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TRANSFER OF THE NBS ABSOLUTE CALIBRATION FOR MEASUREMENT OF HIGH-ENERGY ROENTGEN RADIATION BEAMS

by

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Units for the production of roentgen radiation of energies much higher than those of the gamma radiation from the commonly used radioactive materials ^{137}Cs, ^{60}Co and ^{226}Ra have become available for radiotherapy during the last ten years. Linear accelerators, betatrons and synchrotrons are well-known examples of such units. Since such particular characteristics of high-energy roentgen and gamma radiation, as the skin-sparing effect as a function of the build-up effect, the strongly reduced absorption of energy in bone tissues as compared with that in soft tissues, and increased percentage depth doses, have proved to be of great clinical value, units of the types mentioned have been installed in many radiotherapy clinics.

Quantitative measurements of the exposure is, however, of the same fundamental importance in clinical work with high-energy radiation as it is in the employment of low-energy radiation. When high-energy roentgen radiation

A brief description of the Swedish measurement equipment was presented at the Meeting of the Nordic Radiophysicists, Oslo, 13 to 15 September 1963. The material contained in this paper was presented at the Meeting of the Nordic Society of Radiology, Helsingfors, 4 to 6 June 1964. Submitted for publication 16 August 1965.

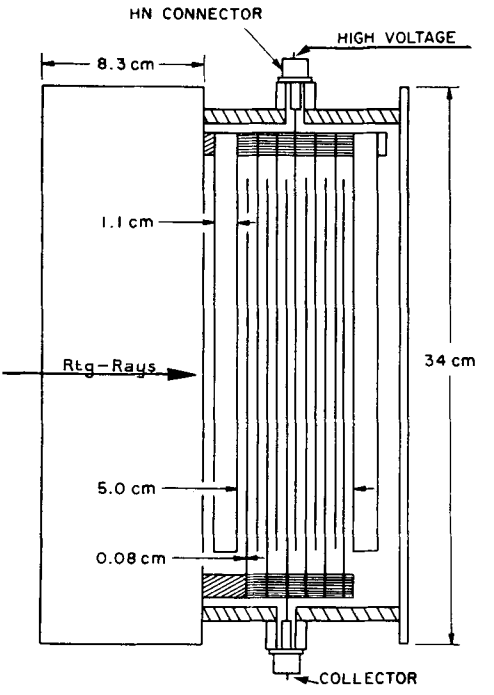


Fig. 1. Schematic cross-section of the NBS P2 chamber. The dimensions given are approximate.

became more commonly available, ordinary thimble ionization chambers were used to indicate the exposure. The chamber was then surrounded by a converter, for example an 11.5 cm lucite cube (ref. 2), and the chamber response was corrected to nominal 'roentgens' with the ^{60}Co calibration factor (ref. 5).

The same method was also used in Sweden at the end of 1957 when the first unit of this type, an 18 MV betatron, was installed at Radiumhemmet. The substandard graphite thimble chamber previously described (ref. 6) was then employed and provided with additional caps of graphite as converters. The ^{60}Co calibration factor of this chamber, provided with a cap of 3.5 mm thick graphite, was originally directly obtained at the NBS in 1956 (ref. 1). The exposure was measured at the centre of beam cross-sections, the exposure rate distribution of which was flattened by separate filters as commonly used in radiation therapy. The flattening effect of the filters was checked by photographic films exposed free in air in a position perpendicular to the beam.

This method, however, cannot be universally used. It fails for example in

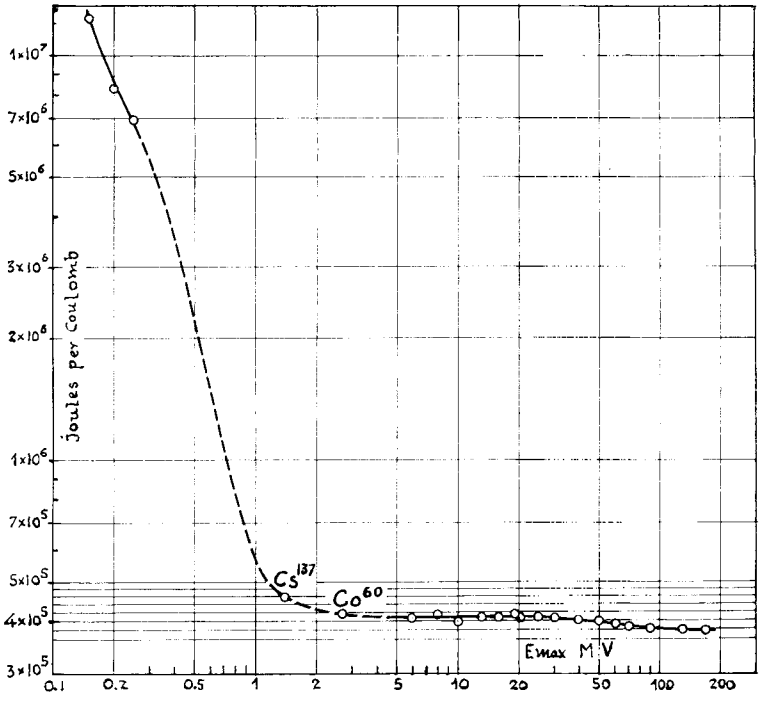


Fig. 2. Variation of the NBS P2 chamber calibration factors with maximum photon energy of the beam. Because of the absence of calibration results and conditional plotting of ^{137}Cs and ^{60}Co gamma radiation the curve drawn is unverified in the gap between 250 kV and 6 MV.

the measurement of total beam energy, since the thimble response is generally not proportional to this quantity but rather to the energy incident on a unit area averaged over a limited part of the beam. High-energy radiation calorimeters were therefore early constructed and used by some institutes in the U.S. for measurement of the total amount of energy transported by a beam of high-energy roentgen radiation. Such a calorimeter is, however, a very complicated instrument which can only be installed at institutes with great resources, but even then the long time and particular care required for the measurements preclude its use each time a knowledge of the quantity mentioned is required.

It is therefore of great value that the NBS has devoted an extensive research work to the design and construction of a special type of ionization chamber, which after an absolute calibration against both a scintillating crystal and a calorimeter enables a convenient determination of the total energy of high-energy roentgen beams to be made. This type of chamber is labelled P2 and has been described in detail in a paper by Pruitt & Domen (ref. 3).

Table 1

Elemental composition of the dural alloys used for the NBS and Swedish P2 chambers

Element	NBS chamber		Swedish chambers
	Percentage by weight		Percentage by weight
	Nominal	Limits	Nominal
Aluminium	93.4	90.9—94.7	93.6
Copper	4.5	3.8— 4.9	4.4
Magnesium	1.5	1.2— 1.8	0.4
Manganese	0.6	0.3— 0.9	0.8
Silicon	—	0 — 0.5	0.8
Iron	—	0 — 0.5	—
Zinc	—	0 — 0.25	—
Chromium	—	0 — 0.1	—
Others	—	0 — 0.15	—

The constructional principle of the P2 chamber is shown in the schematic drawing in Fig. 1. The chamber is a flat transmission ionization chamber, the size of which is sufficient to intercept the whole beam. The chamber is provided with a suitable wall thickness for the front, which the radiation has to penetrate before it reaches the sensitive volume of dry air in the chamber. The air-column is about 5 cm thick and is divided into 12 equal segments. The normally used potential difference between the segment plates is 1 200 V, or about 284 volt per millimetre. These measures effectively contribute to reduce both the solid angle for electron loss and the probability of ion recombination to acceptable levels. All the parts exposed to radiation are made of a dural alloy of specified composition. According to page 1 of ref. 3, the P2 chamber is classified as an NBS Standard instrument, particularly useful as a transfer instrument. Its calibration is expressed as the radiation energy in joules required to produce one coulomb of ionization charge inside the chamber when it contains dry air at a temperature of 20° C and a pressure of 760 mm Hg.

One characteristic of the P2 chamber that is of very great interest is the energy dependence of the response. To illustrate this, some of the calibration factors in joules per coulomb given in ref. 3 have been plotted against the maximum photon energy of the beam on the logarithmic diagram shown in Fig. 2. Due to the thickness chosen for the front wall, it was possible to reduce the variation of the calibration factor with the maximum beam energy to 10 per cent between 6 and 170 MV, using a beam filtration equivalent to 4.5

Table 2

Thickness in mm of the discs forming the front wall of the P2-S1 chamber

Number	Thickness	Number	Thickness
1*	11.45	5	11.84
2	11.84	6	11.89
3	11.83	7	11.86
4	11.84	Sum of 1 to 7	82.55

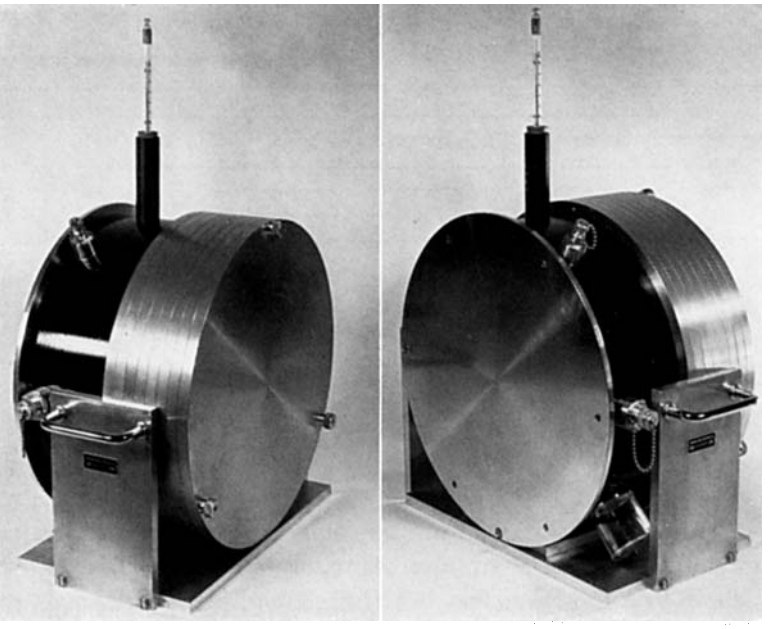
* Number 1 is the closing front disc

g/cm^2 of aluminium, and a beam diameter of 4.2 cm at the front face of the chamber. The calibration factors of the ^{137}Cs and ^{60}Co gamma radiations were plotted against 1.4 and 2.8 MV, approximately corresponding to the maximum energies of roentgen radiation having the same first HVL as the respective gamma radiation. It appears from the diagram that the calibration factors in the region 150 to 250 kV are approximately 30 to 17.5 times greater than those in the 6 to 170 MV region, which in a high degree depends on the increased attenuation of the radiation in the thick front wall.

The diagram in Fig. 2 only generally shows the energy dependence, and may therefore not be used to read or interpolate calibration factors. Experimentally determined factors are for example not available in the wide region between ^{137}Cs gamma and 250 kV roentgen radiation, and the factors of ^{60}Co and ^{137}Cs gamma radiation are conditionally plotted. The curve drawn is therefore unverified in this region.

The features of the P2 chamber mentioned above, together with other interesting properties experimentally verified in ref. 3, indicate that this chamber is a perfectly good and very convenient instrument for the purpose in question, and that its design is such that a reproduction elsewhere would be feasible, provided each important detail be carefully controlled. It was therefore decided in 1962 to start a project, aiming at a transfer of the NBS absolute calibration of the P2 chamber for determination of the total energy transported by high-energy roentgen radiation beams, by producing three identical P2 replica chambers for this institute, one to be kept by the standard laboratory, one by the clinical radiophysics section, and one by the roentgen inspection section.

According to ref. 4, page 107, such a procedure would eliminate the need to reproduce the original calibration experiments . . . "A laboratory with a calibrated replica chamber has the information required to make its own absolute determination of the radiation energy incident on experimental



a b

Fig. 3. Photographs of front (a) and rear surface (b) of the Swedish P2-S1 replica chamber.

apparatus, a number required for quantitative interpretation of experimental results."

The project was facilitated by the release of copies of drawings and specifications from NBS Washington and by their kind loan of an NBS chamber for the purpose of comparison.

A brief report showing the results of our efforts to realize the project and of the comparison between the NBS P2-3 and our chamber P2-S1 is given below. The last-mentioned chamber will be kept by the standard laboratory of this institute.

To ensure that the Swedish chambers would be as exact copies of the NBS P2 chamber as possible it was fundamentally important to use a material of very nearly the same composition of elements and thickness for all the parts exposed to radiation. Some difficulties were encountered but after much search such a material was found. The composition of the material used for the Swedish chambers is shown in Table 1 together with that of the material used for the NBS chambers, quoted from ref. 3 for comparison. As the two materials are very similar in composition, they may be compared by calculating their

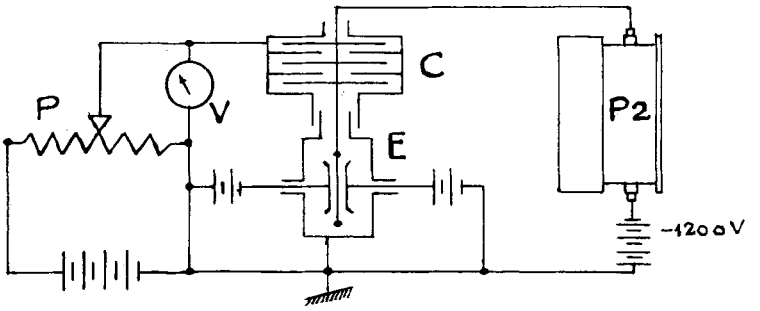


Fig. 4. Charge-collecting capacitor with compensating arrangement for charge measurement. C—charge collecting capacitor, E—single string electrometer used as null-condition indicator, P—potentiometer, and V—precision voltmeter.

'average atomic numbers' from the atomic numbers and nominal percentages by weight of the ingredients as given in Table 1. We then obtain 13.775 for the NBS dural and 13.796 for the Swedish. The density of our material was extensively checked by the dimensions and weights of the different parts, and was found to be 2.795 for the stack plates and 2.796 for the front-wall plates. This may be compared with 2.790 for the material of the NBS P2-3 chamber.

The internal plate assembly, defining the sensitive volume where ionization is produced and collected, contains dry air at atmospheric pressure. This air gap is divided into 12 equal segments by thin dural plates to reduce the probability of ion recombination. These plates are 0.788 $\pm$ 0.012 mm thick, which may be compared with 0.795 $\pm$ 0.007 mm as specified in the chamber drawings. They are separated by ground steel-spacers the average thickness of which is 9.269 $\pm$ 0.007 mm, this value was calculated as the average of all the readings taken at two opposite positions of each spacer, and may be compared with 9.261 $\pm$ 0.007 mm, as specified in the chamber drawings.

From the figures given above we are able to calculate the thickness of the air gap. We then obtain 6(9.269—0.788) = 50.886 mm for the Swedish chamber, and 6(9.261—0.795) = 50.796 mm from the chamber drawings. According to Table 8, in ref. 3, the actual air gap thickness of the NBS P2-3 chamber is 50.69 mm. The two thick outer plates of the high voltage stack, enclosing the air gap, are 11.41 $\pm$ 0.02 mm thick, which may be compared with 11.43 $\pm$ 0.05 mm as specified in the chamber drawings.

The plates enclosing the air gap segments consist of high voltage (—1 200 V from a battery power supply) plates alternating with collector plates. Each plate stack is separately mounted with high grade insulators on the grounded

front wall of the chamber. The whole plate structure is housed in a cylindrical brass shell the ends of which are closed with dural walls.

The front wall of our chamber P2-S1 consists of seven discs the thickness of which are shown in Table 2. No. 1 is the closing disc the thickness of which 11.45 ± 0.03 mm, may be compared with 11.43 ± 0.05 mm as specified in the chamber drawings. The thickness of the seven discs together is 82.55 mm and is the same as that specified in the drawings. The rear wall of the chamber is 6.38 ± 0.02 mm thick, which may be compared with 6.35 mm as specified in the chamber drawings.

Two photographs of the Swedish chamber P2-S1 are shown in Fig. 3. The weight of each chamber is about 40 kg which makes them reasonably portable.

The charge collected from the P2 chambers was determined by a compensating arrangement of the type shown in Fig. 4. The charge was collected by a high-grade insulation capacitor, across which an increasing voltage was then developed. This voltage was cancelled by that supplied by a potentiometer and measured by a precision voltmeter. The null-condition was indicated by a single-string electrometer adjusted to high sensitivity. The capacitors used were calibrated against the standard air capacitor mentioned on page 208 of ref. 7 and having a capacitance of 204.3 $\mu\mu$F $\pm$ 0.1 per cent. The compensating voltage was continuously adjusted during each exposure to maintain the electrometer string as near as possible at ground potential.

When beams of gamma and high-energy roentgen radiation are to be measured, leakage and stray radiation (back ground) cannot be completely eliminated. The air volume of the P2 chamber exposed to such radiation is, however, of the order of 50 times greater than that exposed to the beam. It was therefore considered necessary to correct the reading of the charge produced by the beam by that produced by the background. This correction was obtained by repeating the exposure with the collimating opening closed by a full-length well-fitting lead plug.

The comparison program was originally planned to be carried out up to about 18 MV by the present betatron at Radiumhemmet and to be extended up to about 40 MV by a new betatron at Radiumhemmet. For various reasons, however, the installation of this unit has been very much delayed. In the meantime, a 42 MV betatron had been ordered for the radiotherapy clinic of the Regional Hospital at Örebro and was expected to be ready for operation at the end of 1964. It was therefore decided to inquire of the NBS about the feasibility of extending the time of keeping the P2-3 chamber so as to include that required for this purpose. Fortunately, there had been no request for P2 chambers so the NBS kindly consented to meet our wish. Due to this and to the friendly cooperation of K. J. VIKTERLÖF, Chief Hospital Physicist of the

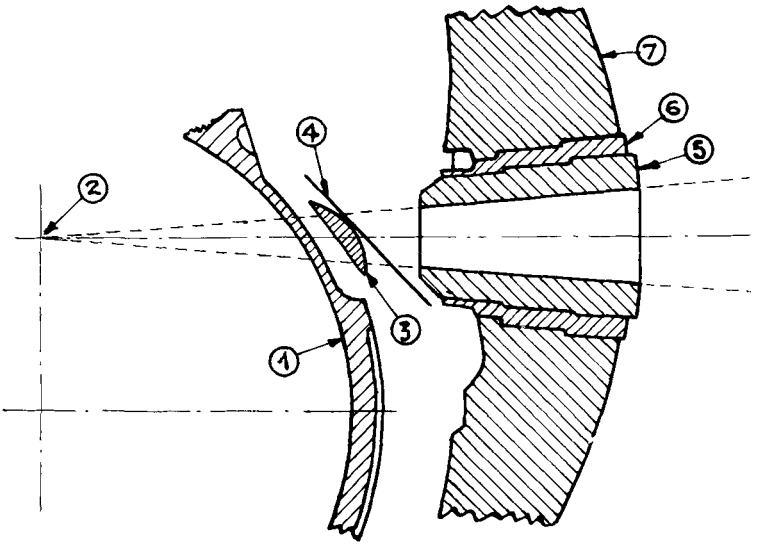


Fig. 5. Schematic section of the 18 MV betatron head showing roentgen radiation beam exit. 1—donut wall, 2—focus, 3—position of flattening filter when such a one is used, 4—mirror of beam-simulating light system, 5—collimator, 6—collimator holder, 7—main lead shield of betatron head.

Regional Hospital at Örebro, the comparison was extended to include 25 and 42 MV.

The comparison of the response to roentgen radiation was made by measuring the charge collected from each chamber when they were given identical radiation exposures as referred to equal readings of a separate monitoring integrating instrument. This instrument was at first compared with the P2-S1, using a moderately filtered 250 kV roentgen beam having a HVL of 17.5 mm Al. The P2-S1 chamber was then only provided with the closing front plate No. 1. The focal distance to this front plate was about 2 metres, and the beam diameter at this distance about 65 mm. Twelve consecutive exposures were made, each of 1.50 min duration and all of them within an operating period of about 45 min, and the P2-S1 reading in volt per 100 monitor scale divisions were calculated. The ratios thus obtained were in order as follows: 98.5, 98.3, 98.3, 98.4, 98.5, 98.4, 98.5, 98.5, 98.6, 98.5, 98.6, 98.5, averaging 98.47 $\pm$ 0.15 per cent and thus showing satisfactory agreement. The response of the P2-S1 chamber with only the closing front plate No. 1 was 7.562 times greater than that with all the front plates. A similar series comparing the monitoring instrument with the P2-3 and comprising 6 consecutive exposures was later obtained by the 42 MV roentgen beam of the Örebro betatron and gave the following

Table 3

Results of the comparison — Average ionization ratio 0.996 ± 0.2 per cent

Radiation	HVL mm Al		Focal distance in m to chamber face	Beam cross-section in mm at chamber face	Ionization ratio $\frac{P2\text{-}3}{P2\text{-}S1}$
	First	Second			
150 kV roentgen	10.7	11.5	2	42 ∅	0.994
200 kV »	13.6	14.8	2	42 ∅	0.995
250 kV »	15.9	16.8	2	42 ∅	0.997
400 kVp »	19.3	19.8	1	42 ∅	0.994
^{137}Cs gamma	34.5	34.5	1	~65 ∅	0.996
^{60}Co »	46.5	46.5	1	~65 ∅	0.995
7 MV roentgen	Inherent filtration		1	45 ∅	0.995
16.5 MV »	3.3 g/cm²		1	45 ∅	0.998
25 MV »	Inherent filtration		1.5	50 × 50	0.995
42 MV »	3.8 g/cm²		1.5	50 × 50	0.996

values of volt per 100 monitor scale divisions: 166.9, 166.9, 166.7, 166.6, 166.7, and 166.8, averaging 166.8 ± 0.1 per cent.

The final step in the comparison procedure was then to study the ionization charge collected by the P2-3 and P2-S1 chambers referred to equal readings of the monitor instrument. This was carried out over a wide range of radiation qualities, using moderately filtered roentgen beams of 150, 200, and 250 kV constant potential and 400 kVp, gamma beams from ^{137}Cs and ^{60}Co, and finally roentgen beams of 7, 16.5, 25 and 42 MV. The quality of the six first-mentioned beams may be characterized by their half-value layers, the first and second being experimentally determined.

The inherent filtration of the 18 MV betatron at Radiumhemmet may be defined as follows. The accelerator tube (donut) is made of a ceramic material, the density of which is 2.6. The donut wall, through which the beam is emitted, is 10 to 12 mm thick. In addition the beam passes through a glass mirror about 1 mm thick and belonging to the beam-simulating light system. This means a total of about 3.3 g/cm² of low-atomic-number material similar to aluminium. No flattening filter was used. Fig. 5 shows a schematic section of the 18 MV betatron head at the roentgen radiation beam exit.

The donut of the Örebro 42 MV betatron is also made of a ceramic material, the density of which is 2.35. The donut wall, through which the beam is

emitted, is 15 mm thick. In addition, the beam passes through a glass mirror about 1 mm thick belonging to the beam-simulating light system. This means a total inherent filtration of about 3.8 g/cm² of low-atomic-number material similar to aluminium. No flattening filter was used.

Systematic errors in the comparison were reduced as much as possible by using the same arrangement for placing the two P2 chambers in identical positions in each beam, and the same measuring equipment with both of them. Each value of the ionization charge collected was obtained as the average of at least three consecutive readings.

The ionization ratio $\frac{\text{P2-3}}{\text{P2-S1}}$ and some other relevant experimental data have been collected in Table 3. It appears that the ionization ratio does not show any trend of systematic variation. Calculation of the average ratio may therefore be justified and gives 0.996 $\pm$ 0.2 per cent.

The results obtained with P2-S1 verifies that the design of the P2 chamber is such that a reproduction is quite feasible if the important details are carefully controlled with special regard to material and dimensions. The problem most difficult to solve seems to be that of finding a dural alloy of very nearly the same elemental composition as that used for the original P2 chambers. However, if such a material is available, the reproduction is mainly a question of accurate machining by which the various parts are given the proper dimensions within the requisite narrow limits. It appears from the results now reported that we have been able to transfer the NBS absolute calibration of the P2 chamber to this laboratory with acceptable accuracy.

Acknowledgements

The author wishes to express his sincere thanks to the NBS, and to J. S. Pruitt and H. O. Wyckoff in particular, for releasing the NBS drawings and specifications and lending us one of the NBS chambers for comparison, to K. J. Vikterlöf, for his friendly cooperation, and to the Anti-Cancer Society of Stockholm for defraying the expenses for two of the chambers. This report and the results of the comparison are published with due permission of the NBS.

SUMMARY

Three identical ionization chambers of the special type developed by the NBS and labelled P2 have been constructed to transfer the NBS absolute calibration for determination of the total amount of energy transported by high-energy roentgen radiation beams. Some characteristics of the Swedish replica chambers are discussed.

ZUSAMMENFASSUNG

Drei identische Ionisationskammern vom Typ NBS, Modell P2, wurden gebaut, um die absolute NBS-Eichung zur Bestimmung der von hochenergetischen Röntgenstrahlbündeln transportierten totalen Energie zu überführen. Einige charakteristische Angaben der schwedischen Kammern werden besprochen.

RÉSUMÉ

Trois chambres d'ionisation identiques du type spécial mis au point par le NBS et appelé P2 ont été construites pour transférer l'étalonnage absolu du NBS, en vue de déterminer la quantité totale d'énergie transporté par des faisceaux de rayonnement roentgen de haute énergie. L'auteur examine certaines caractéristiques de ces chambres répliques suédoises.

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