Improvement of the Iodine Monitoring System at McMaster Nuclear Reactor

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Abstract:

Iodine-125 is one of the radioactive isotopes produced at the McMaster Nuclear Reactor (MNR). It is used especially for thyroid treatment and prostate cancer therapy. However, chronic doses of small quantities of I-125 for workers can harm the body especially the thyroid organ. I-125 gamma photons are very difficult to detect since they have a very low energy. A suitable detection system is required to enable the monitoring of very small concentrations of I-125 in the air. The purpose of this paper is to describe the production and monitoring of I-125 at MNR and to demonstrate an improved monitoring system for the concentration of I-125 released to the air. A computer program, with appropriate peripherals run within the LabVIEW* environment, has been employed to improve the monitoring and advising system, finding the count rate, and analyzing the data. All these are to give the nuclear reactor operators a computerized, simple, safe and flexible monitoring facility.

INTRODUCTION

Among the isotopes produced in MNR, I-125 is the most important one. This radioactive gas is widely used material and demand for it is increasing. It is employed for diagnostic and therapeutic applications. Some of these applications are: in-vitro diagnostic kits (radioimmunoassay), as a source for bone densitometry devices, protein iodination and therapeutic seed implants used in the treatment of prostate cancer, and also as a guide for surgeons in the localization of cancerous nodes in radioimmunoguided surgery (RIGS)[1].

To produce I-125, Xe-124 gas should capture a neutron to form Xe-125 which decays with a half- life of 17 hours to form I-125.

$$^{124}Xe \xrightarrow{(n.\gamma)} {}^{125}Xe \underset{17h}{\xrightarrow{(\beta,\gamma)}} {}^{125}I \qquad (1)$$

Although the radiation that is emitted by this isotope of iodine is of a low energy and thus less harmful than the radiation from other isotopes of iodine (making it very valuable), this versatile isotope can also be very dangerous for our body. A very small amount of it can be very harmful for the thyroid organ. For the people who are working 40 hours in a week in the reactor the maximum allowable air I-125 concentration is 100 Bq/m3.

This research reactor arranges tours for interested people especially students. So to have a protected place for operator, visitors and researchers we need to have an accurate I-125 monitoring system.

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* National Instruments LabVIEW™(Laboratory Virtual Instrument Engineering Workbench)is a software tool for designing test, measurement, and control systems.

THE OLD SYSTEM AND ITS PROBLEMS

An existing monitoring system known as IMAS (Iodine Monitoring and Advising System) is working under the Windows NT environment and is written in the DELPHI language. A Keithley Metrabyte CTM-05/A is used as a counter-timer board that transfers the signal into the PC. There have been several technical and practical problems with IMAS. These problems can be listed as follows:

-It is not easily upgraded to new generation computer equipment.

-The software is developed on the DELPHI platform that not many people are familiar with. Lack of access to the full source code makes it impossible to upgrade or migrate.

-With this system we just have the current data. If data analysis of a specific past period of time is needed, the raw data cannot be accessed.

-There is insufficient error trapping in the numerical algorithms. System crashes can occur.

-The system requires a specific interface device to function (like the Keithley card). Newer PC's do not have facilities (i.e. expansion slots) to accommodate such a device.

- Alarm conditions and the way they are displayed can be confusing if the observer is not familiar with the IMAS system. There are too many (often, not easily understood) conditions that will trigger an alarm.

-There is no visual alarm indicator other than the monitor display. This does not allow anyone not in the immediate area of the IMAS station to be aware of an alarm condition.

-Audible alarm annunciations are too repetitive and cannot be cancelled (even for momentary relief). The annunciation will stop only after the alarm condition clears or the alarm parameters are manually adjusted.

SYSTEM DESIGN

The Iodine-125 monitoring system consists of two parts: the hardware and the software. An air pump, a charcoal filter (Iodine trap, a NaI detector, a data acquisition board (LabJack U12) and an alarm system represent the hardware.

As the air of the reactor site contains iodine gas, to detect and then calculate its concentration we need to have an air pump and also a filter that catches the Iodine. The pumping flow rate doesn’t vary too much in time. So in our analysis we approximate the air pump flow rate as a constant. It is adjustable for the operator in case something in the pump is changed.

The air is passed through the filter by the air pump. When the filter traps the I-125, the detector will notice a rise in filter activity caused by the new Iodine trapped. The filter that is used in the system is a charcoal filter.

Charcoal is a black, porous and carbonaceous material that is 85% to 98% carbon. It is produced by the destructive distillation of wood. It can be used as a fuel, absorbent and filter. For our purpose (trapping the Iodine) a charcoal filter is very efficient. It can capture about 99% of the present Iodine.

Over time, the amount of I-125 in the filter increases. This increase can make the situation difficult for the detector to detect small additional amounts of I-125. The existing iodine behaves as a large background, making it much harder to estimate how much Iodine has been trapped in the last time interval. So we need to change the filter once in a while to make it possible for the detector to observe new Iodine.

The detector that is used for detection of Iodine 125 gamma photons is a NaI detector. This detector has a NaI crystal mounted to a phototube (photomultiplier tube). When the incident radiation interacts in the NaI crystal, sparks of light are produced. These sparks are transmitted into the phototube. Then in this tube, the light produces electrons. The number of these electrons is multiplied by a factor of a million or more.

This kind of detector is good for low energy detection. Generally the energy range that the NaI detector can cover is between a few keV to about one MeV. The energy of I-125 gamma photons is about 33 keV. So a special NaI detector with 1 mm thick crystal is used for this purpose. As the crystal has very small thickness, it can only detect the photons below 100keV making it almost blind to the photons other than I-125's gamma.

There are three NaI detectors in the reactor. The efficiency of all these detectors is around 7%. These efficiencies have been calculated by coincidence counting and liquid scintillation methods[2].

The software of the system is written in LabVIEW 7.1. LabVIEW is an intuitive graphical programming software package that is one of the fastest graphical environments. LabVIEW can communicate with various data acquisition boards. In our system a suitable data acquisition board is needed as a counter and also to output signals for the alarm and annunciation system.
LabJack U12, as a multifunction, accurate, and low-cost interface, can be a connection between the PC and the physical world. It is connected to the computer via a supplied USB cable. One of LabJack's important parts, for our system, is a 32 bit counter that we use to find the count-rate from the NaI detector. Another part of LabJack that is essential for our job is its digital output connections that are used to transfer signals to the alarm system. A signal tower with three lights and a buzzer is a major part of the alarm and annunciation system.

A green light shows that we are in normal operation. An amber light is for warning and means "Iodine Release Occurring" and a flashing red light with a buzzer is an alarm that shows an approach to the administrative release limit. The voltage of this signal tower is 24 volts and we use a TriacOut4, a 4-point solid-state-relay, as switches between LabJack and signal tower, and a transformer to step the voltage down from 120V to 24V.

CALCULATIONS

It is required to convert the measured count-rate to I-125 concentration in Bq/m^3.

The half-life of iodine is about 60 days. The filter is being changed almost every 7 days. To show that it is reasonable to ignore the amount of Iodine that is lost by decaying in the filter, assume the amount of Iodine trapped in the filter has a constant rate of R. If λ is the Iodine decay constant, we have:

$$\frac{dI}{dt} = R - \lambda I \qquad (2)$$

The solution of this differential equation is:

$$I = \frac{R}{\lambda}(1 - e^{-\lambda t}) \qquad (2)$$

The amount of Iodine in the filter without decay is defined I' ($I' =$ Rt). We compare the ratio:

$$\frac{I}{I'} = \frac{(1 - e^{-\lambda t})}{\lambda t} \qquad (4)$$

As λ is $\frac{\ln 2}{60 days}$ and t is almost 1 week, λt is small, so with a good approximation $\frac{I}{I'} \cong 1$ and we can ignore decay in our calculation.

As a result, we can say that the Iodine concentration is directly proportional to the rate of Iodine trapped in the filter or the slope of the count-rate that is acquired from the NaI detector. We note that the NaI detector is counting the amount of Iodine that comes through the air pump and is trapped by the charcoal filter. So the rate of change of Iodine in the filter is proportional to the Detector Efficiency and Pumping Flow Rate too[3]. So we can say that:

$$Rate\ of\ Iodine\ counted\ in\ the\ filter \propto Iodine\ concentration \times Detector\ Efficiency \times Pumping\ Flow\ Rate \qquad (5)$$

The rate of Iodine counted in the filter is proportional to the slope of the count-rate in time.
As a result, we have this relation:

$$Slope\ of\ count-rate\ in\ time = Iodine\ concentration \times Detector\ Efficiency \times Pumping\ Flow\ Rate \qquad (6)$$

Or:

$$Iodine\ concentration = \frac{Slope\ of\ count - rate\ in\ time}{Detector\ Efficiency \times Pumping\ Flow\ Rate} \quad (7)$$

Here the unit of Iodine concentration is Bq/m^3 (1 Bq= 1 disintegration /second). The unit for the slope is Bq/s, the Pumping Flow Rate is stated in m^3/s and detector efficiency is just a number in percent.
But as we usually have Pumping Flow Rate in L/min, we can convert (7) to this equation:

$$Iodine\ concentration = 6 \times 10^6 \frac{Slope\ of\ count\_rate\ in\ time}{Detector\ Efficiency \times Pumping\ Flow\ Rate} \quad (8)$$

Note: 1 m^3=10^{3}Litre, 1min=60s and %=10^{-2}.

To find the count-rate slope in time the least-squares solution is employed. To have a brief description of this method, assume that we have some experimental data in a period of time shown in figure 1.

We assume a model: $Y(t) = mt + b$. When $0 \le t \le T$, N samples is obtained and $y(n)$, where $n = 0,1,..., N-1$,is the real data corresponding to $Y(t)$, where $t = n\Delta$ & $\Delta = 1$.
So in the discrete-time signal model: $y(n) = mn + b$.

If we use least-squares solution we have the following estimation for slope and intercept[4]:

$$m = -\frac{6}{N(N+1)}\sum_{n=0}^{N-1} y(n) + \frac{12}{N(N^2-1)}\sum_{n=0}^{N-1} ny(n) \quad (9)$$

$$b = \frac{2(2N-1)}{N(N+1)}\sum_{n=0}^{N-1} y(n) - \frac{6}{N(N+1)}\sum_{n=0}^{N-1} ny(n) \quad (10)$$

We fit the experimental data shown in figure (1) by $Y(t) = mt + b$ with the above m and b.

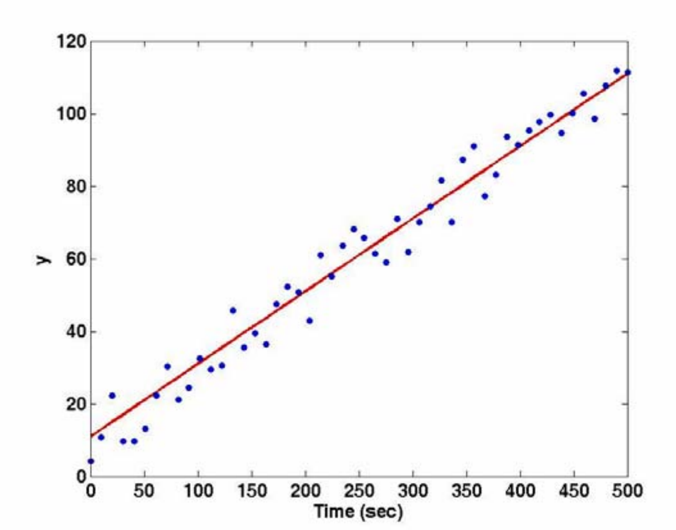

Figure (1): Typical experimental data in 500 second and the best-fitted line approximated by least-square solution.

Since in our program the count-rate has a form of a linear ramp, the assumption of $Y(t) = mt + b$ is completely reasonable and we just need to calculate the slope. To find the more accurate result for Iodine concentration, at each second we consider the data of the last hour.

As described before, when the amount of Iodine increases in the filter, the accuracy of the system decreases because the detector is going to be blind to the new Iodine when the filter is almost full. At this time we have to change the filter. Thus we need to know the error each time we calculate the Iodine concentration especially when the filter is not new. To find the error we assume that the Y is our estimation and y is the real count-rate. The mean square error between Y and y is:

$$\text{MSE}=\frac{1}{n}\sum_{i=1}^{n-1}(Yi - y_i)^2 \qquad (11)$$

Now we can say that: $$\text{Error}=\sqrt{\frac{1}{n}MSE} \qquad (12)$$

So simply we have: $$y_i = Y_i \pm Error_i \qquad (13)$$
$$y_{i-1} = Y_{i\_1} \pm Error_{i-1} \qquad (14)$$

If we subtract eq. (13) and (14) and then divided both sides by Δt and multiply by K we will have:

$$K\frac{y_i - y_{i-1}}{\Delta t} = K\frac{Y_i - Y_{i-1}}{\Delta t} \pm K\frac{Error_i - Error_{i-1}}{\Delta t} \qquad (15)$$

If we assume:

$$K = \frac{6 \times 10^6}{Detector\ Efficiency \times Pumping\ Flow\ Rate} \qquad (16)$$

then from eq. (15) we will have:

$$Iodine\ concenration_{(real)} = Iodine\ concentration_{(estimated)} \pm K \frac{\Delta Error}{\Delta t}$$

So :

$$percentage\ of\ the\ error = \pm 100 \frac{Iodine\ concentration_{(real)} - Iodine\ concentration_{(estimated)}}{Iodine\ concentration_{(estimated)}} =$$

$$\pm 100\ K \frac{\frac{\Delta Error}{\Delta t}}{Iodine\ concntration_{(estimated)}}$$

This percentage is low just after filter changing and then gradually increases. Usually after one week the error is not acceptable and we need to change the filter.

OTHER FEATURES OF THE SYSTEM

The New system has been installed in the reactor and is currently running in parallel to the old system. Some of the other features of the system consist of the following items:

- Display of the average of the Iodine concentration for each filter in a graph and also calculate the running average after each filter change. This graph is different from the main graph that shows the Iodine concentration in each minute. We also have an indicator that contains the more accurate Iodine concentration in each second.

- A manual log entry in case of any abnormal situation in the reactor that can affect the amount of Iodine. In addition an automatic event entry reports any error in the system such as any unreasonable result for Iodine concentration or bad connection between the detector and LabJack, LabJack and the PC, or LabJack and the alarm system. Note that the green light of the signal tower is on just when we are in the normal situation after data gathering (for initialization or after filter changing). So if it is off we can see what the problem with the system is by looking at this event entry. The contents of these two entries along with the time of occurrence are saved in a file for each day. This file is different from the file that is saving all information of each day with an adjustable time span.

- In the event of an alarm, the plant crew can be informed by auto-sending of email messages.

- The operator is able to suspend the audio alarm system from the display after acknowledgment. But in the case of an ongoing alarm situation, it automatically reactivates after 10 minutes.

- The code is password protected for one of the control pages. Only the operator has access to this page. Almost everything in the code is adjustable and the operator can change values at this page. This password protected area is separate from the two other pages, i.e. main and set up page that are designed to be as simple and less crowded as possible for the user.

CONCLUSIONS

Iodine-125 is produced from Xe-124 at McMaster Nuclear Reactor (MNR) for medical applications. Excessive existence of this isotope in the air of the reactor site can be hazardous especially for the staff who are continuously working at the site. Therefore there is a critical need to monitor the concentration of iodine released to the air. In the old iodine monitoring system available at MNR, there have been several technical and practical problems. Consequently a new monitoring system was designed to overcome the previous problems and to provide with further facilities for the staff. The system is developed in the LabVIEW platform and is easily maintainable. The external data acquisition board LabJack is used to transfer the data to the PC. Briefly, by using radiation monitoring techniques and statistical methods, a computerized embedded system is designed to keep the MNR a safe place for operators and visitors.

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