Crickets™ and Curies: Lessons Learned from the Steel Industry-18221

Steve A. Steranka*, Vladislav S. Kondrashov*, and Glenn Paulson**
*RadComm Systems Corporation, 2931 Portland Drive, Oakville, ON L6H 5S4 CANADA
**Glenn Paulson, Paulson and Cooper, Inc., PO Box 1541, Jackson Hole, WY 83001 USA

ABSTRACT

The global nuclear power industry, and to a lesser extent, the decommissioning and demolition of old nuclear weapons plants, obviously present challenges to those in the radioactive waste management field. Some if not many of these challenges have already been dealt with, and resolved, in the steel industry, including its recycling component. This paper presents proven state-of-the-art radiation detection systems used in steel and related recycling facilities, emphasizing current, reliable and flexible technologies for characterization, volume reduction, and remote handling of recyclable solid wastes contaminated and, just as important, not contaminated, with a wide range of radioactive isotopes. It will also cover features of remotely operated waste handling equipment effective in reducing or eliminating exposure of workers engaged in decontamination and demolition work on active and/or inactive nuclear installations.

The industry group identified above has a long-standing policy regarding any radioactivity in potentially recyclable as well as waste materials it receives: if it is detected, it is rejected. The US Steel Manufacturers Association (SMA) put it this way in one of their Public Policy Statements: **"SMA members have not, and will not, accept scrap that is known to be radioactively contaminated**" (emphasis included in the original) (1). This is policy, adopted around the globe, obviously has major implications for decommissioning and demolition projects. To put it bluntly, if rad-contaminated metal, concrete, or other materials are sent to a facility for possible recycling, reuse or even disposal, they may well be rejected. If so, the materials will be returned to the generator–-at the generator's cost—and a new solution will have to be found. This also results in additional costs for the generator.

Facilities in the steel making and metal recycling industries have access to, and routinely count on, a wide range of proven detection technologies and techniques for monitoring incoming shipments and sorting the materials in them. The approaches range from using sensitive handheld instruments for pinpointing and isolating small devices such as isotope-containing gauges and radium dials all the way up to technologies effective for large volumes and weights of contaminated construction and demolition material. In this latter realm, the most suitable, robust, and field-proven system for decommissioning and demolition work is a radiation detection system fitted to a grappling and/or magnetic device, known as the Crickets™ technology, which automatically scans bulk material with no added effort or time in material handling operations. Highly versatile, a Crickets™ system can be put to work on any material-handling system, including grapples handling 1 to 18 cubic yard volumes, while detecting radioactivity in real-time over a very wide dose range, from nanoSv to Sv levels. Other field-proven real-time measuring radiation detection devices can be fixed to conveyor belts with traverse speeds up 3 meters/second, also measuring in real time and over the same dose range, allowing both recyclable and waste materials with a pre-set level of radioactivity to be diverted off the belt. Finally, there are highly sensitive radiation portal installations for detecting radiation from materials being transported by vehicles, including those with roll-offs, dump trailers, and other containers, again in real-time and with the same dose ranges. For vehicles, the speed must be carefully controlled—the vehicles need to travel from 5 to 10 km/h through the scanning zone to ensure that maximum detection capability is maintained.

When radiation detection systems at recycling and steel making facilities detect radioactive material in an incoming shipment, these facilities have a zero tolerance on accepting the cargo. Therefore it is imperative that material from a demolition operation that is slated to be sent for recycling or other reuse be checked at the point of demolition at similar detection levels to avoid possible rejection of a shipment because of its radioactivity. In addition to measuring overall radiation levels (for example, total gamma), when necessary, combinations of different radiation detection media can be used to detect the presence and intensities of specific isotopes such as U-235, Fe-55, Cs-137, Co-60, Am-241, etc., again in real-time and in a similar dose range.

These detection technologies can be fixed or transportable. More important for the rad-waste management profession, this overall systems approach can be tailored and adapted during use on-site in any dismantling, demolition or remediation project, to allow materials to be thoroughly scanned before being released to the recycling stream for reuse, or to appropriate long-term storage and disposal facilities. Potentially recyclable materials with contamination such as steel beams and rebar will set off alarms at recycling facilities, resulting in unnecessary added expenses to the generator, primarily due to increased transportation costs, time delays and additional rad-waste handling and disposal charges. Additionally, there are situations where relatively lightly contaminated materials, once identified and appropriately characterized, can be reused in new construction applications, such as concrete from demolition being used in the base layer for roads or recycled steel used for repair or construction of bridges. In other cases, specific smaller volumes can be sent to specialized rad-waste disposal sites. These radiation detection systems can also be custom tailored to ensure proper handling and disposition of contaminated materials destined for reuse in specific applications where, for example, acceptable levels of radioactivity in NORM or TENORM, for example, can be reused or safely disposed of.

INTRODUCTION

Over the next few years the commercial nuclear power industry is facing a significant increase in the number of reactors that will be closed—decommissioned and in due course demolished. One recent report (2) states that in the previous 5 years, US power companies have retired six reactors and announced the near-future retirement of seven more between 2017 and 2025. This trend is mirrored globally as well. The most recent authoritative information we have from the World Nuclear Association (WNA) from their World Nuclear Supply Chain report projected that globally 84 nuclear power reactors would be "dismantled" between 2015 and 2030 (3). This pace may be quickening—a recent article in the trade press indicates that WNA now projects in its Reference Scenario there will be 118 reactors closed between 2017 and 2030 (see also Ref. 4).

While detailed breakdown data on both past and projected future D&D projects are hard to find in the open literature, it is clear that these are all major projects—big in the volume and the mass of materials to be handled and either disposed of or, where possible, recycled or otherwise reused, as well as large in costs.

Regarding the actual materials in a typical large commercial nuclear power reactor, the steel in a single steam generator weighs about 300 tonnes (much larger in some systems), and a typical PWR has three. The steel reactor pressure vessel for an AP1000 reactor weighs 4,000 tonnes (4). IAEA identifies many other uses of steel (and steel types, e.g., carbon, stainless and alloys) and other metals as well (5). There are also 200 or more pumps, many of them quite large, over 5,000 valves, over 200 km of pipe and over 2,000 km of cable (3). These and many other components of a commercial nuclear power plant are of course all "nuclear grade", not standard industrial grade. They have value—-if they can be properly sorted, characterized, and recycled or re-purposed in some manner.

In addition, there are also on the order of 15,000 metric tonnes (6,000 cubic meters) of concrete just in the "basemat" the reactor and its ancillary buildings sit on—-also potentially of several types (pre-stressed, reinforced, with and without steel, etc.), and considerably more concrete for reactors with cooling towers. (3) The references already cited do not include any estimated quantities (e.g., in tonnes or cubic meters) for many other ancillary but essential components, notably the turbines and other generators as well as the reactor containment structure and spent fuel building, among many other systems and types of equipment.

Regarding the costs, the WNA in 2014 (3) projected an average "dismantlement" cost at just over $1 billion (US) per power reactor, but did not break that down further. For example, it was not clear if this was based on just the on-site "dismantlement" costs, or also included the dollar amounts for ultimate disposal of the waste materials, or any credit for recycling any of the materials the reactor and related components were made of. Based on our review of the current literature and trade press articles, a useful rule of thumb figure at this time is about $1 billion US per nuclear power reactor.

Other sources provide some additional insight. The paper by Semseth et al. (6) presents summary data for a specific German power plant as follows:

Total of Radiologically Unrestricted Materials: 1,233,600 tonnes (~ 69%)

Total of Radioactive Materials: 566,400 tonnes (~31%)

The radioactive material was further broken down as follows: 26,000 tonnes of concrete classified as radioactive waste (~ 1% of the total), 69,200 tonnes of dismantled plant parts (~4%), and 471,200 tonnes of “remaining structures" (not further defined, but ~26% of the total).

Another piece of the puzzle, smaller in scale on a global basis but quite significant in the USA, is the on-going cleanup, including D&D, of a wide variety of structures ranging from small to very large, at the US Department of Energy (DOE) facilities that make up the nation’s nuclear weapons complex. This is of course an on-going effort, with the larger share of D&D activities to be done in the future. Nonetheless, there is already significant activity at many of these facilities. For example, the current US administration’s budget request to Congress for DOE for the next fiscal year has $1.6 billion for D&D activities at several facilities, with about half of that specifically for former uranium enrichment facilities; this D&D work accounts for almost 30% of the total for DOE’s Environmental Management budget request (7). It appears to us that there are other funds for D&D-related work sprinkled around other budget lines, as well. Even though this one-year amount is roughly equivalent to the estimated cost for D&D of a just a single commercial nuclear power plant, its full scope is better judged by the fact that the cleanup of the US weapons complex is currently projected to go on for an additional 50 years—-if not longer. In addition, the D&D work generally comes toward the end of a cleanup process for a specific installation such as Hanford, not at the beginning. As a benchmark from another country for comparison, a recent report places the estimated total D&D costs for Sellafield, the home for the lion’s share of the UK’s nuclear weapons and nuclear power work, at $10 billion (US) (8).

BACKGROUND AND BASIC TECHNOLOGIES

The radiation detection systems utilized by the steel industry have served as solutions for various other industries and applications such as the installations of the US Department of Homeland Security’s Border Security Agency. For example, the radiation portal monitors (RPMs) now utilized at border crossings and port operations were originally developed for and used in the steel industry almost 2 decades before the September 11 terrorist attacks. These RPM systems were initially installed at steel plant weigh scales and entry points where raw materials had to be scanned, with alarm thresholds generally set at levels <u>below</u> the measured ambient background radiation levels at the plant. These alarm threshold levels provide the highest degree of detection capability for heavily shielded radioactive gauges (see Figures 1-a, 1-b, and 1-c) buried in scrap metal in vehicles moving slowly (5–8 km/hr, or 3-5 miles/hr) through the detectors. These gauges contain significant quantities of radioactive material capable of contaminating a large steel-making operation and, depending on the isotope, its finished products. To date there has been a significant number of reported cases where gauges have found their way into steel-making operations and were smelted in electric arc furnaces, causing unacceptable levels of contamination by specific radioisotopes in various steel products (9). These contamination incidents can result in tens of millions of dollars in decontamination of the facility as well as both loss of production and additional waste disposal costs (1).

Figure 1-a

Figure 1-b

Figure 1-c

Note: The US Department of Homeland Security has deemed these types of radioactive sources as potential “dirty bomb” materials which could cause mass disruption if they were to be used with a conventional explosive (10).

Other types of problems have also occurred. For example, in December 2017 the US Nuclear Regulatory Commission (NRC) issued a formal order to an American company regarding an incident where the company attempted to send rad-contaminated metal pipes to a local recycling facility (11). The portal monitor at the recycler detected radioactivity in the pipes as they arrived, and the pipes were immediately returned to the company. Subsequent investigations by the NRC found the company violated several regulations of both the NRC and the US Department of Transportation. As a result, the company is taking a number of corrective actions, notably including the installation, for the first time, of a radiation portal monitor for vehicles entering and exiting its facility. The public records do not reveal the dollar cost of these actions; there has probably been some damage to the company’s reputation as well.

Radiation detection system manufacturers have developed highly sensitive instrumentation to tackle increasing problem of radioactive gauges ending up in scrap metal. As a result of these advancements, a high level of confidence has been gained in detecting radioactive gauges in scrap metal cargos. Nonetheless, accidents continue to happen where radioactive gauges somehow were not detected by the RPM systems and went into steel-making operations, causing unacceptable contamination of final product lines.

More recently, other new and improved radiation detection systems have been developed and widely implemented around the world to serve as essential tools to scan scrap cargos in real-time in order to increase the probability of detecting heavily shielded gauges and other radioactive materials before they enter a process stream. Systems including specialized grapples and magnets (see Figures 2 and 3), more elaborate RPM systems (see Figure 4), and conveyor belt-mounted systems (see Figure 5) are among the more popular in both the steel and scrap metal industries. These systems have many advantages over earlier ones, such as their close proximity to the material being scanned, reliability in locations with low ambient background levels, effectiveness on lower density material (for example, demolition debris, soils, etc.), and longer scanning times. Since the implementation of these advanced systems, the frequency of detection and removal of radioactive gauges has increased significantly, while globally the number of incidents with adverse consequences reported per year has decreased.

Figure 2

Figure 3

Figure 4

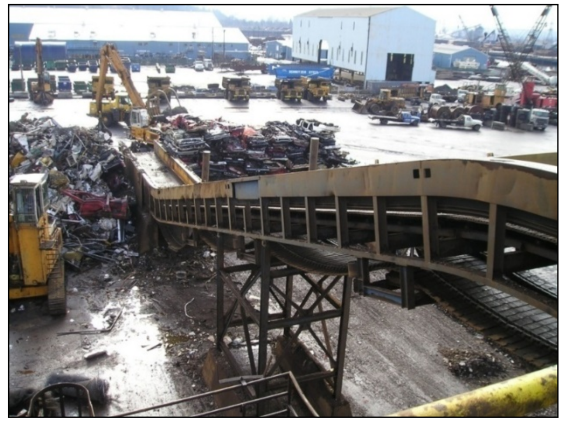


Figure 5

The steel industry in particular has been the driving force behind both suppliers and processors of recycled metal to install large, highly sensitive radiation detection systems upstream as a critical line of defense for detecting radioactive gauges and other rad-contaminated materials. Steel plants have increasingly enforced a “Zero-Tolerance” policy, where if radioactivity is detected in an incoming shipment (even at near background radiation levels), the cargo is rejected (1). This Zero-Tolerance acceptance policy is costing the scrap metal processing industry millions of dollars in lost revenue as well as increased freight and disposal costs. With the scrap metal recycling industry having to recognize the firm rejection policy of the steel industry, it must also adopt the same policy with their suppliers, and tranfer the increased costs to them. One of the scrap metal industry’s major suppliers is the demolition industry.

Significant quantities of metal are supplied to these recycling plants from their sources, one of which is and will increasingly be the nuclear power industry. It is common knowledge the nuclear power industry generates radioactive material. It is the responsibility of the nuclear power industry to monitor and control the shipment of its material whether it is to be recycled or stored/disposed, that is, for recycling or reuse (and free of radioactive contents) versus, for storage or disposal (which can be radioactive to a greater or lesser degree). Demolition companies providing services to nuclear power plant owners where there is a certainty that radioactive material is present can be equipped with appropriate radiation detection systems for detection and segregation of waste streams for subsequent re-use, intermediate storage, or ultimate disposal.

RECOMMENDED RADIATION DETECTION SYSTEMS FOR RECYCLABLE AND WASTE MATERIALS FROM DEMOLITION SITES

The following radiation detection systems approach is recommended for any demolition company handling material from structures where radioactivity may or is known to be present.

There are five components to be considered in the design and implementation of an effective system to meet the needs of the nuclear power D&D community and for related activities for other types of radioactive wastes. All systems must have an appropriate detection medium, the first item on the list below. Typically, one or more of the four other components will also be selected based on the specific project.

1. **Detection Medium:** There are a variety of detection mediums (all scintillator based) utilized in these systems which react to gamma/X-rays and neutrons (12). They are:

a) PVT (Poly-Vinyl Toluene): This plastic scintillation material provides a Yes/No response when elevated readings of gamma/X-rays are detected. PVT is generally the least expensive option, and the detectors are larger in size than the other two options.

b) Sodium and cesium iodide crystals: These synthetically grown crystals provide the ability to detect and identify specific isotopes while also increasing the sensitivity to gamma/X-rays. Detectors using them are more expensive and smaller in size than PVT scintillators.

c) Lithium-based scintillators: These are utilized for detecting neutrons. There are two types; lithium glass crystals for smaller-sized detector applications and lithium glass fibers for large detector applications.

2. **Crickets™ Grapple and Magnet Mounted Systems:**

These radiation detection systems have been installed and operated in mobile excavators and cable cranes successfully over the past 20 years in many types of material handling operations. The detectors can be installed on any grapple or magnet with very few restrictions. These detector panels can be outfitted with any of the detection mediums just listed. The initial installation is straightforward, requiring approximately eight hours by a skilled technician. There are three primary components in such a system: see Figure 6.

The Crickets™, once set up, will operate independent of the crane operator. There are three automated scanning modes which include: surface area scanning, load analyses scanning, and search/locate rate meter scanning. This system is perfectly suited for the demolition of facilities associated with radioactive materials. Materials can be sorted and isolated using all the three modes of the Crickets™ operation. The Crickets™ technology can be configured to operate in virtually any application where detection and sorting levels range from 10 nSv/hr up to 0.1 Sv/hr levels; see Figure 7. The Crickets™ can also be configured to identify any isotopes listed in the isotope standard library, and if a particular isotope is not present in the library, the library can often be modified, depending on the specific isotope(s) of interest in a specific situation.

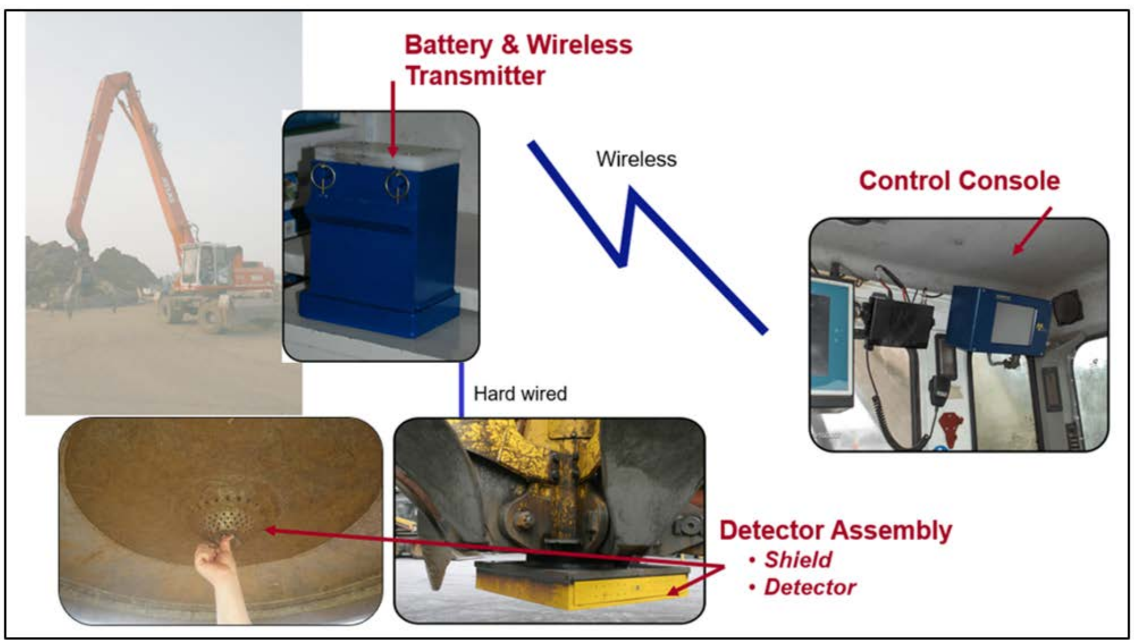


Figure 6

Figure 7

3. **Radiation Portal Monitors (RPMs):**

These are the most widely used types of radiation detection systems for monitoring cargos of both recyclable and waste materials. As can be seen in Figure 8, these types of systems can be custom-configured for any vehicle monitoring application. They are installed where all vehicle traffic carrying cargo must enter and/or exit a facility. These detector panels can be outfitted with any of the detection mediums listed above. Typically, they are installed at the entrance of a weigh scale where the vehicles must be weighed in before entering the facility and are already moving at slow speeds (as noted earlier, < 8 km/hr or <5 mph). When scanning for smaller discrete radioactive sources, slower scanning speeds provide increased sensitivity, which significantly improves the detection probability for detecting compact radiation sources (e.g., gauges, discrete metal objects, etc.).

Figure 8

4. **Conveyor Radiation Detection Systems:**

These systems can be installed on conveyor belts in a variety of locations as shown in Figure 9. The detector panels can be outfitted with any combination of the detection mediums. These detectors can be installed where there is an opportunity to scan the material travelling on the conveyor at speeds up to 3.0 m/s, with configurable alarm threshold levels from 10 nSv/hr to 0.1 Sv/hr.[1] Once the system has been set up, it also will run totally independently and will not require operator action until there is an alarm condition. In the event radioactivity is detected, the system can either stop the conveyor or divert the suspect material out of the regular process stream.

[1] The reviewer of the draft of this paper identified an early approach of this sort, used for separating large soil particles with levels >135 nCi, (reported at that time as > 5,000 Becquerels) primarily of plutonium-239 and americium-241 in coral on Johnson Atoll (12).

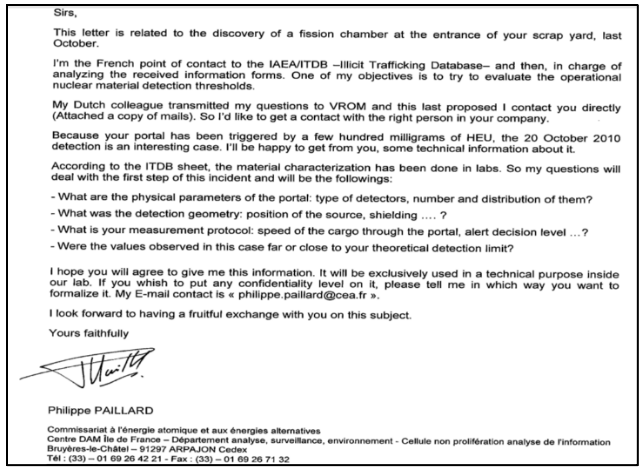
Figure 9

5. **Remote Monitoring and Servicing Capabilities:**

   All these systems have robust remote connection to process-control staff and other appropriate personnel at the actual processing location. In addition, if a network/internet connection is available, all of the above-mentioned systems can incorporate electronic hardware and software capable of being monitored and modified remotely (for example, by the corporate headquarters for the processing facility and/or by the system manufacturer). Having a remote connection allows managers the ability to monitor the system's operation and make changes, for example in alarm thresholds, as may be required. Additionally, in the event of changes in the system's normal operation, e-mails can immediately be sent to specific personnel at the facility with instructions on what steps to take to remedy problems. The manufacturer of the system can also provide remote assistance with routine maintenance and servicing issues, including hardware adjustments and software updates, calibration, etc., reducing the need for on-site visits by the manufacturer's technical staff.

CASE STUDIES

The detection capabilities of these systems plus their ability to operate on a continuous basis prove their ability to perform by detecting the radioactive materials they were designed to find even when the sources are deeply shielded inside other cargo, including mixtures of diverse waste material. This is extraordinarily useful in many settings, ranging from steel plants needing to avoid the smelting of, for example, radioactive gauges, to scrap metal processing companies which need to reject loads due to radioactive content and others, such waste handlers who routinely receive medical wastes containing radioactive isotopes. After installing the appropriate combination of detection systems, owners and operators have time and time again proven the effectiveness of these systems' capabilities by detecting and removing radioactive sources before processing the rest of their raw materials or wastes. To date, there are no detailed analyses done on the success rate across all of these categories of users other than results that clearly show a decline in the number of serious accidents per year where radioactive gauges have been (unfortunately) been mistakenly smelted. On the other hand, there are many reported incidences where these same systems have proven their superior detection capabilities, for instance as reported in a lengthy Dutch news report (see Figure 10), where U-235 had been detected on a number of occasions at a metal recycling facility after material containing this isotope had freely passed through the border security agency's portal radiation monitors. This particular incident drew attention from the European Union’s Security Agency, which requested information on the systems used at the recycling facility for detection of such a difficult-to-identify isotope.



Sirs,

This letter is related to the discovery of a fission chamber at the entrance of your scrap yard, last October.

I'm the French point of contact to the IAEA/ITDB –Illicit Trafficking Database– and then, in charge of analyzing the received information forms. One of my objectives is to try to evaluate the operational nuclear material detection thresholds.

My Dutch colleague transmitted my questions to VROM and this last proposed I contact you directly (Attached a copy of mails). So I'd like to get a contact with the right person in your company.

Because your portal has been triggered by a few hundred milligrams of HEU, the 20 October 2010 detection is an interesting case. I'll be happy to get from you, some technical information about it.

According to the ITDB sheet, the material characterization has been done in labs. So my questions will deal with the first step of this incident and will be the followings:

- What are the physical parameters of the portal: type of detectors, number and distribution of them?
- What was the detection geometry: position of the source, shielding .... ?
- What is your measurement protocol: speed of the cargo through the portal, alert decision level ...?
- Were the values observed in this case far or close to your theoretical detection limit?

I hope you will agree to give me this information. It will be exclusively used in a technical purpose inside our lab. If you whish to put any confidentiality level on it, please tell me in which way you want to formalize it. My E-mail contact is « philippe.paillard@cea.fr ».

I look forward to having a fruitful exchange with you on this subject.

Yours faithfully

Philippe PAILLARD

Commissariat à l'énergie atomique et aux énergies alternatives
Centre DAM Île de France – Département analyse, surveillance, environnement - Cellule non prolifération analyse de l'information
Bruyères-le-Châtel – 91297 ARPAJON Cedex
Tél : (33) – 01 69 26 42 21 - Fax : (33) – 01 69 26 71 32

Figure 10

There are other incidents where no formal case study has been issued, but where there have been requests for assistance to system providers by steel companies who were not monitoring for radioactive material, for example, in India and China, where radioactive gauges were accidently smelted in their furnaces. The finished products ended up being detected by a Homeland Security Portal system, resulting in rejected cargos of mixing bowls (see Figure 11) and tissue box holders (14). Since the installation of the above-mentioned systems at these specific furnaces several years ago, there have been no further smelting of radioactive gauges at these facilities. Many other news reports have been published regarding other incidents.

Figure 11

CONCLUSIONS

1. Most demolition sites have contractual timelines that must strictly be adhered too. Deviating from these timelines can be disastrous, usually resulting in lost revenue. Additionally, there can be situations where previously unknown issues have arisen, such as radiological contamination causing painful repercussions with regards to over-exposed personnel, equipment contamination, project cost renegotiations and/or additional, unexpected material handling, shipping, and disposal charges.

2. In the case of potentially recyclable material being released from facilities known to be engaged in handling and/or processing of radioactive material, companies have to take appropriate measures to ensure released materials are not going to be rejected at end user sites. Detection systems must be used that are capable of at least equaling the end user's detection capabilities.

3. The recycling industries do not automatically follow the relevant government regulations regarding acceptable release limits (15). Instead, the recycling industry typically uses even stricter, that is, even

lower numerical standards. If a cargo being scanned causes an alarm condition in the end user's radiation detection system, the cargo will be rejected, and returned to the original owner of the cargo, invariably resulting in more difficulties, and increased costs, for the owner.

4. The best solution for handling material on-site during any major demolition project is the use of a grapple -mounted radiation detection system such as a Cricket™. These systems will provide the operators of the demolition equipment with the ability to detect, sort and separate material on-site and in real time during the demolition process. Additionally, the operator can handle this material safely from a distance, which is critical when high levels of radiation are or may be present.

5. An appropriate combination of the set of five components of these radiation detection systems can be tailored to meet the needs of specific D&D projects across a very wide range, from the D&D of commercial nuclear power plants to the cleanup of rad-contaminated industrial sites such as the US nuclear weapons plants to dealing with known or potential NORM and TENORM materials and wastes at relatively smaller scales.

6. The approach described here is, at its core, essential to designing and carrying out a cost-effective D&D project. On the cost avoidance side, this approach prevents materials from being sent to a potential user who will reject them—-and send them back. On the cost-effectiveness side, this will allow materials that might have been treated as wastes to become salable “raw materials” for other downstream users, or at the least, minimize disposal costs.

7. Additional details regarding these systems and also hand-held radiation monitoring devices can found at the RadComm Systems booth in the exhibition hall.

8. Finally, there is an associated paper being presented by Dr. Vladislov Kondrashov of RadComm Systems on radon detection that will be of interest for demolition activity where there need to be surveys specifically for radon prior to commencing or actually conducting a demolition project. This is in Session 141.

REFERENCES

1. Steel Manufacturers Association (USA), Extract on Radioactive Scrap from SMA Public Policy Statement, 2009-2010, which can be found at www.cnr.org/SMA_Radioactive_Scrap.pdf, (accessed on January 4, 2018).

2. Vine, D., Emission Implications of Nuclear Retirements, Center for Climate and Energy Solutions, July 2017, Arlington, VA, is only one of several recent summaries of the situation in the US. The reactor retirements include Crystal River (FL), Deqaunee (WI), San Onofre (CA-2 reactors), Vermont Yankee (VT), Fort Calhoun (NE), Palisades (MI), Oyster Creek (NJ), Pilgrim (MA), Indian Point (NY-2 reactors), and Diablo Canyon (CA-2 reactors).

3. A good summary of the international situation as seen by the World Nuclear Association in 2014 is the presentation by WNA’s G. Kaser at the NEA International WPNE Workshop in Paris on March 11 2014, found at https://www.oecd-nea.org/ndd/workshops/pmnnb/presentations/docs/2.1.pdf (accessed on October 30, 2017).

4. Heavy Manufacturing of Power Plants, updated October 2017, World Nuclear Association (accessed using that title on November 1, 2017).

5. IAEA TECDOC-144, Nuclear Power Plant Design Characteristics, March, 2007 (accessed on-line on November 7, 2017).

6. Samseth, J, et al., Closing and Commissioning of Nuclear Power Reactors, UNEP Year Book 2012 (accessed on line under that title on November 2, 2017).

7. DOE/CF-0132, Volume 5, Environmental Management, US Department of Energy FY2018 Congressional Budget Request, May 2017 (accessed on-line on November 1, 2017).

8. Decommissioning and Use Fuel Market Map 2015, a White Paper published by Nuclear Energy Insider, available on-line through www.nuclearenergyinsider.com/nuclear-decommissioning-used-fuel (accessed on-line on November 1, 2017).

9. Wikipedia Reference “Radioactive Scrap Metal”, https://en.wikipedia.org/wiki/Radioactive_scrap_metal, accessed on-line on November 9, 2017)

10. Wikipedia Reference “Dirty Bombs”, https://en.wikipedia.org/wiki/Dirty_bomb (accessed on-line November 9, 2017)

11. US Nuclear Regulatory Commission II-17-051: NRC Issues Confirmatory Order to Global Nuclear Fuel-Americas Facility to Address Issues Related to Scrap Metal Shipment; a press release on this can be found at http://www.nrc.gov:80/reading-rm/doc-collections/news/2017/17-051.ii.pdf (accessed on-line on January 4, 2018). This was also covered in the trade press; see, for example, the December 15 issue of Nuclear Street.

12. Knoll, G. F., Radiation Detection and Measurement (3rd edition), John Wiley and Sons, 2000.

13. Moroney, K. S. et al., Remediation of Transuranic-Contaminated Coral Soil at Johnston Atoll Using the Segmented Gate System, http://wysym.org/archives/1993/v1/161.pdf (accessed on-line on December 29, 2017).

14. Daily News Agency Report - http://www.nydailynews.com/life-style/health/radioactive-tissue-box-holders-yanked-bed-bath-shelves-article-1.1005746 (accessed on-line on November 8, 2017).

15. Clearance Levels for Radionuclides in Solid Materials, TECHDOC 855. (ISSN 1011-4289) IAEA (Vienna, Austria), published in 1996.

ACKNOWLEDGEMENTS:

The primary author would like to express his appreciation to the reviewer of the draft of this paper for comments and an additional reference not previously known, and also the assistance in preparing and editing of this paper to the following persons:

Glenn Paulson, Paulson and Cooper, Inc.
Vladislav S. Kondrashov, RadComm Systems Corp.
Joshua Hunter, RadComm Systems Corp.