replace a battery. This would permit deployment of a large, maintenance free wireless sensor work. The key element for such a device is the power supply, which is the topic of the next section.

## 3. POWER SUPPLIES

For the accident scenario considered here, a complete loss of hardwired power, it is of course vital that energy sources be secured for the equipment. The subject requires special attention because choices influence sensor functionality, communications capabilities, and maintenance requirements. This is not the case with conventional data acquisition systems, which are simply provided whatever power they need to perform their mission. Since there is little prospect of revolutionary improvements in the sensing technologies described above, it is actually the power supply technologies that hold the most promise for useful innovations relevant to our application. The power supply strategy is likely to have a disproportionate effect on the nature and capabilities of the proposed secondary DAS.

The secondary I&C system would draw energy from sources completely independent of the traditional plant backup systems. It is likely to use multiple power supplies since sensors would be distributed over a wide area and hardwiring between them is likely to be impractical. An ideal power supply would:

- harvest energy from the environment

- not limit sensor functionality or the bandwidth needed to manage the accident
- be maintenance free
- have a service life measured in decades
- be commercially available

There are conflicts among these requirements and so compromises will be necessary. It may prove advantageous to use a variety of power sources to match capabilities to the demands of a particular sensor.

A great variety of power supply options exists as enormous research efforts are being applied to the development of batteries, fuel cells, energy harvesting, and similar technologies for the consumer electronics and auto industries. Technologies in these fields have been developing rapidly. The difficulty in finding an optimal solution for the severe accident application lies in the many tradeoffs to be considered. One could begin by defining three strategies, each with its own implications for system functionality and maintenance requirements:

- Batteries. The term is used here in the general sense of a self-contained energy source, e.g., fuel cells, radioisotope generators, as well as conventional electrochemical cells.
- Energy harvesting. Power is supplied from energy scavenged from ambient surroundings, e.g., solar or thermal energy. The system would be completely autonomous and could remain maintenance free until the service life of the electronics is reached.
- A WISP (wireless identification and sensing platform) type system. A central radio transmitter interrogates sensors much like the RFID (radio frequency identification) systems register cars at tolls. The transmitter supplies all the power necessary for the wireless sensors, eliminating battery and energy harvesting dependability issues.

Hybrid systems are also possible, e.g., batteries could be recharged by energy harvesting. Also, energy harvesting systems generally have at least a small amount of storage capacity to bridge short supply interruptions. Still, the above division is useful as it presents extremes: the first system has all the energy it needs onboard, the second gathers it from its surroundings, and the third is remotely powered. In general, the latter two systems will be lower power and have less functionality while the first will require more attention in the form of battery swaps or recharges. During the design of an actual data acquisition system, one would have to consider the entire spectrum of possibilities in concert with the sensing and communications requirements for managing the plant. The remainder of this section touches on technologies associated with the above three power strategies.

### 3.1 Batteries

The term battery is used here in the general sense of a self-contained energy source, such as conventional chemical batteries and radioisotope generators, but not an element like a capacitor, which requires an external energy source for charging. Researchers have investigated many different battery candidates for wireless sensing applications [Bogue, 2010]. With the advent of very low power electronics, even extremely small batteries can now power some of these sensor and communications systems.

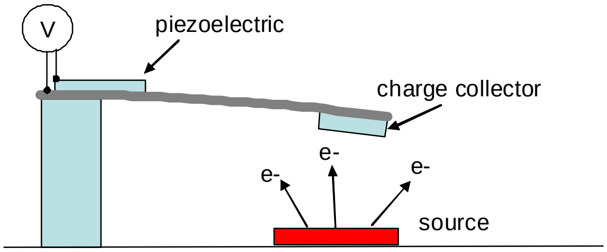

Fig. 4. Cantilever type radioisotope power supply.

Radioisotope generators have long been used as heat sources for thermoelectric generators (discussed in the next section) [Bass and Allen, 2000]. They are capable of producing power on the order of watts for long periods of time, ideal for applications such as space probes, but it is difficult to scale them down into miniature micro-power supplies for wireless sensing applications. Tiny radioactive sources are preferred and so other methods are better at generating electricity from the decay process. One of them uses a reciprocating beam connected to a piezoelectric plate (Fig. 4). Particles from a radioactive source near the beam gradually charge a plate, which is then attracted to the source by electrostatic forces. Charge progressively builds and eventually the beam touches the source and discharges, initiating oscillations that drive the piezoelectric plate. The piezoelectric is connected to capacitors for charge storage while other electronics manage power consumption for the instrument. Another scheme is the so-called betavoltaic, whose main feature is a semiconductor that absorbs the energy of a beta particle and converts it into an electric current in a fashion analogous to that of a conventional solar cell. Batteries have been fabricated based on solid semiconductors [Eiting et al., 2006] and also liquid ones [Wacharasindhu et al., 2009].

Fuel cells are an alternative having advantages associated with the high energy density of liquid fuels. They function by providing a catalyzed reaction area for fuel oxidation that produces free electrons to drive an external circuit. The reaction also produces waste heat and water as byproducts. Like the radioisotope generators, fuel cells have been around for a long time but are not easily scaled down, largely due to the difficulty of engineering micro-flow systems [Knight et al., 2008],

More unusual battery schemes can be sensible in special circumstances such as remote sensing of nuclear waste packages within a repository [Constantinou et al., 2011]. The goal was supply energy to the sensors after many decades, which led them towards mechanical systems such as springs, suspended masses, and cantilever beams driven by magnets.

Batteries may prove to be a suitable power source for the proposed secondary DAS, or they may be found wanting due to issues such as service life. It is beyond the scope of this paper to compare the relative merits of different battery technologies. This section is intended only to provide a general sense of the technologies that researchers and industry are considering for wireless, autonomous sensor networks. The next sections present alternatives to onboard energy storage.

## 3.2 Energy Harvesting

There has been longstanding interest in reducing the power consumption of electronics to manage component operating temperatures and increase efficiency. Great strides have been made and now devices can function with a tiny fraction of the power required by their predecessors. This dramatic reduction has made it possible to operate relatively complex electronics by tapping diffuse energy sources such as solar, thermal, vibration, and radiofrequency. This introduced the possibility of stand-alone sensor systems operating solely with energy harvested (or scavenged) from the environment. Electronics and energy harvesting technologies have now progressed to the point where self-powered, wireless sensor nodes are becoming commercially available. This represents the ideal solution for the proposed secondary DAS and the following is devoted to some rapidly developing technologies associated with energy harvesting.

### *3.2.1 Thermoelectrics*

Thermoelectric generators (or Peltier elements) are solid state devices that employ the Seebeck effect, which produces a voltage across a joined pair of dissimilar conductors exposed to a temperature differential. The familiar thermocouple is an example of a device based on this principle. The Seebeck effect can be used to pump heat against a temperature gradient, as in a thermoelectric cooler, or to drive a load by maintaining a temperature gradient across the device. Figure 5 shows the basic configuration of a thermoelectric device, which typically employs special n and p-type semiconductors chosen to optimize a combination of high Seebeck coefficient, high electrical conductivity, and low thermal conductivity. The semiconductors are bonded to an electrical conductor to form an electric circuit. The attached heat sinks act as intermediate elements of a thermal circuit that accepts and rejects heat from the ultimate heat sinks. In practice, numerous semiconductor pairs are linked in series in order to generate a usefully high voltage. All thermoelectric devices share the same basic geometry, but designs and materials vary to optimize characteristics such as output voltage, power, or efficiency.

In perhaps the most common configuration, the cold side heat sink is attached to a device requiring cooling, such as a chip or a detector, and DC power is supplied to the device to move heat against the temperature gradient. Thermoelectric coolers find use in many specialized applications where compactness and simplicity are critical. In an energy harvesting mode, heat transfer between the heat sinks maintains a temperature gradient across the device, which it utilizes to establish a voltage and drive an electrical load. The obvious appeal of energy harvesting with thermoelectrics is that waste heat and temperature gradients are in great abundance in any power plant.

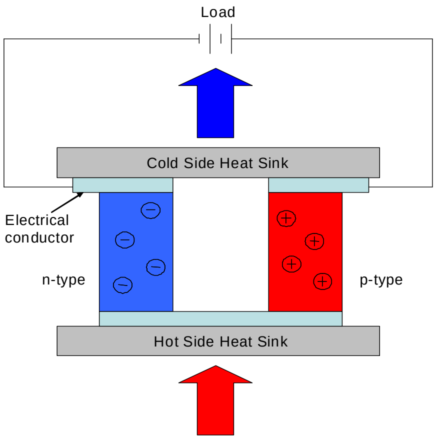

Fig. 5. Schematic representation of a thermoelectric device.

Though this technology is well understood with many mature applications, the field is active with efforts to improve performance and move into newer applications like energy harvesting [Hudak and Amatucci, 2008]. It is beyond the scope of this work to discuss the many promising research efforts in this area, but it is useful to note that significant efforts are being devoted specifically to the powering of portable sensor systems (Venkatasubramanian, 2007, Böttner, 2007).

Nextreme Thermal Solutions manufactures miniature thermoelectrics for use in energy harvesting applications. Though less than 2 x 2 mm, the unit shown can generate more than 45 mW at a $\Delta T$ of 120°C. Micropelt GmbH has incorporated a similar device into a heat exchanger designed to tap into a warm water source. It is able to power industrial wireless sensors from hot water at 70°C. The company also produces a self-powered sensor system based on the same thermoelectric technology. The device provides wireless transmission and can function with differential temperatures down to ~40°C. Thermo Life Energy Corp. employs a different type of design to produce generators that can function at very low temperature differentials. The ability to use low grade waste heat opens up applications such as the powering of microelectronics with body heat. Power output from these devices is very low, but when used in conjunction with a small battery, they are suitable for wireless systems. The battery supplies peak power for short data bursts and afterwards the thermoelectric generator slowly recharges it during a relatively long dormant period. These examples demonstrate that commercial technologies are available to support an autonomous sensor network based on the harvesting of plant waste heat.

### *3.2.2 Other energy sources*

Solar powered instruments are, of course, also energy harvesters. It was shown that vendors offer light duty wireless instruments for office environments. Heavy duty industrial instruments seem to have less functionality, but clearly there is no technical obstacle to producing a full function solar powered unit, especially if it is not critical to minimize the size of the solar cell array. Solar power seems a near ideal solution for this application, but it is conceivable that ambient light, even emergency lighting, would be unavailable during the blackout. Batteries could be used to store energy to bridge the blackout, but then battery life and maintenance issues resurface. Though solar power is perhaps the most appealing energy harvesting source for wireless sensor networks in general, for this application it might be least available just when needed most.

Mechanical vibration and water flow are abundant in a power plant and these sources of energy may also be harvested [Hudak and Amatucci, 2008 and Knight et al., 2008]. But like solar power, they may not be available when most needed. Alternatively, ambient VHF and UHF radio waves provide a more omnipresent source of power for harvesting. A prototype system made use of a small, table-top antenna to harvest energy from a TV tower 4 km away to power a commercial hygrometer that normally operated on AAA batteries [Sample and Smith, 2009]. Though it is feasible to power electronics with ambient radio waves, the strength of this energy source will vary with both the distance and power of the transmission tower.

The energy harvesting approach is an appealing alternative to batteries since it offers the possibility of powering sensor nodes without maintenance for the life of the electronics. However, ambient energy sources, while often plentiful, can be intermittent and prove unavailable at crucial moments. It would be far preferable if a device could operate without batteries by harvesting energy from a dependable source so that sensor data will remain available at all times. This type of device is presented next.

### 3.3 WISP

The energy harvesting strategies outlined above involve scavenging of heat or radiation from a sensor's environment. In many instances energy supplies will be continuous and dependable with little risk of interruption. If sporadic interruptions are anticipated, small batteries can be incorporated into a device to ensure steady sensor operation. These types of devices are certainly suitable for the proposed DAQ, but they do not quite correspond to the ideal instrument: a wireless device that is both battery-free and immune to the vagaries of energy scavenging. This is the concept embodied in the Wireless Identification and Sensing Platform (WISP).

WISP is modeled on the more familiar Radio Frequency Identification (RFID) technologies, an example being open road tolling systems. These systems consist of a transceiver, or "reader", and a transponder or "tag", which is little more than a microchip with an antenna (Fig. 6). The reader sends a radiofrequency carrier wave to the tag to collect information stored in its chip. Energy from the transmission itself is harvested to power the tag's chip. Tags generally lack the power necessary for active signal transmission and so communication is accomplished by modulating the carrier wave transmitted by the reader. Some tags reflect a portion of the transmitted signal back to the reader in a manner analogous to radar. Others inductively couple with the reader's magnetic field like the primary and secondary windings of a transformer as the schematic illustrates. The passive communication link is a critical feature as it allows the system to function with the meager amounts of energy available from the radio signal. Regardless of the communication mode, RFID provides a means to remotely collect information from an electronic device that powers itself solely from an incoming communications signal. Tags can be divided into two categories: "passive" devices that rely entirely on the radio transmission for power, and "active" devices that include a battery to boost performance capabilities such as read distance.

Combining a sensor with the tag would transform it into the ideal device for our application. WISP takes this extra step by incorporating one or more sensors into the tag while retaining the ability to operate solely with energy harvested from the incoming carrier wave. Temperature sensors, strain gauges, and light sensors

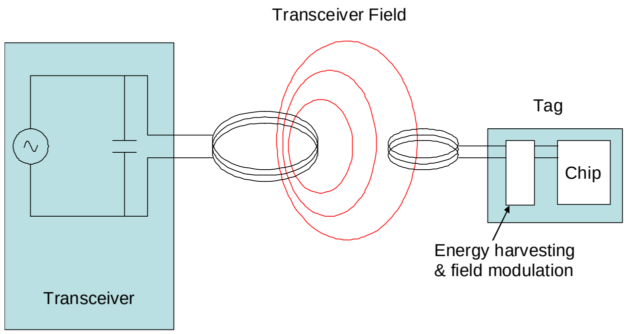

Fig. 6. General principle of a passively-powered RFID system.

have been incorporated into demonstration devices shown to operate at distances of several meters from the reader [Yeager et al., 2008, Virtanen et al., 2011]. For an example of a functional WISP with both an accelerometer and a temperature sensor, see Buettner et al., 2009. The device can be read with a standard long-range reader at a rate of several Hz from a distance of roughly 3-4 m. This technology is still rather young and there are continuing efforts to reduce the size of devices and power consumption while also adding functionality.

WISP is defined as a battery-free platform [Sample et al., 2008] though in principle batteries could be added to increase range, bandwidth, and functionality. But such an "active" WISP would be similar in principle to conventional battery-operated wireless instruments. Therefore WISP is considered here strictly in the passive sense since it represents our ideal device that relies neither on batteries nor energy scavenging from potentially unreliable ambient sources.

Implementation of WISP within the proposed secondary I&C would look much like a conventional wireless sensor network in which the instruments are powered by batteries and/or energy harvesting (Fig. 7). But the WISP-based instruments function only upon receiving a communications signal. If necessary, the devices could be fitted with supercapacitors that store enough energy for sensor operation between reader queries. One advantage of this system is that any number of readers could be used to poll sensors. If on-site readers are damaged by an accident, new readers could be brought in from off site to operate and poll sensors.

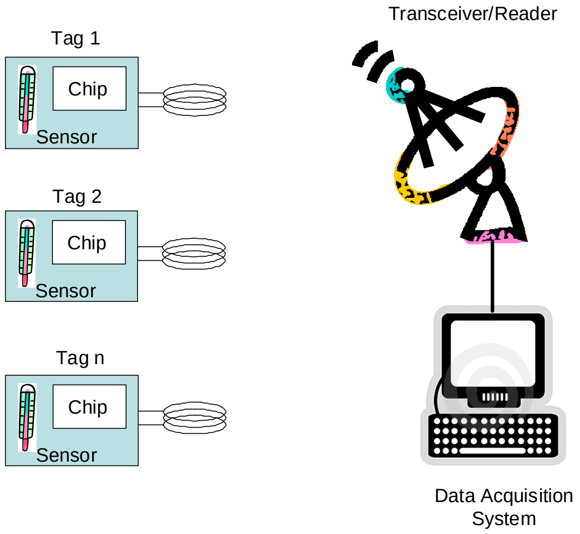

Fig. 7. WISP implementation in the proposed secondary I&C system.

Many WISP development efforts focus on miniaturization to make tags unobtrusive, mobile, and inexpensive while still enhancing device functionality. These are not critical factors in our application and so performance capabilities beyond that of standard WISPs should be attainable if needed. Other ongoing development work considers communications limits associated with tag movement. Signal strength is affected by orientation of the antenna with respect to the reader, tag/reader distance, and reader transmitting power [Merilampi et al., 2011]. Power to the tags can be boosted with a directional transmitter, an increase in antenna size, and by increasing reader power, though the latter is limited by communications regulations. Our application would benefit from an expected lack of sensor movement so that both the tag orientation and distance could remain constant. In addition, multiple readers could be deployed to ensure strong signals.

Transmission security is always a concern with any wireless system. WISP differs from standard wireless systems in that power levels are so low that there is often little to spare for the processing needed to encrypt the signal. Still, this issue is also being addressed by industry and researchers as WISP continues to mature.

## 4. Summary

We have described a strategy and assortment of devices for a data acquisition system that can operate during a station blackout involving complete loss of power to the main I&C systems. This proposed backup system, denoted the “secondary DAS”, consists of a wireless sensor network that is completely separate from the plant’s conventional equipment. Each instrument has its own sensor, communications hardware, and power supply. Power for the devices may be drawn from batteries, energy harvesting, or a hybrid of the two. Sensor readings are collected at one or more remote work stations such as battery-operated laptops running communications and data acquisition software that are, like the hardware, entirely independent of the plant’s conventional systems.

The proposed secondary DAS would refrain from using any preexisting sensors of the main I&C system. Though this approach forgoes some advantages associated with using existing equipment, it yields a number of benefits: with no hardwired connections between the secondary DAS and the main I&C system, the reliability of the old system remains unaffected by the new one. Installation of a completely separate system is expected to be less expensive than one linked to the main I&C system as there would be no need to integrate new technology with old. This strategy frees one to choose devices that are best suited for the task without the need to consider compatibility with the existing I&C system.

The monitoring of a severe accident does not require exotic instrumentation and so the sensors of the secondary DAS are rather conventional. Technologies for measuring pressure, temperature, flow, and level are quite well developed and though they continue to evolve, there are no breakthroughs on the horizon that would be of importance for this application. The proposed strategy is to use simple sensors that require very little power while providing just enough accuracy to be useful in accident management. The secondary DAS need not have the accuracy of the plant’s main system and so unconventional sensing methods can be considered. The best example is flow metering, which generally requires considerable hardware and expense. But flow rates during a severe accident need not be measured with the accuracy required of a typical plant flow meter, and so one may consider much simpler and cheaper methods such as cross correlation flow meters. Though not accurate enough for daily use, they can provide an indication of high/low or reverse flow with nothing more than two temperature sensors. This exemplifies the ideal instrument for the secondary DAS: simple, low power consumption, relatively easy to install with minimal impact on normal plant operations.

## 5. Future work

Plant monitoring during a complete blackout can be accomplished with a network of self-powered wireless sensors. There exist today commercial devices that are likely to be suitable for at least some of the necessary process measurements. If these devices are found wanting, one could await the rather rapid developments in this field, which are being driven by many industries with similar interests. As a result, there would seem to be little need for direct NRC involvement in hardware development, except perhaps for sensing needs particular to the nuclear industry, such as radiation monitoring. But even in this seemingly niche area there is already significant work, such as that related to nuclear safeguards [e.g., Waguespack and Wilson, 2010 and Katsis et al., 2010].

Future work could begin by settling on a strategy for plant monitoring. Is it indeed desirable to have an independent secondary DAS? Is it acceptable to use wireless systems for data acquisition in a nuclear plant? Since the secondary DAS is likely to be a very small network of sensors, process parameters must be prioritized. Are any links with the primary I&C system permitted or desirable? Since these devices would serve an important safety function, it may be necessary to conduct a formal tradeoff study similar to that of Constantinou et al., which investigated energy source options for wireless sensing in nuclear waste repositories with the notion that these systems must operate for many decades.

Once a strategy for plant monitoring has been defined, one should determine whether the new capability is needed immediately, directing one to today's off-the-shelf products, or whether there is time to await improvements in hardware capability. This governs what devices are available for deployment.

This study was well underway when the Fukushima accident occurred. Though the original scope did not extend to scenarios entailing core damage, there is understandable interest in using this material to address some of the I&C weaknesses observed at Fukushima. Some very basic pressure, temperature, and flow measurements were unavailable once the accident began, making it more difficult to manage and analyze. If the loss was due only to damaged cables or power supplies, the measurements could have been successfully backed up with commercial battery operated wireless systems. Selected measurements in U.S. plants could be backed up for such a contingency using commercial hardware. No research is needed in this area.

However, if instrument losses were due to ambient conditions, for example flooding, high temperature, high pressure, or the presence of steam, commercial wireless sensors may fail along with the hard-wired units. It is well known that operating characteristics of commercial instruments are dependable only within a defined ambient condition envelop. If a small number of wireless sensors are to act as the ultimate backup in the event of a severe accident, it would be best if they, at least, could withstand extremely harsh ambient conditions. Future work could involve the following:

1) Identify the service limits of present day commercial industrial wireless transmitters. A typical industrial unit can be expected to operate in noncondensing atmospheres at 1 bar and temperatures below ~80°C. More severe conditions could be expected in a steam-filled containment.
2) Test selected commercial wireless sensors under adverse containment conditions. Transmitters could be submersed underwater for brief periods, held in steam or high pressure atmospheres. This would explore the survivability of transmitters that might serve

as the only window into plant conditions in a severe accident like Fukushima. Test data may already exist from other NRC efforts or unpublished tests conducted by vendors.

3) Explore methods for improving the survivability of wireless devices. Accident management at Fukushima would have been helped by a modest network of hardened wireless sensors that were able to withstand the trials of the accident and could be relied upon to provide accurate data.

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