Radiation safety issues regarding X-ray emittable devices below 10 kV applied voltage

Ichiro Yamaguchi [1, *], Koji Ono [2], and Naoki Kunugita [3]

[1]*National Institute of Public Health, Wako, Saitama, 351-0197 Japan*
[2] *Tokyo Healthcare University, Meguro, Tokyo, 152-8558 Japan*
[2] *University of Occupational and Environmental Health, Kita-Kyushu, Fukuoka, 807-8556 Japan*
*Corresponding author's e-mail: yamaguchi.i.aa@niph.go.jp

Abstract. The exemption criteria for radiation generators or an electronic tube is (i) They do not in normal operating conditions cause an ambient dose equivalent rate or a directional dose equivalent rate, as appropriate, exceeding 1 μSv/h at a distance of 0.1 m from any accessible surface of the equipment, or (ii) The maximum energy of the radiation generated is no greater than 5 keV, according to IAEA GSR Part 3 and RSG1.7. In Japan, apart from the national comprehensive regulations, the Industrial Safety and Health Act covers X-ray equipment and defines the specific X-ray equipment required to use irradiation tubes and filters and limit the irradiation field adequately. However, exemption for X-ray equipment has yet to be implemented in Japan as of Dec. 2020. Therefore, there are differences in radiation safety protocols adopted by Japanese facilities for X-ray emittable devices used in applications such as X-ray fluorescence analysis and electronic microscopes. For the distribution of the newly developed basis weight gauge with a sub-5 kV X-ray generator, implementation of the international exemption level in Japanese regulations is expected. Although it is not explicitly mentioned in GSR Part 3 or RSG1.7, the recommended reference depths would be 10 mm for the operational quantity ambient dose equivalent and 0.07 mm for directional dose equivalent, since for low energy photons the reference depths should be 3 mm and 0.07 mm respectively, as evaluated according to Para 2.34 to 2.38 of GSG7. However, the exemption level was derived by using a scenario to keep each effective dose below 1 mSv a year, without mentioning an equivalent dose to the lens of the eye of 15 mSv nor an equivalent dose to the skin of 50 mSv in a year. For this reason, it was thought that the exemption level indicated by IAEA for X-ray equipment should be implemented in Japan and the exemption criteria regarding depth for ambient or directional dose equivalent rates should be clearly defined depending on photon energy. Furthermore, dose constraints for teachers and junior high school students should be established through stakeholder involvement.

KEYWORDS: Exemption, X-ray emittable devices, dose constraints for students

1 INTRODUCTION

The exemption criteria for radiation generators or an electronic tube is (i) They do not in normal operating conditions cause an ambient dose equivalent rate or a directional dose equivalent rate, as appropriate, exceeding 1 μSv/h at a distance of 0.1 m from any accessible surface of the equipment, or (ii) The maximum energy of the radiation generated is no greater than 5 keV, according to the International Atomic Energy Agency's (IAEA) GSR Part 3 [1] and RSG1.7 [2].

In Japan, apart from the national comprehensive regulations, the Industrial Safety and Health Act covers X-ray equipment and defines the specific X-ray equipment required to use irradiation tubes and filters and limit the irradiation field adequately. However, exemption for X-ray equipment has yet to be implemented in Japan as of Dec. 2020. Therefore, there are differences in radiation safety protocols adopted by Japanese facilities for X-ray emittable devices used in applications such as X-ray fluorescence analysis and electronic microscopes. For the distribution of the newly developed basis weight gauge with a sub-5 kV X-ray generator, implementation of the international exemption level in Japanese regulations is expected. Furthermore, Crookes tubes including old types are popular in junior high schools and updated government course guidelines mentioning Crookes tubes will be fully implemented in 2021 so that teachers have access to radiation safety information, since it is difficult to measure low energy and pulsed X-rays in a junior high school [3]. Therefore, a unique project for providing accurate radiation dose measurements of Crookes tubes in schools is underway in Japan.

The purpose of this study is to propose a method to solve radiation safety issues regarding X-ray emittable devices below a 10 kV applied voltage.

2 METHODS

We performed a comparison of Japanese legislation and IAE**A** documents and attempted to organize issues based this comparison.

3 RESULTS

3.1 Regulatory Exemption for X-ray Equipment

The IAEA has established an exemption level for X-ray machines. However, Japanese laws do not specify exemption levels for X-ray systems except for medical X-ray equipment.

3.1.1 Exemption levels indicated in IAEA's BSS for regulations of X-ray equipment

IAEA GSR Part 3 defines exemption levels for X-ray equipment with an annual dose of less than 10 μSv [1]. IAEA also uses the dose equivalent rate as an indicator of the exemption level for X-ray devices, but it does not specify the type of dose equivalent and the relationship between the exemption level and the 70 μm or 3 mm dose equivalent is not clear. Therefore, it is considered necessary to define what should be the exemption level. Here, the 70 μm and 3 mm dose equivalents are allowed to be up to 50 and 15 times higher than the 1 cm dose equivalent at public dose limits, respectively.

On the other hand, since the IAEA exemption level is supposed to be applied to sources not exceeding 10 μSv, the exemption level is considered to be applied to sources not exceeding 0.5 mSv for the equivalent dose to skin and 0.15 mSv for the equivalent dose to the lens of the eye in comparison with the public dose limit.

3.2 Public dose limits considering low energy photons

While IAEA has defined public dose limits including the lens of the eye and skin adding the effective dose, Japanese legislation does not explicitly set public dose limits.

3.3 Dose constraints applied to the use of an X-ray generator in a science class

3.3.1 Setting dose constraints

While the IAEA has defined dose constraints, Japanese law has not introduced the concept of dose-bound values.

3.4 Radiation safety and education

3.4.1 The basic radiation safety concept from Ministry of Education, Culture, Sports, Science and Technology (MEXT) in Japan

As the debate over nuclear power has become a social issue, neutral statements about nuclear power are adopted, such as “Radiation and nuclear energy are not used only to generate electricity. They are also used for applications such as semi-conductor manufacture and medical irradiation. Ensuring safety is the first premise of research, development, and use of radiation and nuclear energy. Based on law, MEXT enforces strict safety regulations on the use of research and test reactors, radioactive isotopes, and so on through inspections and examinations of facility designs. It also implements measures against nuclear accidents and environmental radiation [4].” Any technology will also present potential disadvantages to society, hence safety and technology assessments are essential.

For the first time in nearly 30 years, "radiation" was introduced to middle school science in 2012 due to full implementation of updated curriculum guidelines.

Newly updated curriculum guidelines that will be implemented from 2021 will further enhance the education of radiation and recommends Crookes tubes to be used to study electrons, stating "In addition to mentioning X-rays in relation to vacuum discharges, it should also be mentioned that radiation with the same properties as X-rays such as transmission exists and is used in medicine and manufacturing industries”.

3.5 Physical experiments with Crookes tubes in science classes

3.5.1 Radiation safety considerations

Physical experiments with Crookes tubes can be conducted safely in middle and high schools through careful consideration. Technical radiation safety issues regarding these science classes can be solved through consultation with nearby professional organizations. The Crookes tube radiation safety project is currently underway in Japan.

3.5.2 Maximum dose rates

It has been confirmed that power output can vary greatly depending on the treatment of devices. For example, a device with a 70 μm dose equivalent of more than 33 mSv has been found for a 10-minute irradiation at a distance of 15 cm from the Crookes tube. Extending the distance between the discharge poles in this device increases the dose even more, and aggressive intervention is required.

However, even in such cases, it has been confirmed that the dose can be reduced dramatically if the device is properly set up.

3.6 Accidents regarding low energy photon emission devices

3.6.1 X-ray diffractometer exposure accident

A case study of abnormal radiation exposure to diffractive X-ray equipment workers discovered from personal dose monitoring reported an automatic recording type X-ray diffractometer with a tube voltage of 30 kV and a tube current of 10 mA. The cause of the accident was found to be a downward-facing window shutter that was open (forgotten to be closed when replacing the X-ray tube) from which the X-rays escaped.

3.6.2 Example of exposure due to equipment disassembly

On April 28, 1994, a commercial technician disassembled the shutter of a research X-ray diffractometer (RIXT2500, power: 18 kW, target: Cu, applied voltage: 50 kV, current: 200 mA). At the time, he felt a warm sensation at the base of his right fourth and fifth fingers, which alerted him to the fact that X-rays were being emitted. He immediately shutdown the power supply, and with no symptoms went home without any treatment. Fourteen days after the exposure, part of the skin layer turned white and continued to worsen. The estimated dose absorbed by the skin layer was estimated to be 100–200 Gy for a three-minute right hand palmar exposure.

3.7 Regulatory developments in each member country

Although not systematic, these are examples that were mentioned regarding the Crookes tube.

3.7.1 Canada

Radiation safety manuals for science classes in a high school have been developed together with recommended safety procedures for the selection and use of demonstration-type gas discharge devices in schools [5].

3.7.2 Finland

Rules are in accordance with GSR Part 3 [6]. According to "Use of ionizing radiation in the teaching of physics and chemistry" established by STUK, "Cold cathode type discharge tubes are liable to generate X-radiation. This X-radiation causes no hazard if the discharge tube voltage does not exceed 5,000 volts. No adjustable voltage source with a maximum voltage exceeding 5 kV may therefore be used with a discharge tube unless there is also a voltmeter or some other means of ensuring that the voltage does not exceed 5 kV."

3.7.3 Ireland

Rules are also in accordance with GSR Part 3 [7]. Educational use of equipment that is not exempt is restricted (Table 1).

Table 1 Safety in School Science in Ireland

SAFETY IN SCHOOL SCIENCE
• Schools that have equipment, such as discharge tubes and high voltage rectifier tubes that are capable of emitting X-rays should take note of the following points: • Equipment, such as discharge tubes, that are not designed for but are capable of emitting X-rays (usually at voltages in excess of 5 kV) must be of a type designed for educational use and must be acquired only from a supplier licensed by the RPII to distribute such equipment. Schools should not acquire or accept donations, however well intended, of equipment designed to generate or capable of emitting X-rays. Wherever possible, hot cathode tubes should be used as discharge tubes. • Students may only operate equipment capable of emitting X-rays while under the supervision of the science teacher. • Equipment capable of emitting X-rays should only be operated for short periods. • The beam of radiation from equipment capable of emitting X-rays must never be pointed towards students or teachers. • Equipment capable of emitting X-rays must be shielded with lead sheeting. A lead thickness of about 2 mm will provide more than adequate shielding for this type of equipment. • Equipment capable of emitting X-rays must be electrically isolated when not in use and placed in secure storage. • Damaged or misplaced equipment capable of emitting X-rays must be reported immediately to the teacher responsible for radiation safety. • Disused equipment capable of emitting X-rays must be rendered inoperable and may then be disposed of as ordinary waste equipment. • Records must be kept of each item of equipment capable of emitting ionising radiation that is held by a school. These records must include the date of acquisition, the name and address of the supplier, the equipment type and identification number. • A record must be kept of the usage of each item of equipment capable of emitting ionising radiation. This record should include the date and time that the equipment was removed from its storage location, the time over which it was used and confirmation that the equipment was immediately returned to storage at the end of its use. The science teacher involved must sign each entry in the record.

3.7.4 UK

Rules are also in accordance with GSR Part 3. Educational use of equipment that is not exempt is prohibited. An example of one administrative division is shown. According to "Work with ionising radiation: Ionising Radiations Regulations 2017", dose constraints for members of the public are set as follows: [8]

- "Where employers anticipate that any work activity or facility is likely to expose members of the public to direct radiation or contamination, they should apply a dose constraint.
- It is recommended that the constraint on optimisation for a single new source should not exceed 0.3 mSv a year.
- Employers should take this recommendation into account in establishing a dose constraint for members of the public.
- The constraint should be applied to estimates of dose for representative individuals likely to receive the highest average dose from the work."

3.8 Comments to IAEA DS470

3.8.1 Background

IAEA has also proposed a regulatory approach with regard to radiation safety. In order to ensure radiation safety in the use of radiation sources in education and research, the IAEA's Coordinating Committee approved a document development brief in September 2012, which is expected to be submitted to the respective Safety Standards Committees (assumed to be primarily the Radiation Safety Standards Committee (RASSC)) for approval in 2020, albeit later than originally planned due to the revision work on GSR part 3. The draft document DS470 "Radiation Safety in the Use of Sources in Education and Research" was presented in September 2009 and discussed at RASSC 49 in November 2020, and we compared RASSC 49 with the realities of the Japanese educational environment and the current state of regulation in Japan and present the issues for regulatory development.

3.8.2 Overview of comments

Those who commented on the scope of the RASSC were Germany, Japan, Pakistan, the United Arab Emirates, the United Kingdom, and the United States. Germany commented on the diversity of X-ray devices, and this was dealt with in conjunction with the comments with Japan. The description of the Crookes tube, which is mentioned in the revised guidelines for teaching in Japan (science for the second grade of junior high school) to be implemented next year, was enriched in Annex I (I-3), and the results of research in Japan were also discussed.

4 DISCUSSIONS

4.1 Regulatory Exemption for X-ray Equipment

It is considered that Japan should introduce the IAEA exemption level for X-ray systems. Due to the lack of clear legal regulations for devices that generate secondary radiation, the application of laws and regulations to electron microscopes and other devices in universities varies from region to region, and there have been requests for the development of regulations.The regulatory department on occupational safety had interpreted the current regulations as exempting items that generate X-rays as a secondary source, and wanted to watch the discussion on exemption from the regulations [9].

4.2 Public dose limits considering low energy photons

It is thought that Japan should also introduce explicit public dose limits in its legislation. In addition, the use of public dose limits for the lens of the eye and skin is also considered necessary because low energy radiation results in localized exposure.

4.3 Dose constraints applied to the use of an X-ray generator in a science class

4.3.1 Setting dose constraints

It is thought that the dose constraints should be introduced in Japan as well.

Specific dose constraints need to be set considering the opinions of teachers and parents. The pros and cons of introducing coverage should also be examined by teachers, based on cost-benefit analysis and other factors. Experts in various fields need to help with this decision.

4.3.2 Collaborative work for setting dose constraints

Dealing with risk is also a social challenge. Therefore, the contributions of civic organizations should be recognized as well. Collaborative work between local civic organizations and teachers has practical benefits, and such efforts could also be used as a subject for risk education. Japan and Eastern European member states are learning various lessons in responding to nuclear disasters and other risks. Moreover, difficulties in responding to disasters involving environmental pollution have been experienced by various member states. Collaborative efforts could also prove useful in solving this challenge.

4.4 The basic radiation safety concept of MEXT, Japan

After the nuclear accident in Fukushima, radiation education in junior high school science was made more substantial, but it is still an issue to be addressed in the field. The fact that the nuclear energy is a social issue also complicates the issue. The implementation of radiation safety management in educational settings has become an issue in preparation for the implementation of the revised Courses of Study in Japan.

4.5 Physical experiments with Crookes tubes in science classes

4.5.1 Radiation safety considerations

As low energy photons are emitted in pulsed form, it is necessary to obtain the assistance of a professional organization to determine the amount of radiation in educational settings, and this is the reason why the academic community is working on this project.

4.5.2 Maximum dose rates

Even in very rare cases, there are devices that exceed the annual dose limit for occupational workers after about 6 hours of exposure, so countermeasures are necessary to "prevent excessive exposure due to improper use" of devices that fall below the regulatory exemption level under proper conditions of use.

The output of the device depends on the condition settings, and even for a very common device, the maximum output setting is around 14 mSv/h as Hp(0.07) at 15cm from the Crookes tube, making it necessary to ensure that teachers and students are safe by employing easy screening techniques to avoid burdening the faculty.

4.5.3 Manufacturer initiatives

Manufacturers voluntarily conduct radiation safety checks on their educational products. If we establish a new international standard for the sale of hardware as a general consumer product for educational purpose, it should be helpful to teachers in the future.

In addition, because some devices with high output forcibly increase the discharge voltage, there is a need to standardize the systematic maintenance of devices, as well as the development of a simple voltage measurement method to verify whether the devices can be used safely.

In any case, it is possible to regulate the sale of devices that can exceed 10 μSv under normal use by taking the necessary measures to educate distributors as stated in GSR Part 3.

4.5.4 Optimization of radiation safety from an educational perspective

It is possible to lower the dose further by inserting shielding or resistors to ensure the safety of educational materials, but it is necessary to consider the extent this can be reasonably achieved, taking into account the opinions of teachers and parents.

4.6 Accidents regarding low energy photon emission devices

Cases of radiation damage due to low energy X-rays have been reported, but these cases were caused by deviations from safe handling procedures. In order to ensure safety, procedures must be established and followed.

4.7 Regulatory developments in each member country

Regulations had been developed in accordance with the provisions of the documents of international organizations, and guidelines had been developed to ensure radiation safety in the field. Due to the limited resources available, it is necessary to identify equipment with potential risks in order to ensure the effectiveness of radiation safety assurance.

4.8 Comments to IAEA DS470

It is important to disseminate guidelines for the safe use of Crookes tubes with high educational effects, taking into account the opinions of the teachers' union, PTA, and other stakeholders. In addition, among the comments from Japan, the sharing of information on good practices among the member countries should be considered at RASSC 49, based on the opinions of the member countries, such as the handling of nursing students who deal with patients that have undergone nuclear medicine examinations, which is also an issue for Occupational Radiation Protection Appraisal Service (ORPAS), and practical radiation protection of co-medicals in medical institutions, which is handled by radiologists at medical institutions in Japan. This was presented by the Secretariat as a matter of concern. Pakistan made reference to the ethical aspects of the project. The UK's comments were also based on the actual situation in the UK.

5 CONCLUSION

Japan's comments on DS470 are reflected in the draft amendments on the treatment of Crookes tubes and the establishment of national exemption levels in Japan is a current issue. X-rays emitted from the Crookes tube can be used as highly effective educational content, however sufficient safety must be ensured. It is advised to regulate the dose that teachers receive from repeated use in a year considering that exemption levels other than using the effective dose should be set for low energy photon exposure. A provision for exemption from regulation of radiation generators in GSR Part 3 considering low energy photons and clarification regarding induction limits of directional doses are required.

6 ACKNOWLEDGEMENTS

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