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MONITORING SYSTEM OF MERCURY TARGET FAILURE USING RADIOACTIVITY MEASUREMENT

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ABSTRACT

The monitoring system for the mercury target failure using radioactivity measurement has been developed at JSNS, and the test operation was started in October 2009. As results of the test operation, the radioactive products generated from the stainless steel of the mercury target vessel were observed in the sampling gas from the intermediate layer of the mercury target, and it was also observed that intensities of the radioactivity showed a correlation with the proton beam intensity. In order to detect the target failure as rapid as possible, we selected two kinds of nuclei, ^{88}Kr and ^{122}Xe, that are most sensitive for the failure detection. By sensitivity analysis, we showed that the failure of the target vessel could be detected at a very early stage of the target failure by using our system.

1. Introduction

A mercury target vessel has serious damage due to cavitation induced by pressure wave for pulsed proton beams. It has been reported that a lot of pits and cracks through thick stainless steel of the mercury target vessel were observed at SNS of ORNL. [1]

The mercury target vessel of JSNS [2] has the double-walled structure, which has an intermediate helium-layer between water-cooled and mercury layers. Therefore, the mercury including radioactive products cannot leak from the outer shell even if the inner shell has through-holes due to the damage. In order to detect mercury leak from the inner shell, we installed resistance-type monitors in the intermediate layer. We expect that considerable leak from the inner shell can be detected with the resistance sensors. In addition, we have developed a leak-monitoring system using radioactivity measurement in order to achieve more rapid leak-detection and create redundancy of the leak monitoring. We started the test operation in October 2009, and the data to validate the system performance has been acquired. In this paper, we will report the summary of the test results and our studies on the followings:

- How to detect the failure using this system as rapidly as possible
- Analysis of sensitivity for the failure detection

2. Concept of the Detection System

The monitoring system consists of a circulation loop and a gamma-ray detection system. A conceptual drawing the system is shown in Fig. 1. Piping for sampling the helium gas was installed in the intermediate layer of the mercury target. The piping length from the target and a gamma-ray detector is about 80 meters. A pump unit, which consists of a circulation pump, pressure gauge and flow monitor as shown in Fig. 2, was set at the "water-and-gas analysis room" in the basement. A diaphragm-type pump is adopted to avoid leakage of helium gas. A high-purity germanium detector was set in front of the measurement port. The detector and the measurement port are covered with lead bricks for shielding. The helium gas in the intermediate layer is pressurized to 0.2 MPa in absolute. In the operation, the helium gas is circulated with the flow speed of 10 L/min so that all gas in the system is fully circulated less than in one minute. (The total volume of helium gas in the helium layer and pipes are about 10 L.)

Using this system, we expected that failure of the inner vessel would be detectable by a process as follows:

- Radioactive products are released to the helium layer in the mercury target,
- Those are transferred via a sampling line to the measurement port,
- Gamma rays emitted from the radioactive products are detected with the gamma-ray detector.

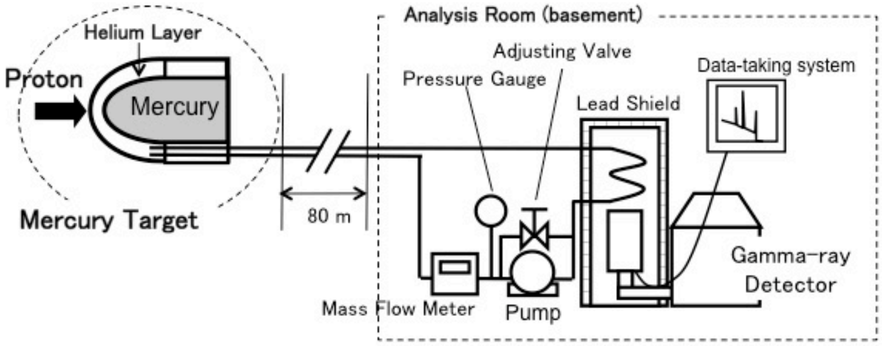


Fig. 1 Conceptual drowning of the system for monitoring mercury-target failure

Fig. 2 Photograph of the pump unit (left) and the full-set of the monitoring system including a gamma-ray detector, data-taking system and lead shield (right).

3. Test results

Operation test of the monitoring system was started in October 2009. Gamma-ray energy spectra obtained at off- and on-beam are shown in Fig. 3 and 4, respectively. No gamma-peaks were observed before the beam operation except those of natural background as shown in Fig. 3. After beginning the beam operation, considerable gamma-peaks appeared in energy spectrum shown in Fig. 4. We tried to find out the origin of the radioactive products observed in the gamma spectrum. Our questions were

“Were those products produced from the mercury in the inner vessel” and “Dose this mean the target failure?” We could say “No” definitely. As results of peak assignment, we found that all measured products in the on-beam spectrum originated from stainless steel of the target vessel because the all products were light nuclei with mass numbers less than 59, and because we did not observed heavy products such as Kr, Xe, Hg, etc. in the spectrum. In addition, we could clearly see the correlation between a gamma-intensity and the proton beam intensity. In Fig. 5, the variation of 511-keV gamma intensity was plotted with the proton beam intensity during the beam operation in October 2009. The graph shows that the system works just like a “proton beam monitor” with slow response.

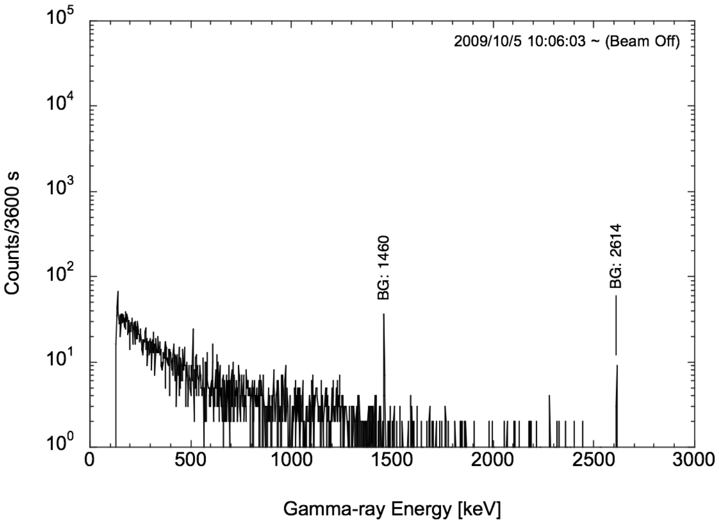


Fig. 3 A gamma-ray spectrum before proton-beam operation. The gamma-energy is shown for each peak. “BG” means gamma peaks of natural background.

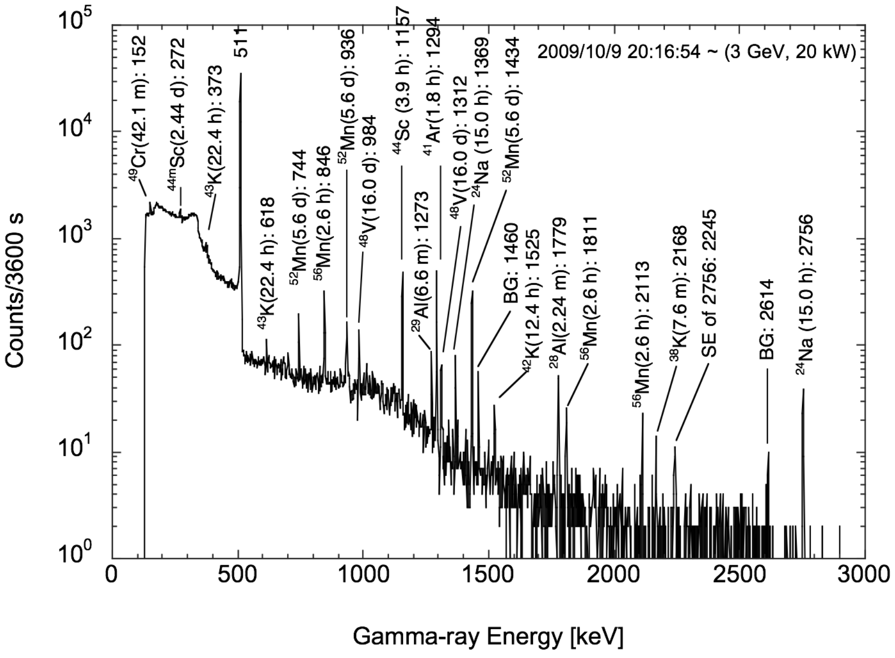


Fig. 4 A gamma-ray spectrum during the proton beam operation with the intensity of 20 kW. A nuclide, a half-life and a gamma-energy are shown for each peak. “SE” and “DE” mean single- and double-escape peaks, respectively. “BG” means a natural background.

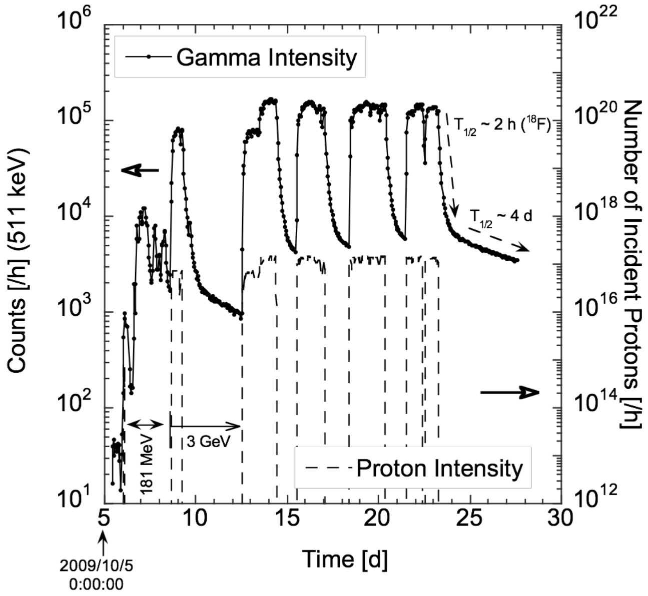


Fig. 5 Correlation between the gamma intensity of 511 keV and the proton-beam intensity. The gamma peak of 511 keV corresponds to a radioactivity of ^{18}F since the gamma counts deceased with a half-life of 2 hours after the termination of proton-beam operation. The operation started with 181-MeV protons without acceleration of 3-GeV synchrotron. During the beam operation with 181 MeV, the data of proton-beam intensities were not acquired correctly, since the proton beam monitors were not adjusted for 181 MeV.

4. Which Nuclide Should We Focus for the Rapid Detection?

In order to detect target failure as rapid as possible, we should focus on the detection of high-sensitive isotopes in the gamma-ray spectrum. We adopted the following three criteria for the isotope selection:

(i) Heavy nuclei with mass numbers more than ~60
(ii) Gas products
(iii) Nuclei emitting high-energy gamma rays with E_γ>2 MeV (E_γ: Gamma-ray Energy)

The criterion (i) means that, since light nuclei generated from stainless steel should be regarded as "background", heavy nuclei should be focused for the failure detection. The criterion (ii) was adopted because gas products have relatively higher efficiencies for transportation from the target vessel to the sampling port via the sampling line. Considering (i) and (ii), Kr and Xe isotopes are preferable for the failure detection. In addition, according to the criterion (iii), radioactive isotopes emitting high-energy gammas are more preferable, because background level is relatively lower in the high-energy region.

On the basis of these three criteria, we selected the following two isotopes for the failure detection: ^{88}Kr and ^{121}Xe. The decay data of the isotopes are shown in Table I. [3] A detection image of ^{88}Kr in a gamma-ray spectrum is shown in Fig. 6. In case of target-failure, it can be expected that a lot of gamma peaks coming from the radioactive products in mercury will appear simultaneously.

In order to monitor the gamma peaks of ^{88}Kr and ^{121}Xe continuously, we designed the monitoring display shown in Fig. 7. In the display, trends of the gamma intensities of 2196 and 2393 keV for ^{88}Kr and 2643 keV for ^{121}Xe are shown with those of proton-sensitive gammas of 511 keV for ^{18}F and 1294 keV for ^{41}Ar for checking the system performance. In addition, the total gamma counts at high energies region of E_γ> 2 MeV are shown in the graph because the counting rates in the high energy region is more sensitive for the failure. The data in the trend graph is updated every hour. The graph is always displayed at the control room of Materials and Life Science Experimental Facility (MLF) of J-PARC during the beam operation.

Table I Decay data of ^{88}Kr and ^{121}Xe

Nuclide	Mode	Half-life	Major gamma rays: Energy [keV] (Intensity per decay in %) [a]
^{88}Kr	β^-	2.84 h	196.3(25.98), <u>2195.8(13.18)</u>, <u>2392.1(34.6)</u>
^{121}Xe	ε+ β^+	40.1 m	132.8(10.9), 252.7(13), 445.2(7.7), 310.5(5.4), <u>2643.4(2.2)</u>

[a] Gammas with underlines were adopted for failure detection.

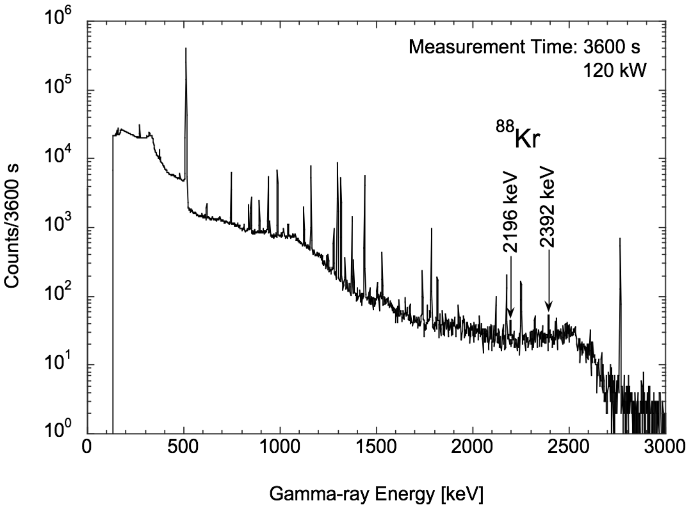
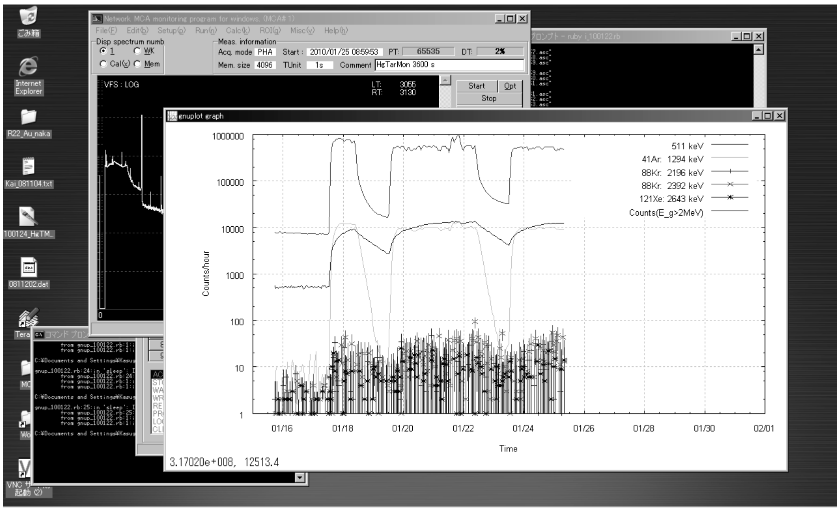


Fig. 6 An image of failure detection of the mercury target vessel. In case of target-failure, gamma-peaks for other nuclei with A>60 (A: mass number) will be appearing simultaneously.


Network MCA monitoring program for windows. (MCA# 1)

Disp spectrum numb: ● 1 ○ WK ○ Cal(x) ○ Mem

Meas. information
Acq. mode PHA
Start : 2010/01/25 08:59:53
PT: 65535
DT: 2%
Mem. size 4096
TUnit 1s
Comment HgTarMon 3600 s

VFS : LOG
LT: 3055
RT: 3130

3.17020e+008, 12513.4

Fig. 7 Display designed for monitoring the failure at the control room of Materials & life science facility of J-PARC. The data in the graph are updated every hour.

The trends of gamma intensities between January 17th and February 7th in 2010 are shown in Fig. 8. The proton beam operation was done at 120 kW. The gamma counts for the failure detection of 2196, 2392 and 2643 keV were all less than 100 counts. By considering the fluctuations of the background levels at $E_\gamma > 2$ MeV, more than 100 counts are required for "real peak" detection that means "target-failure". The data show that our target still kept healthy during the operation.

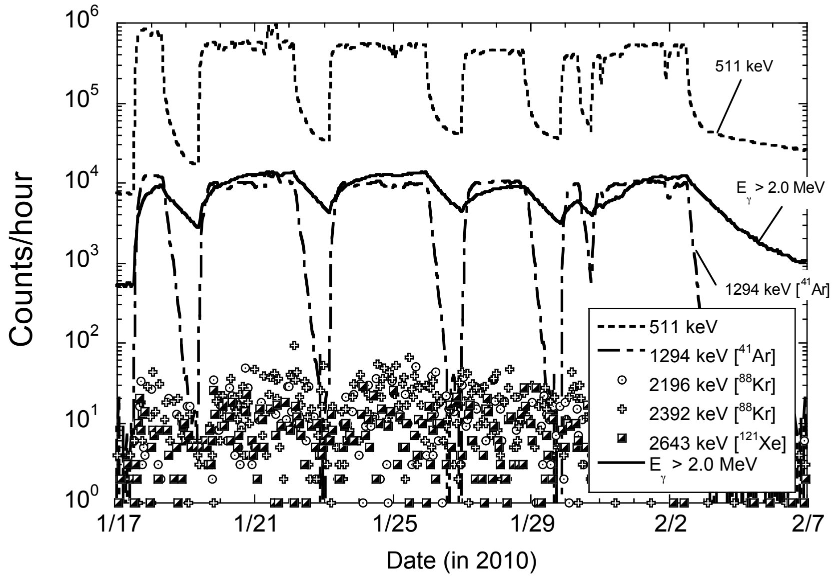


Fig. 8 Trends of the gamma intensities between January 17th and February 7th in 2010. The gamma data of 511 keV and 1294 keV, which correlate with the proton beam intensity, are shown for checking the system performance. It can be expected that the gamma counts of 2196 keV and 2392 keV for ^{88}Kr and those of 2643 keV for ^{121}Xe will be increased significantly in case of the target failure.

4. Sensitivity Analysis

How much radioactivity needs to be leaked from the inner vessel to the helium layer to detect the target failure? For getting the answer, sensitivity analysis was carried out for 2392 keV gammas of ^{88}Kr under the proton-beam operation with 120 kW. In order to recognize a "real peak" at $E_\gamma > 2$ MeV, more than 100 counts/hour is needed. For obtaining more than 100 counts/hour of 2393-keV gamma peak of ^{88}Kr, radioactivity concentration of ^{88}Kr in the sampling gas needs to be more than 1 Bq/cm^3 by taking into account the volume of the sampling port and the gamma-ray detection efficiency. The total volume of the helium gas in both the helium layer and sampling pipes is about 1×10^4 cm^3. Thus ^{88}Kr-gas concentration of 1 Bq/cm^3 corresponds to the leakage of 1×10^4 Bq (= 1 Bq/cc × 1×10^4 cm^3) to the helium layer. The total ^{88}Kr activity produced in the mercury is about 2×10^{10} Bq for 120 kW operation in our estimation using DCHAIN-SP code [4]. This means that the small leak-fraction of 5×10^{-7} [$=1\times10^4$ Bq/2×10^{10} Bq] can be detected with our system. Gas products can escape through a tiny pinhole, even though liquid mercury cannot be released through it. Therefore we suppose that detection of the target failure at very early stage can be realized using our monitoring system.

5. Summary

Test operation for the monitoring system of mercury target failure using radioactivity measurement was started in October 2009. In the gamma-ray spectra obtained in the test operation, radioactive products generated from stainless steel of the mercury target vessel were detected, and we observed that the gamma-ray intensities were correlated with the proton beam intensities. For rapid detection of the target-vessel failure, the gamma rays of ^{88}Kr and ^{122}Xe were focused for the detection. By considering the sensitivity analysis, it can be expect that the failure of the target vessel can be detected at a very early stage of the target failure.

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7. References

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