Radionuclide Monitoring

By Anders Ringbom and Harry Miley
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The very first article of the Comprehensive Nuclear-Test-Ban Treaty (CTBT), which holds the essence of the entire Treaty, states that “Each state party undertakes not to carry out any nuclear weapon test explosion or any other nuclear explosion…” It is therefore obvious that the ability to establish the nuclear nature of an explosion must be an essential component of the CTBT verification regime. This was well illustrated in October 2006, when the Democratic People’s Republic of Korea (DPRK) conducted its first nuclear test. Based on data from the CTBT seismic network, the yield could be estimated at 0.7 kilotons (kt), far less than the very first nuclear test, Trinity, conducted by the United States in 1945, which was about 20 kt. The seismic signals from the DPRK test could, in principle, have been created by a large conventional explosion, so it was not until atmospheric radioactive isotopes in the form of noble gases were captured, measured, and associated with the explosion, that the nuclear nature of the event could be established (Ringbom et al., RN-26/D)[1,2].

At the International Scientific Studies Conference (ISS09), more than 30 posters were presented which described recent investigations on the detection of radionuclides from nuclear explosions. In this article we will try to portray the development described by these posters, together with a basic description of the scientific challenges and the techniques used to meet them.

RADIOACTIVITY PRODUCED IN A NUCLEAR EXPLOSION

A nuclear explosion creates a huge amount of radionuclides. If conducted in the open atmosphere, characteristic fission products mainly attach themselves to normal atmospheric dust. Dirt lofted by the explosion in the atmosphere or local rain can deposit a significant fraction of the particulate debris locally, but the remaining debris can travel across continents, and even around the world.

There are examples in the past when atmospheric test debris was detected on each of three circumnavigations of the globe. Since a high percentage of radioactivity is released, the detection threshold will be very low for atmospheric explosions. Studies presented at ISS09 show that the International Monitoring System (IMS) can easily detect such particulate debris (Werzi, RN-20/D).

The situation is quite different if the explosion is conducted underground, which is a scenario considered more likely today, as illustrated by the two tests conducted by DPRK in October 2006 and May 2009. In the case of an underground test, most of the radioactivity will remain in the cavity formed by the explosion. However, a smaller part of the radioactivity produced in a nuclear explosion comes in the form of noble gases, which do not react with the rock and soil and thus have a good chance of reaching the surface.

Today, scientists recognize a few isotopes of xenon (133Xe, 131mXe, 133Xe, and 135Xe), and one isotope of argon (37Ar) for the purposes of determining the nuclear nature of an event. The latter isotope is not a fission product but produced by fission neutrons which may transmute natural calcium in the surrounding rock into 37Ar.

Xenon escape has been observed many times in nuclear tests conducted over the years. There are several different modes of noble gas escape. During the first hours after a test, high temperature and pressure can create fissures in the geological or engineered containment leading to an immediate vent of radioactive gas. This can be followed by seepage for the next few days. A third mode is caused by barometric pumping, demonstrated in the so-called “Non-Proliferation Experiment” in 1993, where it was shown that periods of low atmospheric pressure tend to transport gas to the surface through faults (Carrigan et al., OSI-26/B), [3]. In this experiment, a chemical explosive of approximately one kt was detonated in a cavity at the Nevada Test Site, together with containers of non-radioactive tracer gases.

Prompt release or later seepage may release a small percentage or only a fraction of a percent into the atmosphere. In reality it is very difficult for monitoring scientists or even testers to predict the amounts released from a particular underground explosion due to the many unknown factors involved. Local geological conditions may not be sufficiently well known and the explosive energy of the explosion may be miscalculated. However, promising theoretical models tackling aspects of this problem were presented at ISS09. One example is found in Annwedt et al., OSI-25/B, where barometric pumping observed [3] was simulated by modelling the fault zones in the vicinity of the test explosion.

It should be mentioned that it is not only noble gases that have been observed escaping from underground tests. Release data from U.S. tests (Ely et al., OSI-17/B), as well as a few independent measurements (De Geer, RN-23/D), all presented at ISS09, show that small fractions of other nuclides have been observed. In particular radioactive iodine ($^{131}$I) is capable of escaping into the atmosphere, and calculations show that there is a possibility of detecting the iodine if so called ultra-low background measurements were applied (Aalseth et al., RN-09/D).

**DETECTING THE RELEASE**

When complete, the International Monitoring System (IMS) radionuclide network will consist of 80 stations which collect and measure aerosol
particles, of which 40 stations collect and measure xenon. The systems that detect aerosols use a mature technique which has been refined over six decades. High-volume air samples are used to collect the particles onto filters that are later measured using gamma-ray detectors. Substantial progress has been made here in creating high-volume, reliable automatic systems. The combination of high volume air sampling, sensitive detection, and a dense network have resulted in a system that was assessed by the ISS scientists as fully meeting the design criteria (see Figure 1) despite the fact that it is only about 70 percent complete (Werzi, RN-20/D), and could thus withstand large outages and still detect very low-yield tests.

When the CTBT was opened for signature in 1996, mature techniques for detecting radioactive noble gases and systems for deployment in a worldwide network were not available. The lack of a demonstrated automatic technique for detecting the nuclear nature of an underground event prompted a multi-national development campaign to produce highly sensitive, fully automatic radioxenon systems with 12 or 24 hour sampling time resolutions [4]. Refined versions of those systems are now being deployed on an experimental basis. The principle for collection and purification of xenon gas is based on the physical properties that differentiate xenon from other gases like nitrogen, oxygen, and carbon dioxide.

After collection, concentration and purification, the final xenon sample is transferred into a measurement system which measures the nuclear decays of the radioactive species if they are present. The systems have an impressive detection capability corresponding to a few hundred atoms of radioactive isotopes per cubic metre of air, when the typical sampled volume is in the range of tens of cubic metres of air. Furthermore, the high time resolution results in improved accuracy when using atmospheric transport models in order to locate the source of release. By August 2009 more than 20 of the 40 planned radioxenon systems within the IMS were already operating and sending data to the International Data Centre (IDC) in Vienna.

In order to discriminate between radioxenon releases from a nuclear explosion and other sources of release, it is important to be familiar with the normal radioxenon concentrations in the atmosphere. The deployment of the new generation of xenon measurement systems has produced a unique, continuously growing data set that has led to a better understanding of this background. Studies of this data set

(Ringbom et al., RN-19/D; Wotawa et al., ATM-16/E) as well as studies of reported radioxenon emissions (Kalinowski et al., RN-01/E), presented at ISS09, show that the atmospheric background of radioxenon today is dominated by a few isotopic production facilities, with a much smaller contribution from nuclear power reactors and a few other sources. The studies also indicate that the observed $^{133}\text{Xe}$ levels at most stations can be explained using known releases in combination with Atmospheric Transport Modelling (ATM) (Wotawa et al., ATM-16/E).

The detection of more than one radioxenon isotope is important in order to be able to screen out irrelevant civilian activity. It turns out that the isotopic ratios from nuclear power plants in general are different from the ones expected from a nuclear explosion, and radioxenon experts are presently working on developing a robust categorization scheme using radioxenon isotopic ratios (Kalinowski et al., RN-24/D). ATM development also plays an important role when developing techniques for the discrimination of nuclear explosions from other sources (see ATM section on page 29).

The isotopic signature from medical isotope production facilities can in some cases be more similar to a nuclear explosion signature. This stresses the importance of controlling or closely monitoring the releases from these facilities, an area for future scientific study.

The new radioxenon background data presented at ISS09 could also enable more realistic assessments of the coverage of the planned radioxenon network to be compared to design studies conducted over a decade ago. A study presented at ISS09 (D’Amours and Ringbom, RN-16/D) reveals that while the overall detection capability of the radionuclide network for $^{133}\text{Xe}$ is essentially as was anticipated, the most short-lived isotope, $^{135}\text{Xe}$, which has a half-life of nine hours, would be detected by no more than two stations (see Figure 2). This assessment strongly suggests that the network performance would be much more robust with 80 stations in operation, i.e. the same network density as used in the particulate network. Robust here means providing accurate atmospheric backtracking with maximum screening out of industrial sources.

**FURTHER DEVELOPMENT**

One overall impression from ISS09 is that many of the ideas presented seem like starting points rather than ending points, and there is definitely room for scientific development in many areas. Sensor technology is developing fast, and the use of more sensitive radiation detectors is one example. If one wants to go even further, single atom counting, which exists today, could also be applied in principle. A modification that is perhaps closer
to realization is the development of simpler collection and purification systems for noble gases. This could lead to even more reliable and less expensive systems, or possibly to more sensitive systems which could detect the shorter-lived xenon isotopes more often.

Another area of study discussed at ISS09 was the understanding of the transfer mechanism between underground tests and the surface. More understanding of leakage could be obtained from future repetition of the 1993 “Non-proliferation Experiment”, for instance, in which controlled underground gas releases are detected at the surface, validating scientific models of seepage in different geological conditions.

CONCLUSIONS

- The detection of radioactive products is important in order to determine whether an underground explosion was nuclear or not, as well as for detecting atmospheric tests. If the IMS does not detect any radioactive debris, an on-site inspection may be needed to determine the nuclear nature of an event.

- Aerosol detection is a very sensitive technique which has the capability to detect atmospheric explosions well below the level that was considered necessary during the Treaty negotiations. It might also be used to detect underground tests if ultra-low background measurement techniques are applied to stations and laboratories.

- Extensive development and deployment of equipment for radioxenon detection has been performed over the last decade, resulting in highly sensitive, fully automatic radioxenon systems. This development has led to a rapid increase in the knowledge of anthropogenic atmospheric radioxenon background. The main contributor to this background comes from a few medical isotope production facilities, and IMS detection levels and confidence would improve if these releases were reduced.

- A robust scheme to screen out industrial radioxenon releases is needed. Although the basic requirements for the IMS have already been met, the number of planned radioxenon stations should be increased to improve coverage for all four CTBT-relevant isotopes and thus improve discrimination.

- Further understanding of the transfer mechanisms for fission gases from the Earth’s crust to the atmosphere from a nuclear explosion is required.

- The radionuclide systems of the IMS are very sensitive already, but there is still room for further development, both with respect to sensitivity and reliability.

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Dr. Miley has worked at the intersection of pure science and science for national security for over 20 years. During the 1990s, he was a contributor to the Nuclear Explosion Monitoring (NEM) programme of which he was later appointed director. He also led a team of scientists and engineers in the development of the Radionuclide Aerosol Sampler/Analyzer (RASA), which is used today by the CTBT’s verification regime.

BIOGRAPHICAL NOTE