SMALL-SIZE BETATRONS FOR RADIOGRAPHIC INSPECTION

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Abstract: The report describes characteristics and parameters of small-size pulse betatrons developed by Research Institute of Introscopy at Tomsk Polytechnic University. They are used as sources of X-ray radiation but have much higher radiation energy compared to X-ray devices, and are not widely known.

Main types of these betatrons, MIB-6 (PXB-6) and MIB-7.5 (PXB-7.5), are manufactured jointly with the firm JME Ltd (UK).

Introduction: A betatron is a cyclic induction electron accelerator. This specific group of betatrons are of a small-size, i. e. betatrons with light weight and small dimensions, which makes for their application in various branches of industry and in medicine.

In this report, small-size betatrons are considered as sources of X-ray radiation for non-destructive testing. They resemble traditional X-ray devices and are specified by the same parameters. The distinguishing feature of these betatrons is a much more complex way of electron acceleration, allowing higher energy and X-ray radiation penetration with a small-size device.

The only world developer of small-size betatrons was and still is Research Institute of Introscopy at Tomsk Polytechnic University (TPU). In recent years, a number of firms have emerged; their work, however, is mainly directed toward application of these radiation sources.

The rector of those times A. A. Vorobiyov and professor L. M. Ananyev began research works on small-size betatrons in 1956.

At present, professor V. L. Chakhlov is at the head of this work.

Development of the first industrial sample of a small-size betatron of energy 6 MeV and bremsstrahlung dose rate 0.3 R/min at 1m was finished in 1967. 80 such devices have been produced. Russian industry was their major consumer but about 10 items were delivered abroad.

During the mid-70s a new generation of small-size betatrons was developed. By that time, Tomsk RII accumulated a great amount of theoretical and practical material on forming more efficient structures of a betatron magnetic field, and the research of the mechanism of electron capture into acceleration.

Achievements of power semi-conductor electronics, and application of new materials made possible the design and manufacture of compact systems of pulse supply, small-size betatrons that ensured accelerator operation at 200 Hz and more. These improvements increased the radiation dose rate almost by a factor of 20, the weight and the consumed power being the same.

Over the last years, in development of new models a particular emphasis has been placed on reliability enhancement, creation of novel systems of control, dosimetry and design improvement. Cooperation with the firm “JME Ltd.” (United Kingdom) played a significant part along these lines. It is this firm that supplies the Western market with the small-size betatrons.

This cooperation that started in 1987, RII supplied its partner with adjusted radiators along with a set of spare accelerating chambers. The other betatron units are manufactured by the firm JME Ltd. JME Ltd also provide sales and after-sales service of the betatrons.

Results: A modern small-size betatron (Fig. 1, digital picture of a complete betatron) consists of four units: radiator, power supply unit, control panel and remote dosimeter. During operation the accelerator units are connected by flexible cables.

Fig. 1. Portable X-ray betatron PXB-7.5

The heart of a betatron is a radiator that consists of an electromagnet, sealed-off accelerating chamber, systems of electron injection, orbit expansion and contraction and ionization chamber, for dose measurement.

A power supply unit contains: controlled rectifier with protection system, current pulse generator for supplying the radiator electromagnet and a circuit for restoring the lost energy in the magnet/capacitor bank resonant circuit.

A betatron is equipped with dosimeters, built-in and remote, that measure radiation dose in front of and behind a controlled object, and a timer that sets the exposure time.

An automated system of betatron control provides input of initial data (setting the energy of accelerated electrons, exposure time, dose), accelerator adjustment for the radiation maximum, diagnostics of operation modes of accelerator units, automatic end to exposure dependant on either reaching a set dose as measured by the dosimeters, or upon reaching the required exposure time.

The dimensions and the weight of betatron units are such that the devices are easily transported by any kind of transport and can be supplied from both stationary industrial electric mains, and self-contained sources of rated power not less than 3 kVA.

At present, a number of small-size betatrons for energy from 2.5 to 10 MeV are developed; their main parameters are given in the table.

Parameters	MIB-2.5	MIB-3	MIB-4	MIB-6	MIB-7.5	MIB-10
Peak energy of bremsstrahlung radiation, MeV	2.5	3	4	6	7.5	10
Dose rate at 1m from the target, cGy/min	0.1	2	1	3	5	16
Pulse repetition rate, Hz	50	400	200	200	200	100
Power consumption, kVA	0.7	2.5	2.0	3.0	3.0	3.6
Radiator weight, kg	27	50	56	100	110	275
Total weight of units, kg	45	120	120	180	220	405
Size of focal spot, mm x mm	0.2x3	0.2x3	0.25x2	0.25x3	0.25x3	0.3x3
Maximal controlled thickness (of steel), mm	-	130	150	250	300	350

The Russian abbreviation “MIB” means small-size pulse betatron. The English abbreviation “PXB” means portable X-ray betatron. It is a joint product. The power supply units and control panels differ slightly in appearance.

The first two types of betatrons for energies 2.5 and 3 MeV are intended for use as portable units during different kinds of repair and recovery works. In our opinion, the recently developed 2.5 MeV betatron is the lightest accelerator of this energy in the world. It can work from a storage battery, of 48 Volts and 9 Ampere·hour capacity will suffice for about 1 hour of betatron operation.

Next 3 types of betatrons in the table are more universal. They can be used both in field and stationary conditions. The largest dose rate is achieved with the betatrons of 6 and 7.5 MeV energy. Most likely, they have the most optimal combination of weight, dose rate and penetration.

The largest small-size betatron the 10 MeV betatron – is meant to be installed in workshops of large engineering plants. It is recommended to use it for evaluation of more than 180-200 mm of steel and large volumes.

Discussion: The small-size betatrons as radiation sources have a number of advantages in comparison with other sources.

In all betatron types the energy of accelerated electrons can be adjusted in relative units from 0.3 to 1. The x-ray beam is made up of all energy levels up to the maximum set. This range is limited only from the upper Mev set

On the control panel, as the energy of a γ-quantum cannot exceed the energy of accelerated electrons. This allows for an optimal control of a wide range of products varying in thickness and material, using one device.

Moreover, the betatron focal spot has very small dimensions, which enhances detection of small defects. The focal spot peculiarity is that it has a sharply defined linear shape. Focus size along the radiator axis is an order more than in the median plane. That is why, it is possible to improve detection of small defects by aligning the focus line along a supposed crack direction or along a concrete reinforcement.

A betatron, as with any other accelerator is a complex device but it is simpler and its maintenance is easier than other NDT accelerators, such as linacs.

A betatrons only disadvantage is its rather moderate radiation dose rate. However, recently more sensitive registration techniques have been intensively developed, for instance, storage screens, real-time systems, etc. This issue becomes less significant with time, as faster registration techniques become available.

It is impossible to demonstrate the defectoscopic characteristics of all small-size betatrons within the context of this paper. Examples are found in exposure and sensitivity graphs of MIB-7.5 (PXB-7.5) betatron (Figs. 2-5).
Variety of NDT requirements gives no way of making a universal holder for small-size betatrons, a customer either orders it individually in accordance with their NDT procedure or produces it themselves. Let us give several examples. Fig. 6 shows the inspection of a casting process in a foundry in Great Britain. In this case, the customer produced a manipulator that makes it possible to rotate the radiator in two directions, and to raise and lower it. The inspection is performed with the use of an X-ray film. This particular betatron has been operated very intensively, 20 hours per day, over several years. In the beginning they experienced problems due to a short lifetime of the accelerating chamber. The design of the chambers and the technology of their production has been improved and after that some chambers have worked for more than 1000 hours.

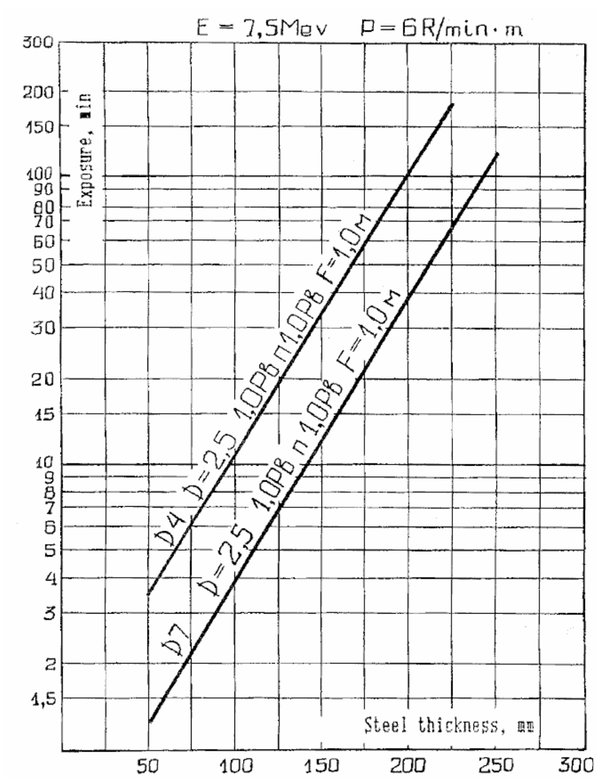

Fig. 2. Exposure thickness curve for steel.

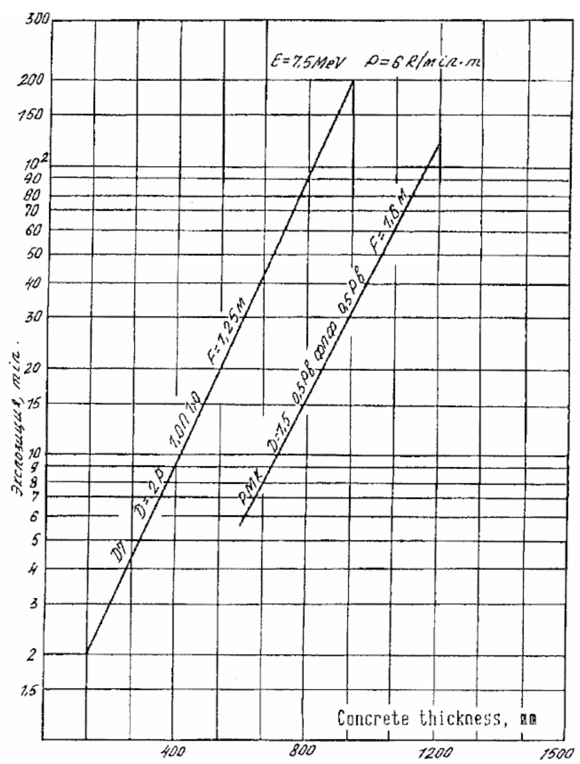

Fig. 3. Exposure thickness curve for concrete.

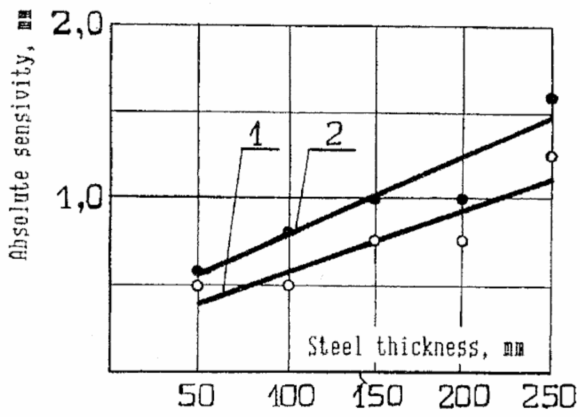

Fig.4. Dependence of defect sensitivity on steel on
thickness.
1 – sensitivity according to groove penetrameter
2 – sensitivity according to wire penetrameter

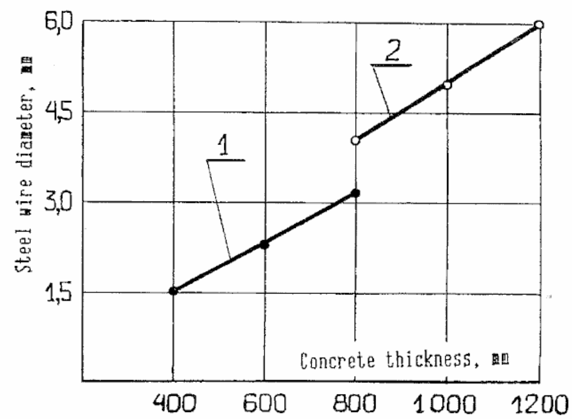

Fig.5. Dependence of steel wire sensitivity
coating thickness.
1 – Film D7, F=1250 mm, D=2.0
2 – Film PM-KD7, F=1600 mm, D=1.5

Fig. 6.

It is worth noting that the price of a spare chamber, which is supplied together with a high-voltage unit, is about 3% of the price of the whole system. Its replacement takes 15-20 minutes.

Fig. 7 shows a control station of an oil refining reactor at “Volgograd Neftemash” plant (Volgograd). The controlled reactor is presented in Fig. 8.

Fig. 7

Fig. 8

The betatron is installed on a movable platform that can move by rail along the reactor. The radiator is mounted on a rotating arm and can move along it, as well as rotate in its suspension. An X-ray film is used for NDT. It takes the betatron 12 minutes to X-ray 110 mm at 1.6 m focal distance.

There are firms that develop and supply with their own inspection systems that use a small-size betatron as a radiation source.

An example the advantages and the successful use of the betatron is found in a system developed by Material Measurements Ltd (Great Britain), and whose trade mark is Megascan^{TM}. The system can use either PXB-6 or PXB-7.5

Radiation is registered by imaging plates that are of different size and sensitivity. Then, an image received from the plate is processed by digital techniques.

Megascan^{TM} is intended for inspection of railway bridges and other critical building constructions.

The firm MML cites the following data: during X-raying 1m of reinforced concrete on PXB-7.5, the exposure time can be as little as 20 minutes, of for 1.5 m of concrete 1.5 hours.

The process of bridge inspection and image acquisition is shown in Figs. 9 and 10.

MML developed a technique that lets the traffic of one lane flow when the exposure is on, while the traffic stops on the other lane by traffic lights for a short period of time.

Another possible application area of the small-size betatrons. At rather high energies, the betatron can be used not only as an X-ray source but also as a neutron source.

Such a source can be used for inspection of large-size containers by a radiographic method and, if there are any suspicions, detect fissionable materials using neutrons. The betatron is easily transformed into a neutron source by placing a target-converter behind the output window. The converter material should provide the maximum possible neutron output under exposure to bremsstrahlung. We performed the corresponding experiments on betatron MIB-10 with the maximum energy 10 MeV. We measured integral outputs and energy ranges of neutrons out of lithium deuteride (LiD), beryllium, depleted uranium and lead. Materials containing deuterium yield the best results. In this case, a converter of a reasonable size provides integral output $1.6 \cdot 10^9$ neutrons per second on MIB-10. Using sensitive techniques of fission neutrons registration results in detection limit $(1\text{-}2) \cdot 10^{-3}$ gram for ^{235}U.

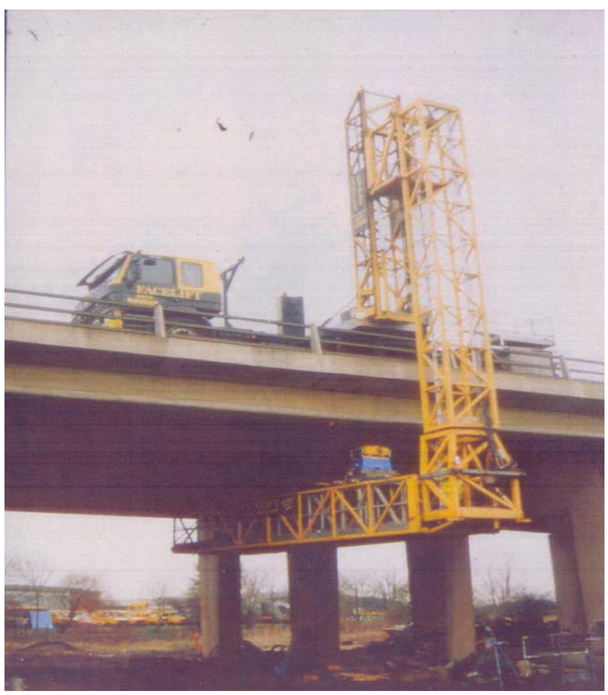

Fig. 9

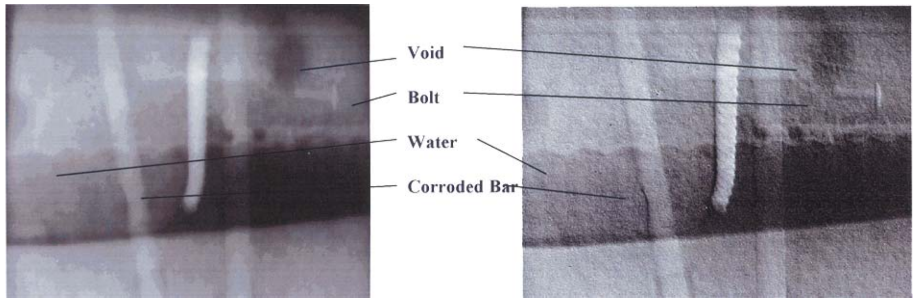

Fig. 10

Conclusions: Thus, at present the small-size betatron is an electron accelerator that has been brought to perfection over many years of purposeful work. It is mainly used as an X-ray source for non-destructive testing.

Its advantages are:

- possibility to X-ray products in a wide range of thicknesses up to 350 mm in steel and 1500 mm in concrete;
- small size of the focal spot;
- high sensitivity; at registration on an X-ray film the sensitivity may reach 0.5% of the thickness of a controlled product;
- complete radiation safety of a switched-off betatron,
- a single-phase mains is required for power supply; consumed power does not exceed 3 kVA;
- no special cooling systems; only built-in fans are used for cooling.
- easy to transport, operate and maintain; great potential service life;
- rather low cost and maintenance charges.