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Radiation Safety Federation, the 68th seminar of radiation protection

- IAEA Role in Establishment of Radiation Safety Standards and Guidance -

A study of Crookes tube used in the education field

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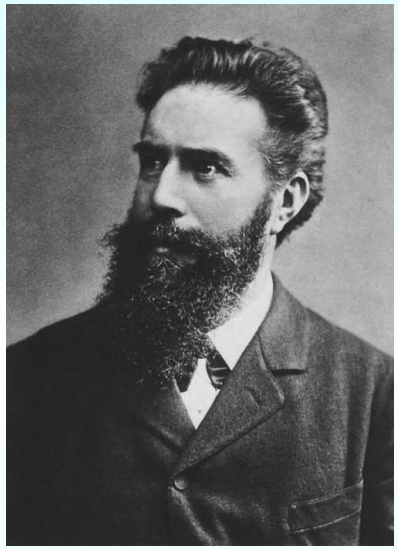
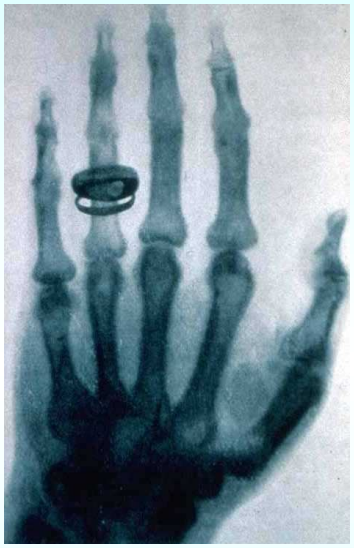
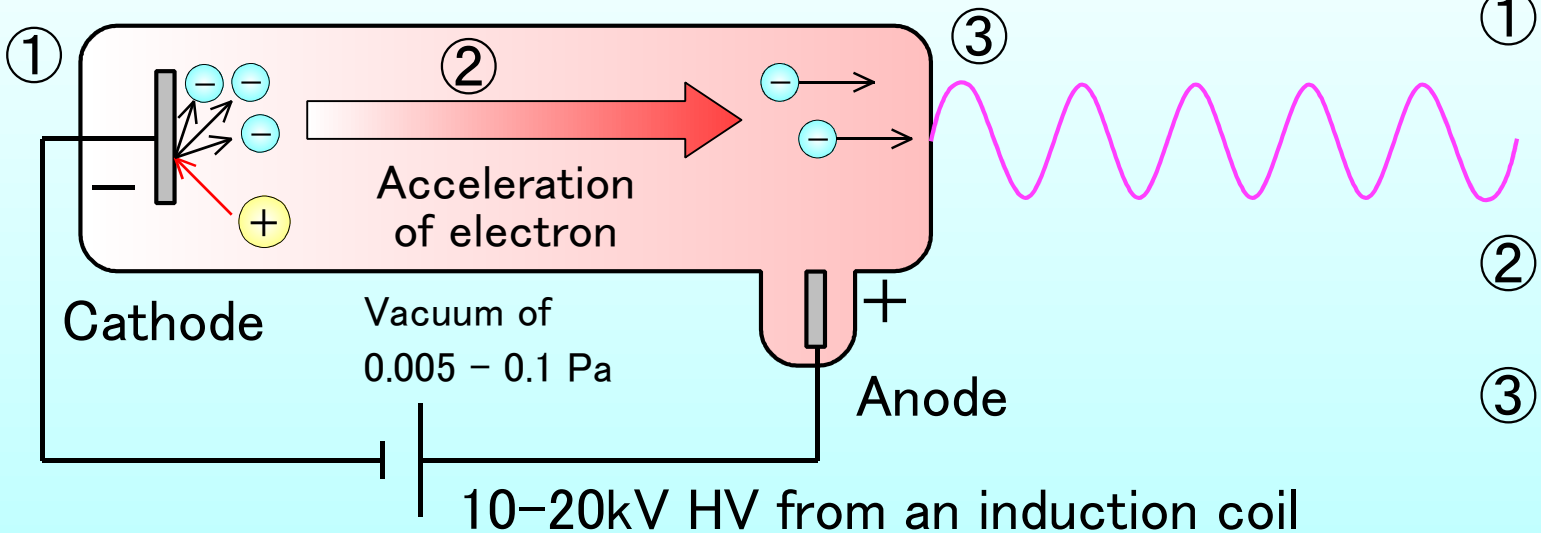
What is Crookes tube?

Wilhelm Konrad Rontgen
1895, Found the X-ray during the experiment of discharge tube
1901, Got the first Nobel prize in physics



William Crookes





① At the cold cathode, cation in air is accelerated and knock out secondary electrons.

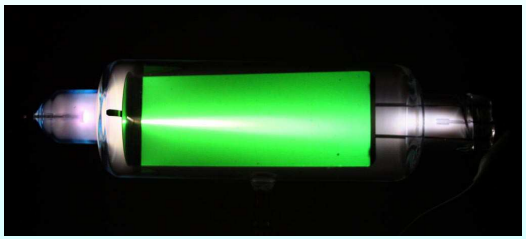
② These electrons are accele –rated as the applied HV.

③ Accelerated electrons hit glass wall and radiate bremsstrahlung X-rays.

How to Establish Safty Management for Crookes tube?

Crookes tube has been used in junior-high science classes in Japan, and the primary purpose is to teach the characteristics of electrons and current, not for radiological education. Therefore, some teachers are not recognizing the radiation of X-ray from Crookes tube, and most of them have no information of the dose. However, it is possible to expose high dose of X-ray to students using a Crookes tube, where Hp(0.07) reaches 200mSv/h at a distance of 15cm.

Some discharge tube that use hot cathode is operated with only several 100V, and even with cold cathode, some equipment can be operated at about 5kV. With this low voltage, radiated X-ray is shielded completely by the glass wall.



A Crookes tube operated by 5kV (Horizon Co. VT-7010)

5kV CW high voltage unit driven by 9V battery

Junior-high school in Japan have quite limited budget!

Basic Plan

By using low voltage type equipment, teachers never required to consider the radiation and students can observe electron beam very safely.

The problem is resolved completely!

Advanced Plan

1) Cannot replace legacy devices with economical reason
2) Advenced education program that utilize X-rays radiated from Crookes tube

Anyway, radiation safty guideline to limit X-rays dose is required.

ICRP Basic Radiation Safety Criteria

Justification:

No practice shall be adopted unless its introduction produces a net positive benefit.

・Is the experiment required? Is it accepted to show with photo or video?

→The experiment using Crookes tube gives quite strong impact to students and have excellent educational effects.

Optimization:

All exposure shall be kept as low as reasonably achievable (**ALARA** concept), economic and social factors being taken into account.

・Low voltage operated equipments can make the exposure to zero and it is firstly recommended. However, economic factor make it difficult to replace all equipments in all schools. Therefore, optimization on operation conditions (applied voltage, current, distance, time and shielding) is required.

Dose limitation:

The dose equivalent to individuals shall not exceed the limits recommended for the appropriate circumstances by the Commition.

・In Japan, dose limit for general public proposed by ICRP Pub1990/2007 is not taken into the domestic low. Now we survey international regulations and the actual control conditions to settle the reasonable management target dose.

Problems on management of X-rays from Crookes tube

Dose Constraint for Education Field is not Discussed well

Dose limit for general public have been proposed by ICRP Pub1990/2007 as 1mSv/y, but it is for all additional exposure. ICRP Pub 36 is the only instance.

Definition of X-ray Device is not Clear

In Japanese domestic low, `X-ray device' is not defined strictly. There is no exemption level that gives a confusion to safety management of X-rays in many fields.

Difficult Estimation of Effective Dose

For 20keV X-rays, the half value layer is about 1cm in human body. Absorbed dose to tissues in body depends on its depth from the surface. The transmittance is changed with energy of X-ray drastically around this energy range and the X-rays have broad spectrum.

Further more, dose distribution in horizontal plane is not uniform, so aligned and expanded radiation field is not applied. Therefore, 1cm dose equivalent does not give an approximation of effective dose.

Problems on Estimation of X-rays from Crookes Tube

Low Energy X-Rays (around 20keV)

Not only conventional survey meters for public use, but also reliable NaI survey meters for general radiological management are useless for low energy X-rays from Crookes tube.
(below 50keV pulse is ignored by conventioal NaI surver meters)

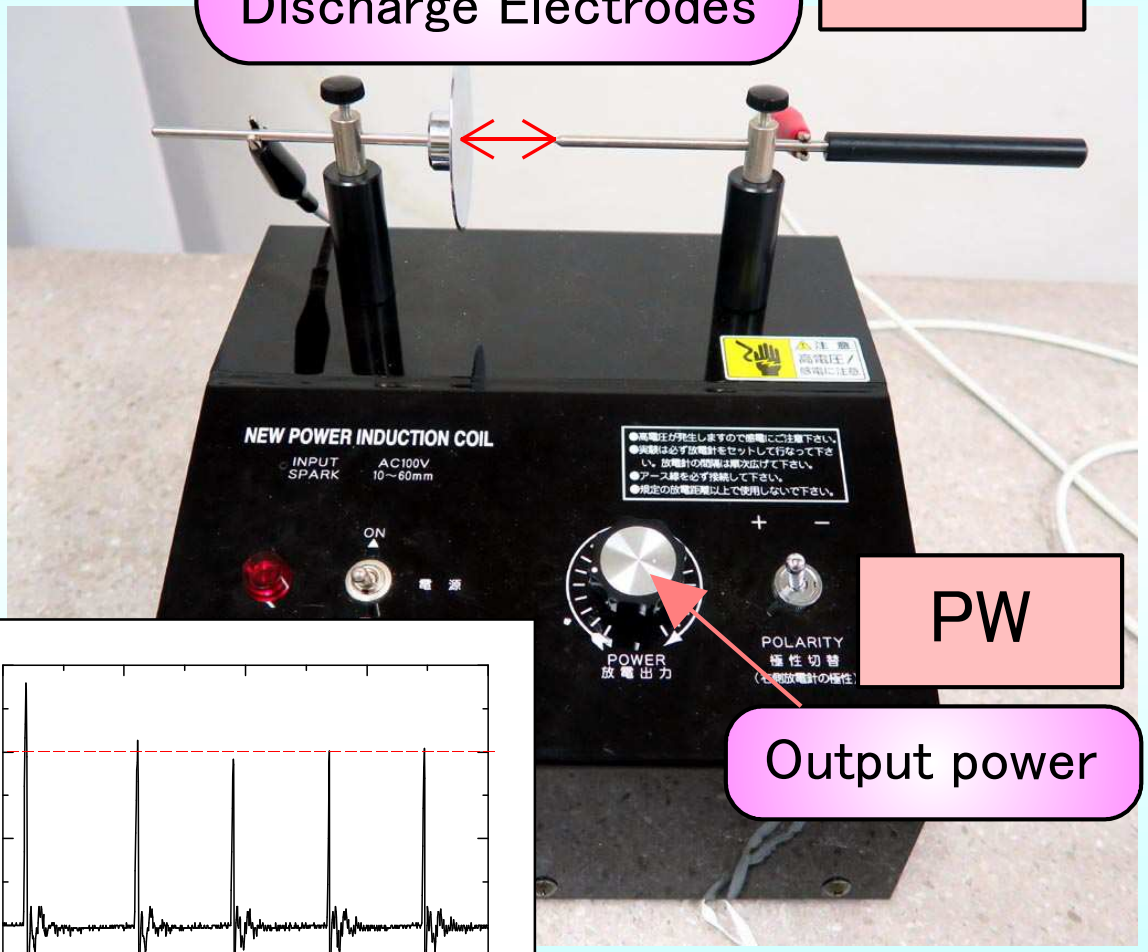
Radiated in Sharp Pulse

Even using detector with Be window for low energy X-rays measurement, radiation in sharp pulse give pile up and dose is estimated as very small value. Only ionization chamber that measure averaged current or solid detector that integrate the absorbed dose is useful.

Not Fixed Applied Voltage from an Induction Coil

Induction coil generate high voltage pulse mechanically, that is affected by electrical conductivity of connected Crookes tube or some conditions such as temperature. Therefore, the output power dial cannot settle the output voltage to a particular fixed value.

High Voltage Applied by a Induction Coil



Distance of discharge electrodes 20mm,
Output power 4, Averaged current 80 μ A

Output power dial changing the voltage impressed to the primary side of a transformer, and that control output voltage, but it cannot settle a particular fixed voltage. The output voltage is affected with the conductance of the connected crookes tube or any other factors.

On the other hand, the dielectric breakdown voltage in the air is about 1 mm for 1 kV, therefore the distance of discharge electrodes can limit the maximum voltage to a fixed value. If the distance is settled to 20mm, the maximum voltage impressed to a Crookes tube was limitted to 20keV, therefore it work as a safety device.

Exemption and Clearance Level

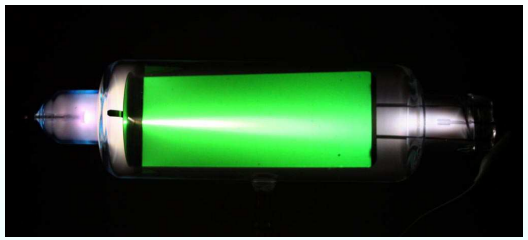
For a Radiation source: IAEA GSR Part3

Radiation generators of a type approved by the regulatory body, or in the form of an electronic tube, such as a cathode ray tube for the display of visual images, provided that: 70μm ? 1cm?

(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 0.1m from any accessible surface of the equipment; or

(ii) The maximum energy of the radiation generated is no greater than 5 keV.

A Crookes tube operated by 5kV
(Horizon Co. VT-7010)



Most Crookes tubes radiate higher dose than the clearance level (i).

For a Public People: ICRP-Pub64, IAEA BSS and NCRP Report No.180

ICRP/IAEA: trivial individual dose, NCRP: negligible individual dose
10μSv/y with a source or practice. (under optimized protection)

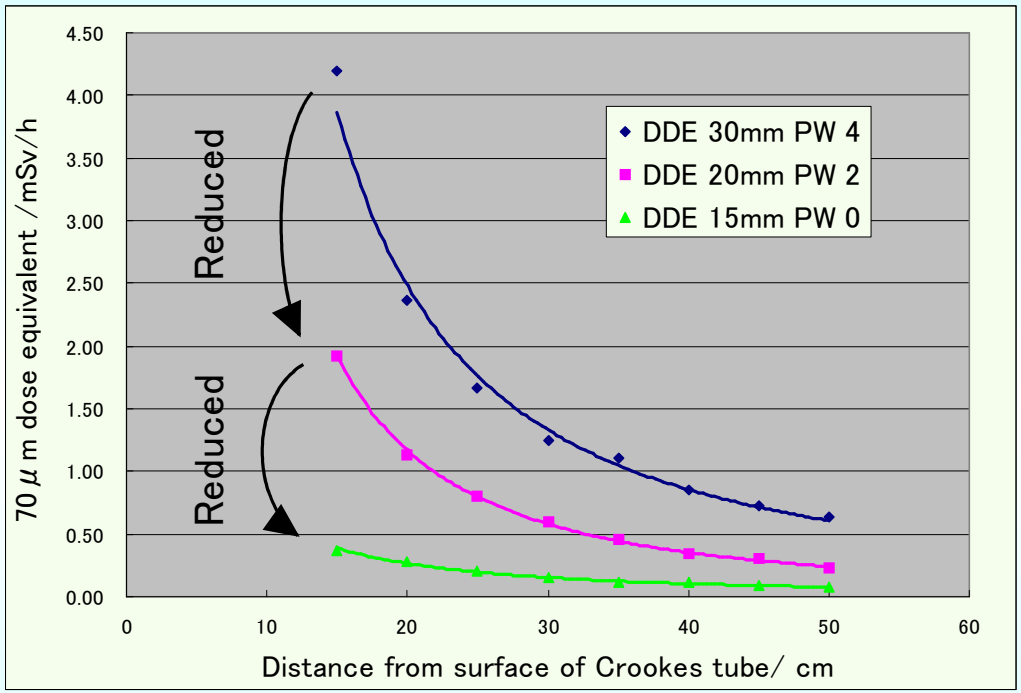
Achievable level with optimized operation conditions.

Dose Limit: ICRP-Pub36

ICRP Pub36 Protection against Ionizing Radiation in the Teaching of Scienc gives the dose limit as: 0.5 mSv/y (effective dose equivalent) or 5mSv/y for each organ (dose equivalent), and 1/10 dose for each class.

Dose Control

Distance of discharge electrodes: 30, 20, 15mm
Output power was set to the just firing voltage.



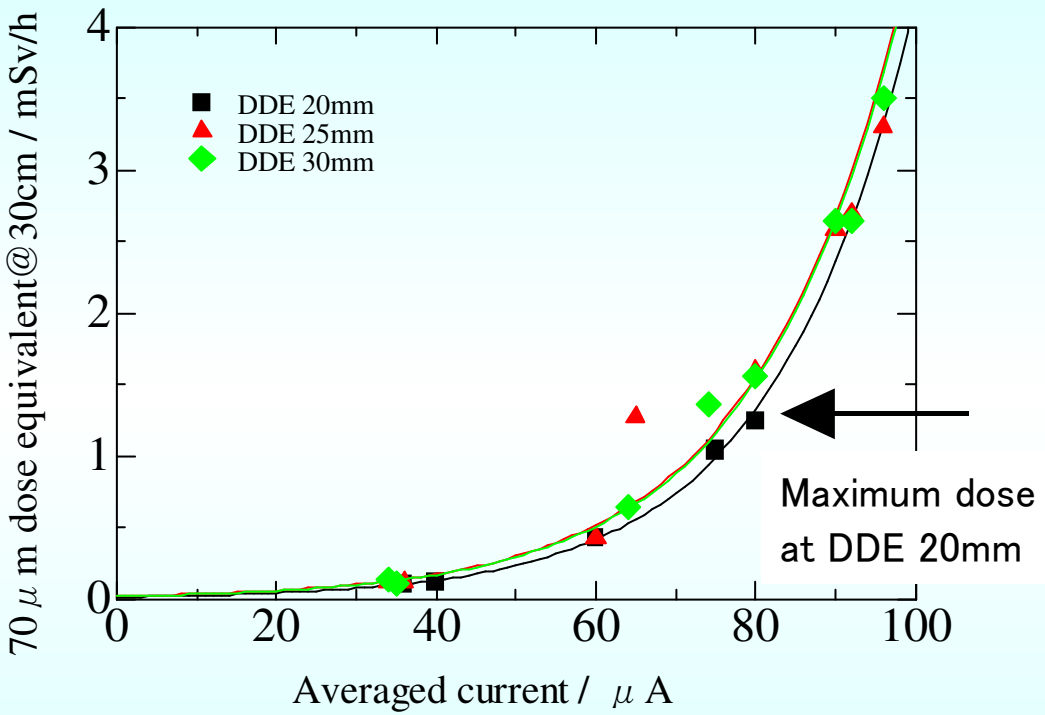
・Dose is reduced drastically with the voltage limitation

Distance of discharge electrodes must be shorter than 20mm

・Dose is changed with distance as the inverse square law

At a distance of 1m, dose is reduced to 1/100 from that of 10cm.

Averaged current was changed with output power.
The averaged current was measured by simple analog current meter.

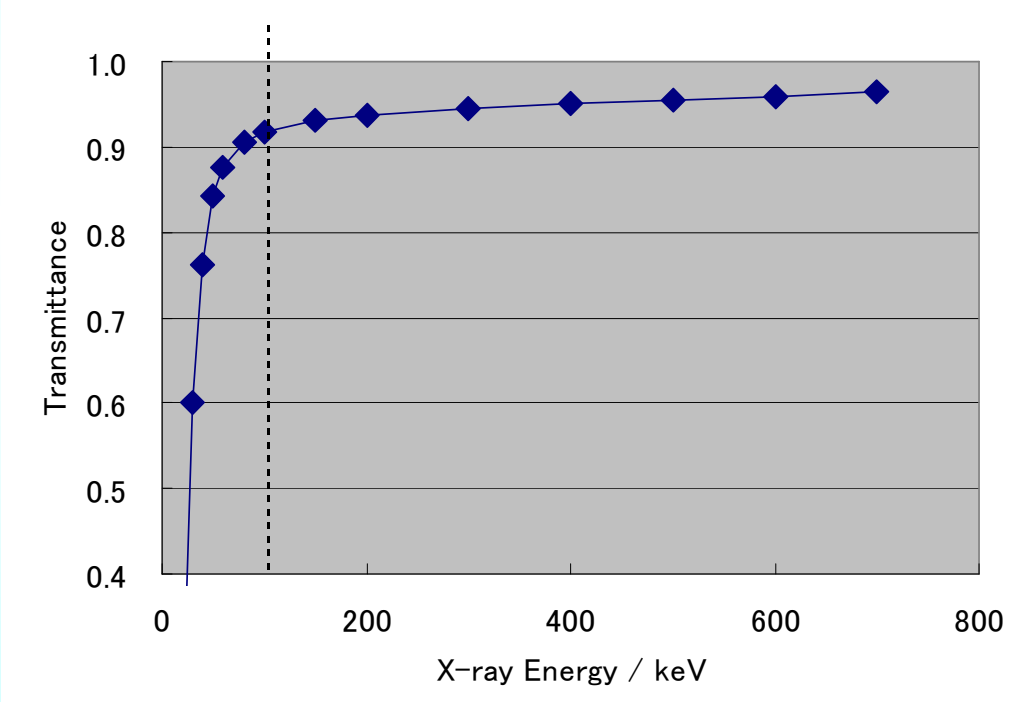


・Increasing current rising dose exponentially

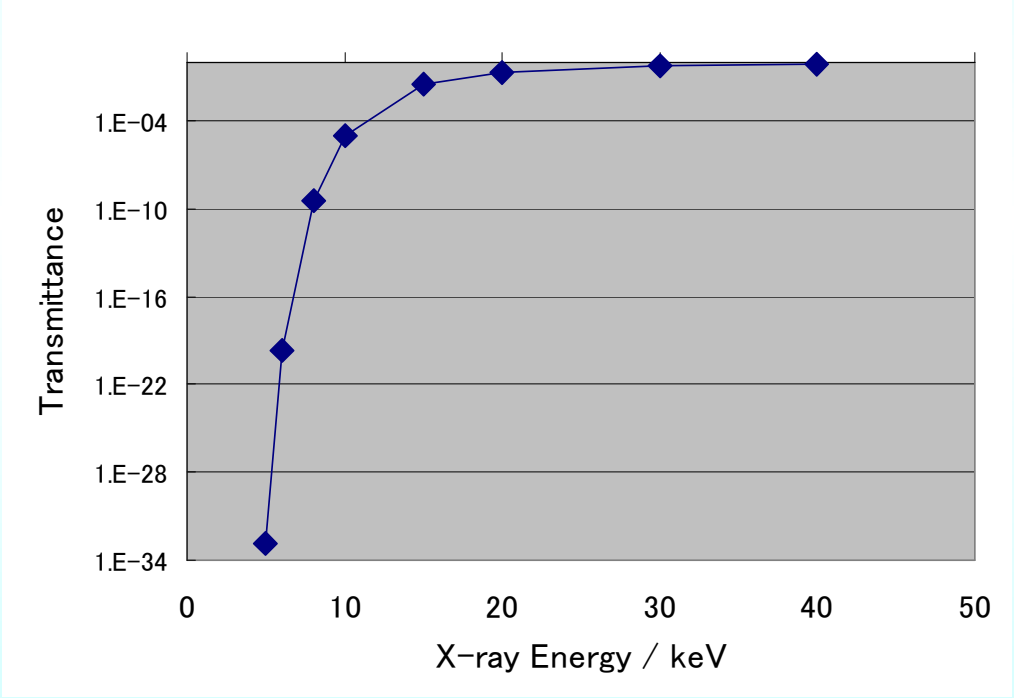
The output power increase current and also voltage. The voltage changes the energy of X-rays that changes transmittance drastically. Therefore, output power must be kept as small as possible. Furthermore, discharge electrode act as a safety valve to limit the voltage.

Drastic Dose Change with Slight Voltage Change

The radiated X-rays are shielded by the grass tube that forms Crookes tube it self. Slight energy change around 20keV gives drastic change in transmittance.



Above 100keV, transmittance changes slightly



Transmittance at 30keV is higher 100 times than that of 15keV

Transmittance of 2mm glass for X/ γ -rays

Exploration at Real Education Field

Setting of induction coil were same as their usually.

Measurements of leaked X-rays from 38 Crookes tubes at junior-high school in Japan were performed using radiophotoluminescence dosimeters by science teachers.

The dosimeter were sticked on 2L PET bottle and put from distances of 15, 30, 50cm and irradiated during 10min for each. The radiophotoluminescence dosimeter was Glass Badge type FX (Chiyoda Technol) that can estimate effective energy and can estimate back ground radiation with Sn shielded element.

In the 38 Crookes tubes, $H_p(0.07)$ with 10min exposure was;

31 tubes < 100 μ Sv @ 1m (extrapolated)

18 tubes < 50 μ Sv @ 15cm (detection limit)

One tube radiate 600 μ Sv in 10min at 1m with minimum output power.

The tube showed intermittent beam and lookes current was small.

Additional study with ionizing chamber: Minimum power、at a distance of 30cm

DDE 30mm: 2mSv/h

DDE 50mm: 30mSv/h

DDE 20mm: 40 μ Sv/h

at 1m、10min radiation gives only 0.6 μ Sv exposure

Charactor of High Dose Crookes Tube

Inside of the Crookes tube, vacuum is not so high and some gas molecules are enclosed. These molecules are ionized by natural radiation and anions are accelerated to cathode to knock out secondary electrons (cold cathode).

There is some Crookes tube that lack of gas. In old equipment, gas molecules are absorbed to glass wall gently or some equipment lack gas on the manufacturing.

With such Crookes tube, electrons are difficult to flow and more high voltage is required to emit beam. With induction coil, electromagnetic energy is charged to the coil until enough voltage is obtained that applies higher voltage than aimed with the output power . That increase transmittance of X-ray to glass wall.

At the age of Roentgen, necessity of gas-pressure control is well known and some "softener" devices were incorporated that released a small amount of gas.

To Reduce the Dose from Crookes tube

First of all

Replace to low voltage equipment

10,000 Junior-High School × 400USD / ea. = 4Million USD is required in Japan
But Crookes tube is used at just a 1 lecture in 3 year.

Inherent Safety
No concern is required

With Economic Factor, Safety Guideline for Conventional Crookes tube is Required

1) **Applied Voltage**
2) **Beam Current**
3) **Diatance**
4) **Shielding**
5) **Time**

Reduce Radiated X-rays

Radiation Protection Three Principles

Reduce applied voltage gives low transmission of X-rays to the glass wall drastically.
When we shielding, acrylic is not effective but thin glass is enough effective.
To take distane is most easy way to reduce dose.

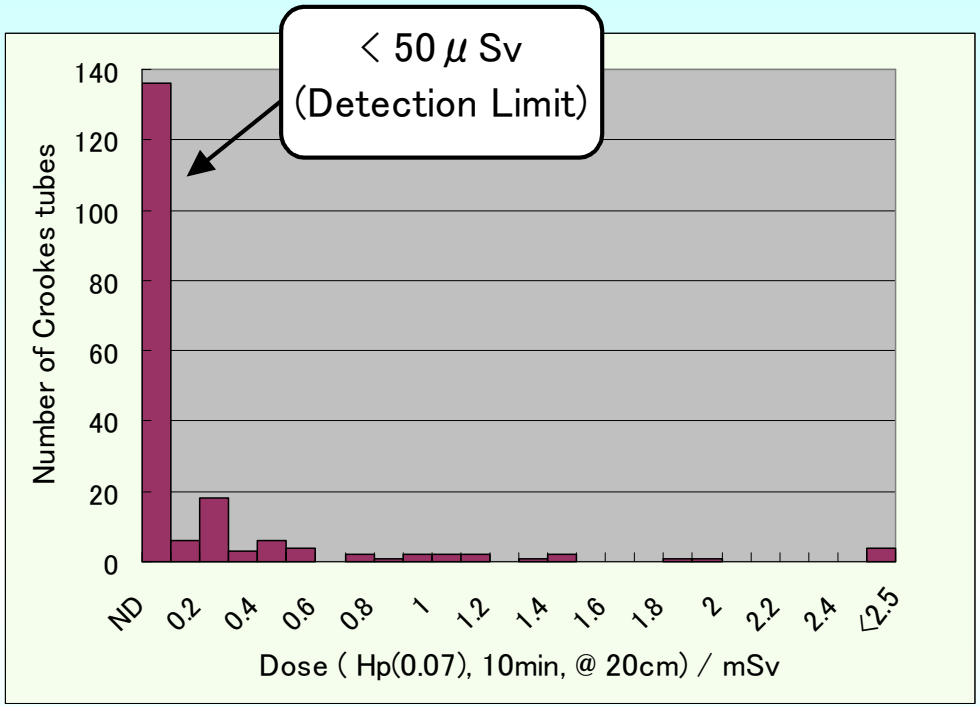
Provisional Guideline

Is it enough?
Substantiate study is required.

- **Set output power as low as possible**
- **Never remove discharge electrodes and set the distance smaller than 20mm**
- **Take distance as far as possible. For student, more than 1m is recommended.**
- **Keep the display time shorter than 10min.**

Validation of the Provisional Guideline

The second exploration was performed at Aug–Nov/2019 to validate the efficiency of the provisional guideline.



August: 95tubes from 27schools, September: 18tubes from 8schools, October: 67tubes from 18schools, Nobember: 11tubes from 4schools were evaluated based on the provisional guideline.

136 tubes in 191 tubes:
Hp(0.07) < 50 μ Sv (detection limit)
exposured at 20cm in 10min.

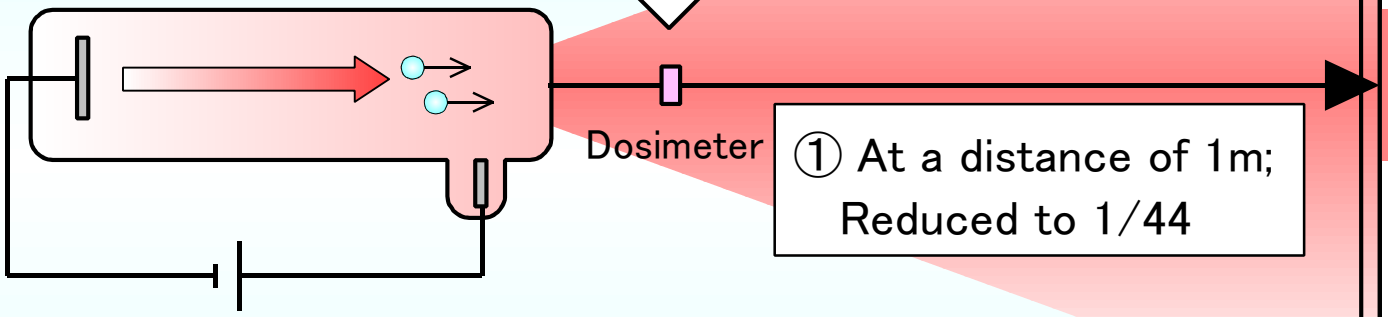
The other 55 tubes showed dose distribution in lower side than the first exploration. On the other hand, the highest dose was 10.4 mSv.

These doses are the measurements results obtained Glass Badge type FX they were put at the distance of 20cm and exposured during 10min, and evaluated in $H_p(0.07)$. We have to estimate the effective dose for true students and teachers in the true education field.

To Estimate Effective Dose

EVEN

At the center of front,
Hp(0.07)=200mSv/h at 15cm



For Eye Lens, Equivalent Dose is also must be estimated.

① At a distance of 1m; Reduced to 1/44

② 20keV X-rays are reduced to one half every 1cm in body. Hp(10) does not represent Effective Dose.

③ In Holizontally, Peripheral Dose is smaller than that measured at the cente (50cm shift gives 2/3 reduction)

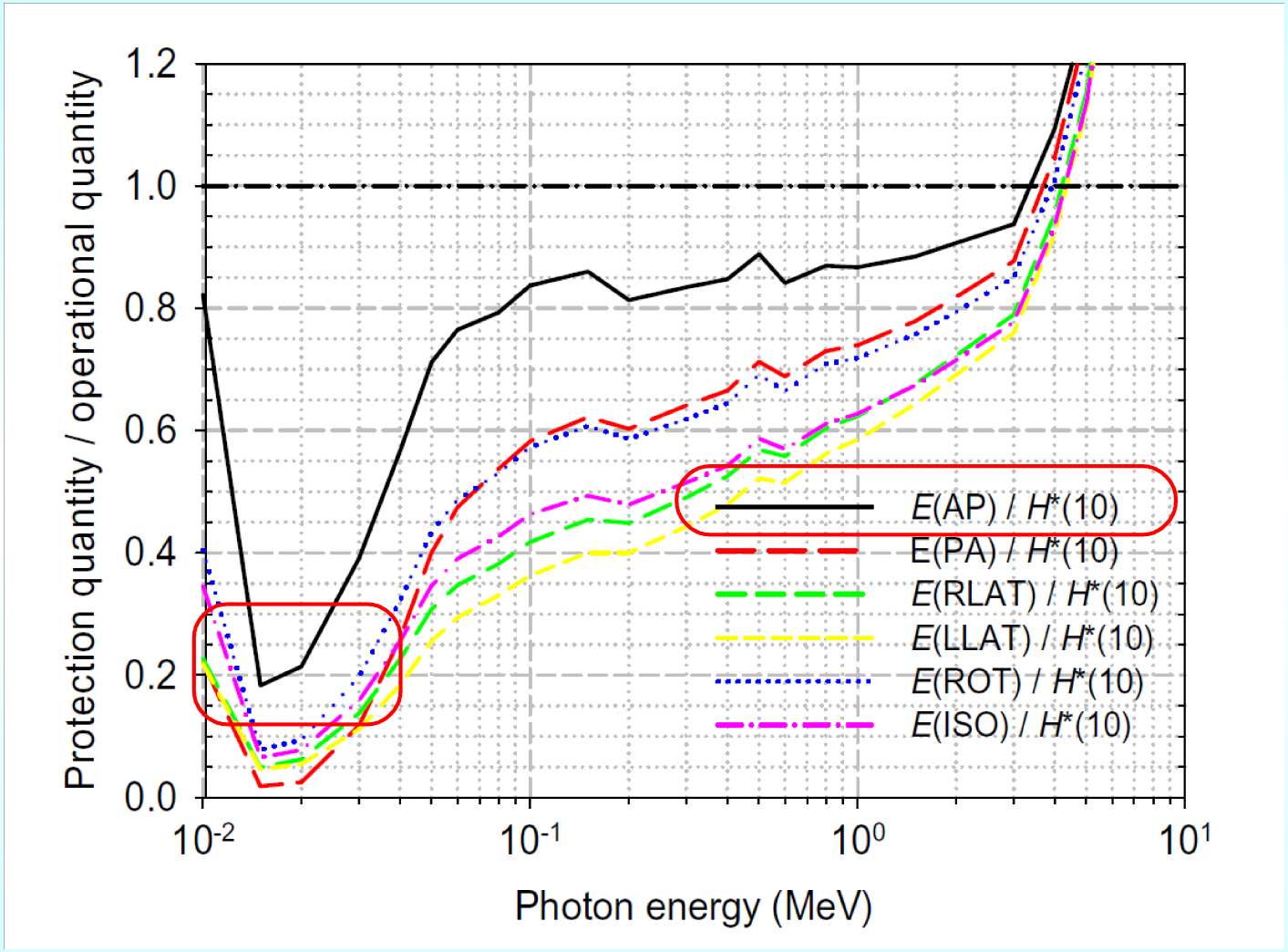
ICRP Pub116 Fig.5.2

E(AP) ≒ 1/5 Hp(10)
≒ 1/10 Hp(0.07)
at 20keV

It is assumed that in 10min demo, Effective Dose is resulted within 50 μSv.

Calculation with PHITS code using:
- Hp(0.07) or Air Kerma
- Energy spectrum
- Horizontal Distribution

Difference Between Protection and Operational Quantity



ICRP Pub116
Fig. 5.2

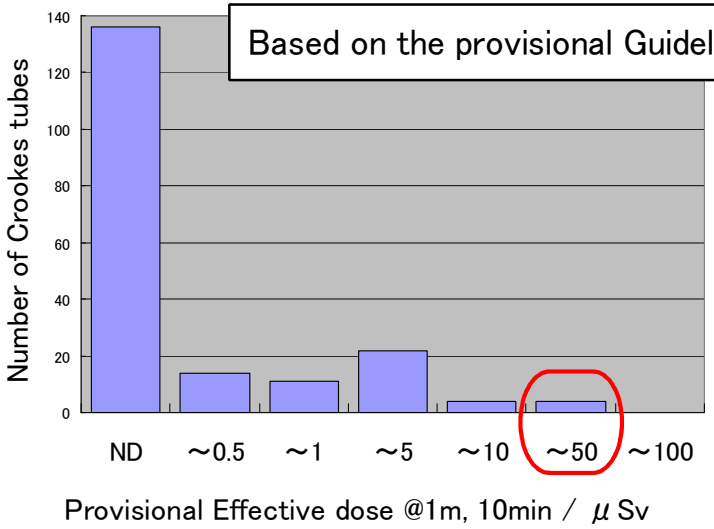
Ratios of photon effective dose (present report) to ambient dose equivalent.
Students observe a Crookes tube, then orientation is fix to AP.
At 20keV, H*(10) gives 5 times overestimation than Effective Dose.

Exploration at Real Education Field

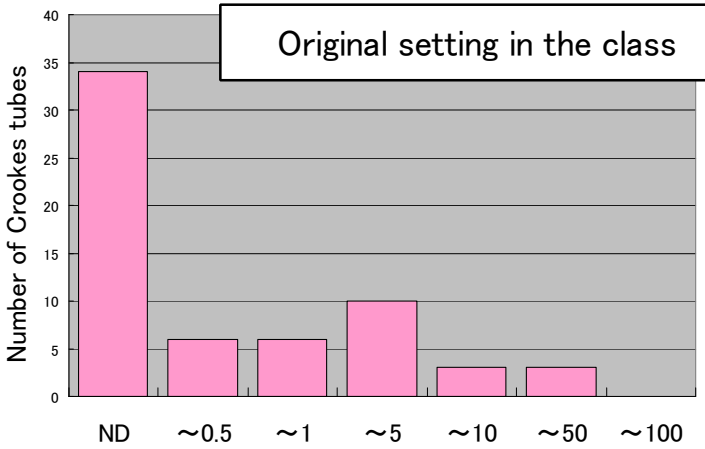
Raw date by Glass Badges

- ○measurement distance 20cm → students take a distance than 1m : 1/25
- ○Hp(0.07) @ 20keV → Effective dose : Provisionally 1/10
- ○Measurement time 10min → Integrated experience time for teachers 10min : Same

Based on the provisional Guideline



Original setting in the class



The effective dose of the 187 tubes in 191tubes measured with provisional guide line were evaluated smaller than 10 μSv, that is exemption level of IAEA BSS, at 1m in 10min.
Only 4 tubes showed larger dose than 10 μSv, 3 were smaller than 20 μSv and the highest was evaluated as 42 μSv, that is smaller than the dose limit in ICRP-Pub36, 50 μSv.

Why several tubes showed a little higher dose is not resolved. Some screening technique is now under considering using leaf electrode that is act as open air ionizing chamber or conventional survey meter (with plastic scintillater) calibrated with low energy X-rays.

If it is turned out that the equipment radiate rather strong X-rays, it is easy to resolve it. Take a little more distance is the most easy way. Shielding with glass aquarium is also good choice. Only 1.9mm glass reduced dose to 1/20-1/50, but acrylic resin with low Z reduce dose to only 1/3 with 1cm thick plate.