MINIMUM SIZE AND ECONOMIC OPERATION OF UP-TO-DATE SINGLE-TANK INDUSTRIAL X-RAY APPARATUS

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Rapid developments in material testing techniques are equivalent to ever increasing requirements so far as non-destructive testing apparatus and, first of all, X-ray apparatus is being concerned. It seems to be unavoidable that testing procedures should be applicable not only in industrial X-ray laboratories, but also at the site of installation of the details to be tested, e. g. on boilers, steel tanks, bridges, steel structures, pipelines, aircraft structural parts, castings and welded joints, equally well in the light and chemical industries, in factories or building sites, installation operations, etc. (see Figs. 1 and 2).

Tests must be performed very frequently on difficultly accessible places, in high elevations or depths, narrow places — possibly without major preparatory operations and time losses. Obviously, the operating range of industrial X-ray equipment having adequate performance will extend to a field the broader the smaller the size of the X-ray generator. Thus it may seem appropriate to investigate the possibilities of size reduction and limits with due regard to permissible stresses in structural materials and also to permissible heating.

The material and thickness of the object to be tested will define unequivocally the necessary voltage of the high-tension generator in order to generate an X-ray radiation of specified penatrating power. In case of ferrous materials the necessary voltages are given by the following table:

Table I

Object gauge	15	30	65	80 mm
Peak voltage	90	120	200	250 kV

Current load capacities of known industrial X-ray tube types are, as a rule, between 5 and 30 milliamps. For the sake of portability, current intensities in the neighbourhood of 5 mA appear, to be the most favourable, because in this case no external water-cooling system nor high-tension rectification is needed, thus providing substantial advantages in the size and operation of the apparatus.

In order to attain the necessary insulating strength and economical service life, the main design effort should be concentrated on properly defining the general layout ot the high-tension transformer and the heating transformer, the suspension unit of the X-ray tube, the oil-filled insulating gaps and the proper choice of the oil-circulating pump.

To obtain a high-tension transformer of sufficiently low weight, iron cores of reduced cross-section shall be chosen, this being limited by the copper losses and voltage drops increasing proportionally with any reduction in section. For the sake of obtaining favourable and economical dimensions, the section of the iron core column should be determined by the following formula:

$$Q = 0{,}013 \cdot B \sqrt{\frac{P}{\nu}}$$

where B denotes the peak value of magnetic induction in Gs, P the rated power per column in kVA-s and ν the frequency of the supply current. B should be chosen with its maximum permissible value according to the sheet quality and within the permissible range of current demand. In the design of the secondary windings it should be taken into account that air must be removed freely during evacuation and that gas particles set free in the oil during normal operation must be able to leave the unit even without additional evacuation. High-tension coils of substantially reduced dimensions are liable to cause creeping discharges and therefore their layer insulation must be dimensioned, accordingly.

Insulating distances between transformer parts under high-tension may be

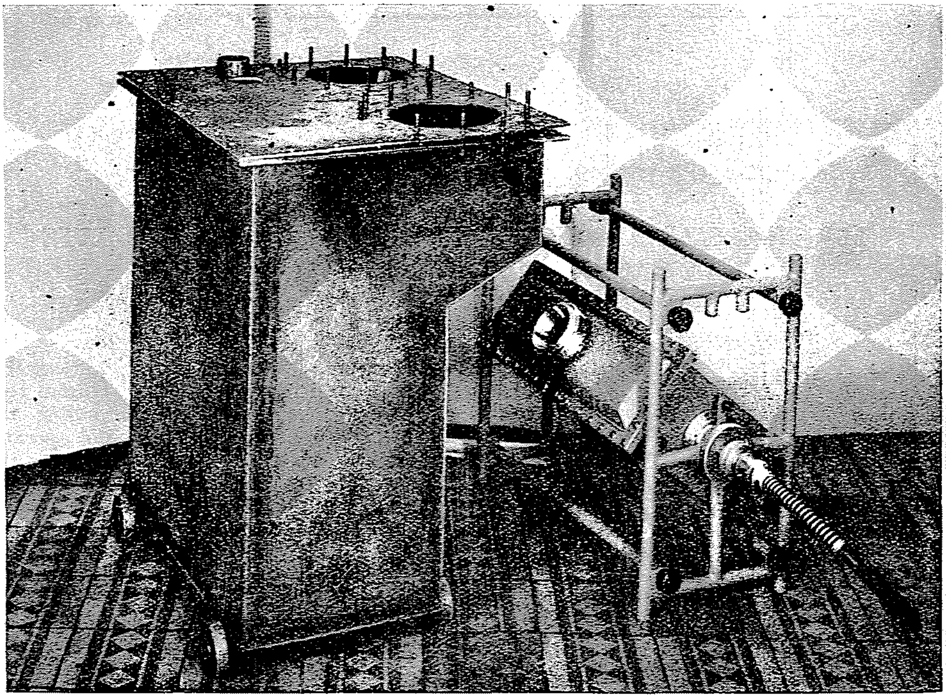

Fig. 1. X-ray apparatus "Liliput 120" during testing of a transformer tank

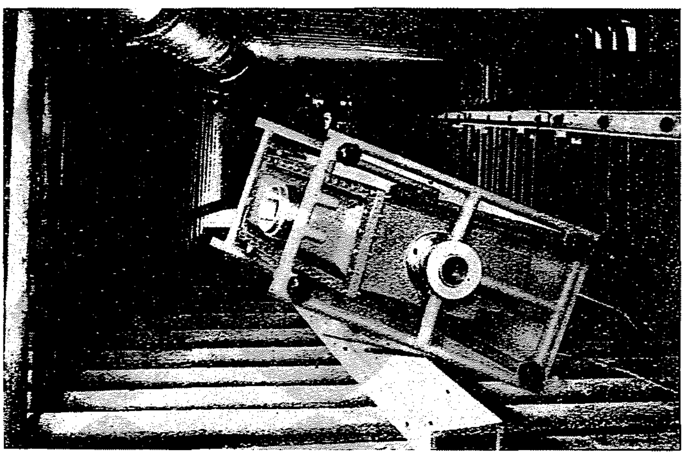

Fig. 2. X-ray apparatus "Liliput 120" during tests performed on the tube system of a boiler economizer

effectively reduced by choosing proper rounding-up radii for the high- and low-tension surfaces and by applying insulating coating layers at the places of maximum field strength, supposed that an insulating oil of appropriate dielectric strength is being applied. The same statements apply also for the heating transformer.

Tank dimensions are defined by the size of the necessary X-ray tube. X-ray

By using up-to-date insulating principles, tanks of relatively low dimensions and weight may be obtained (see Fig. 3), but as a consequence of tank heating it is not the smallest apparatus which simultaneously constitutes the most economical design solution, as it will heat up more rapidly due to its smaller heat capacity and reduced cooling surface. Thus its permissible operating time will be reduced. In order to find the most

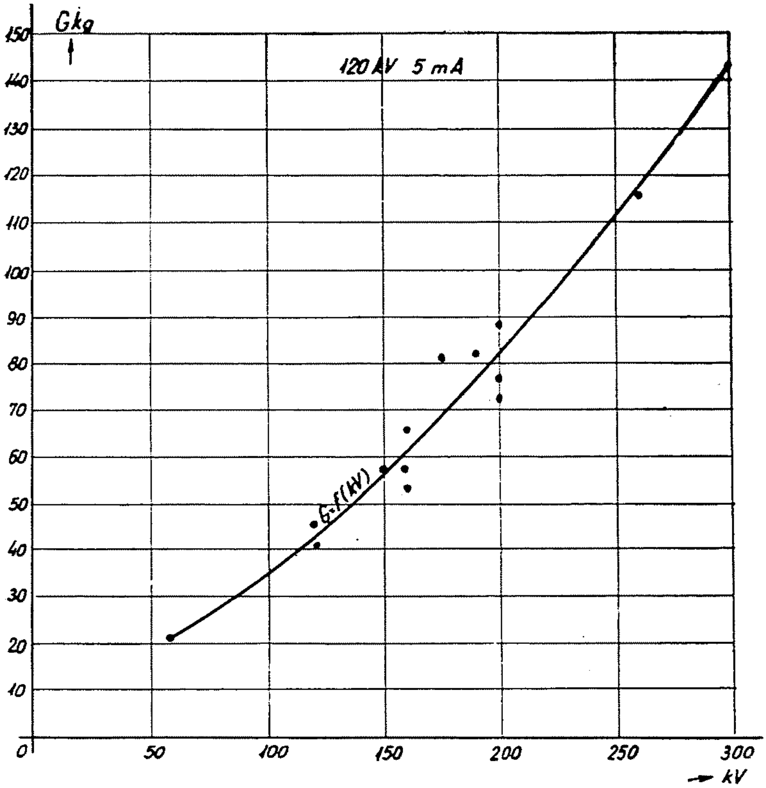

Fig. 3. Weight data of known types of single-tank industrial X-ray generators

tube types for 5 milliamps continuous load capacity and for voltages between 90 and 300 kilovolts are of approximately the same size even for tubes of different origin and their main dimensions may be expressed by the following empirical relations:

overall tube length with electrodes:

$$h = -50 + 2.6\ \mathrm{E}$$

tube length without electrodes:

$$h' = 30 + 1.5\ \mathrm{E}$$

maximum tube diameter:

$$d = 25 + 0.37\ \mathrm{E}$$

where E denotes tube peak voltage in kilovolts and dimensions are given in millimetres.

favourable compromise between the advantage offered by increased mobility and the disadvantage of reduced operating time, let us analyze the heating of the generating unit of the single-tank "Liliput 120" X-ray apparatus built according to design by the author and compare it with the heating of a generator of identical load but built with a weight 30 per cent below the former value. Generator load should be 5 milliamps in both cases. Copper and iron losses and X-ray tube losses give an accumulated loss of 470 W. Data influencing heating are summed up in the following table:

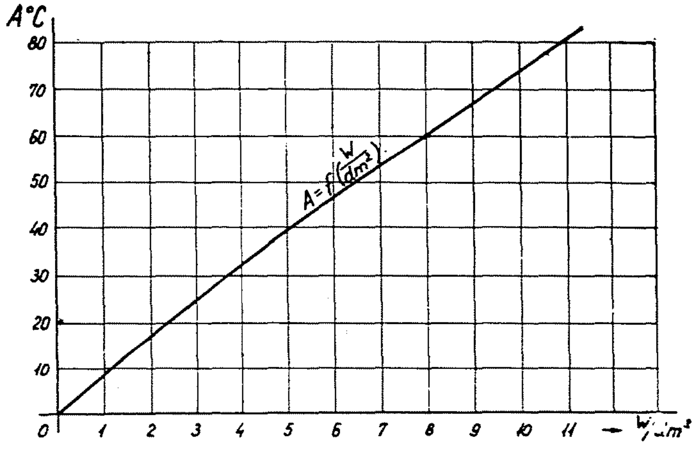

Fig. 4. Excess heating temperatures of oil-immersed transformers in continuous operation as a function of the specific load in watts per sq. dm

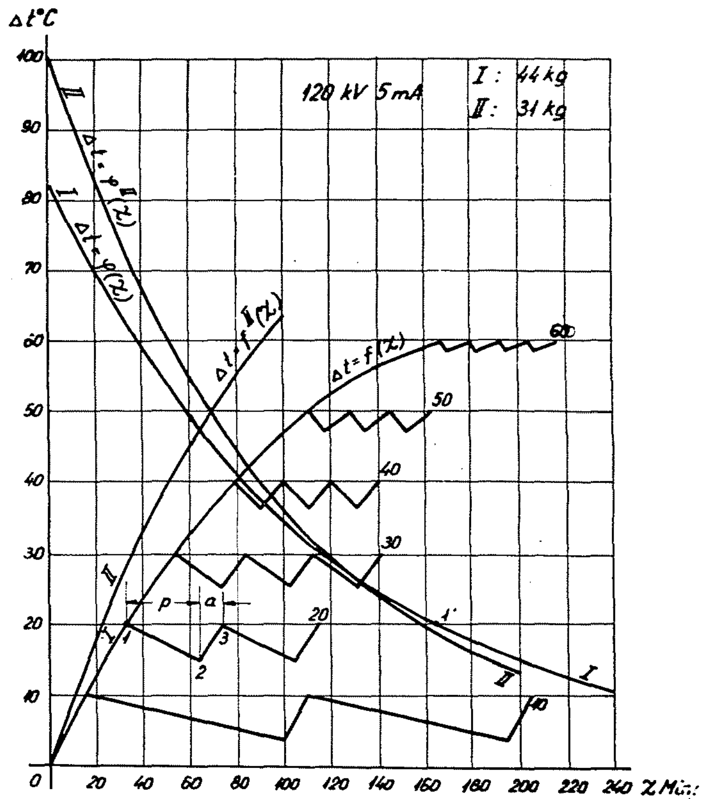

Fig. 5. Heating and cooling curves of X-ray generators (for 120 kV and 5 milliamps) in case of continuous and intermittent operation

Table II

No.	Weight filled-up with oil G, kg	Cooling surface F sq. dm.	Heat capacity kg x spec. heat C	Losses watts W	Watts per sq. dm.	Time constant, min. Z
I......	44	42	9,6	470	11,2	120
II......	31	33	6,85	470	14,2	100

In continuous operation generator temperature tends to a final maximum excess given in Table II and denotes the time during which the heated body would reach its final temperature without loosing heat to its environment.

Time constant is given by the following formula :

$$Z = \frac{A \cdot C}{W} \cdot \frac{4180}{60} \text{ minutes}$$

It can be seen from this analysis that the final temperature of the X-ray generator is far in excess of the limit value of 45 to 50° C, permissible with regard to

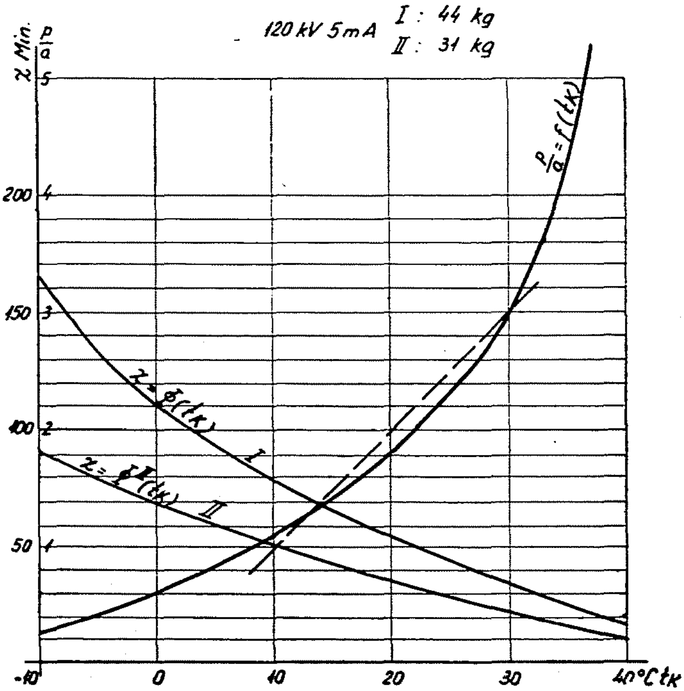

Fig. 6. Permissible operating times (Z) and permissible pause-operating-time ratios (for intermittent operation) against ambient temperature for X-ray generators (for 120 kV and 5 milliamps).

temperature A over that of ambient air and its value is given by the curve shown on Fig. 4 as a function of specific load in watts per sq. dm. The heating curve represents the superposition of the heating due to the Stefan—Boltzmann radiation law and to heat conduction. It is commonly applied in transformer design. Maximum excess temperature for cases I and II with continuous load attains the following magnitude, when compared against ambient temperature :

$A_I = 82°$ C, $A_{II} = 100°$ C. The time constant of heating may be computed from the values of A and those of C and W the X-ray tube and oil expansion. Thus operational times must be determined during which the limit temperature of 50° C is being attained for different ambient temperatures. The generally known exponential formulae for heating and cooling are the following ones :

$$\Delta t = A \cdot (1 - e^{-z/Z}) \text{ and } t = A \cdot e^{-z/Z}$$

By substituting the values for the apparatus to be investigated, as enumerated in Table II, the following equations are obtained for the heating and cooling of the generator of the X-ray apparatus "Liliput 120" :

$$\text{I. } \Delta t = 82 \cdot (1 - e^{-z/120}) \quad \text{or } \Delta t = 82 \cdot e^{-z/120} \ {}^{\circ}\text{C}$$

$$\text{II. } \Delta t = 100 \cdot (1 - e^{-z/100}) \quad \text{or } \Delta t = 100 \cdot e^{-z/100} \ {}^{\circ}\text{C}$$

The solutions of these equations are represented by the curves on diagram Fig. 5 for the original apparatus (I) and for that of reduced weight (II). It can be seen from these curves, what values of operating durations may be obtained for different heating conditions; curves of thermally permissible operating time durations may be plotted against ambient temperature (see Fig. 6, permissible excess temperature being equal to $50 - t_k$, where t_k denotes the ambient temperature). Maximum permissible durations of uninterrupted operation Z may be read for maximum load conditions (120 kV, 5 milliamps).

Some important values of operation time may be seen from the following table:

Table III

Ambient temperature, C°	—10	0	10	20	30	40
Operating time, Gen. I. min.	165	110	80	56	35	16
Operating time, Gen. II. min.	90	70	51	35	22	10

Thus the average reduction in operating time — as a consequence of weight reduction — attains 37 per cent.

After having attained the limit temperature of 50° C an appropriate pause should be inserted so that — after cooling down — operation could be continued periodically if, by proper choice of the duration of pauses and operating periods it could be ensured that the cooling down during pauses is equal or higher than the heating-up during the subsequent operating period. Let us denote the duration of pause by p and that of operation by a. Try to find the ratio p/a, where during intermittent operation no further increase in temperature is being observed. By selecting the operating time less than one-tenth of the time constant, curves representing the heating and cooling periods may be taken for straight lines parallel to the tangents of the cooling or heating curves in the relevant diagram points. Take as an example the point *1* on Fig. 5, draw the cooling curve as a straight line parallel to the tangent in point *1'* up to point *2* and then the heating curve parallel to the tangent in point *1* up to point *3*. The ratio p/a as obtained from triangle 1—2—3 is given by $p/a = 3$.

Performing the same operations for the points of 10, 20, . . ., 60°C excess temperature the curves of p/a as shown on Fig. 6 are obtained as functions of ambient temperature. For the ambient temperature range between +8 and +34° C the plot of the ratios p/a may be substituted by the dotted curve as shown on Fig. 6. From this one may conclude that during intermittent operation the ratio of pauses and operating times is approximately equal to one-tenth of ambient temperature (in °C).

Summary

A detail analysis of the single-tank industrial X-ray apparatus "Liliput 120" of Hungarian design and production — this being the most up-to-date apparatus offered by the export trade company Medicor, Budapest — shows the following results:

Use of up-to-date design and high-quality materials will permit to attain relatively low generator weight and small sizes (Fig. 3). Any further reduction of size and weight as experienced with different known apparatus of other produce is no longer justified because of the increased heating effect and correspondingly reduced operating time due to size reduction.

Maximum permissible uninterrupted operating time and — for intermittent operation — the ratio of pauses and operating has been determined as a function of ambient temperature, the latter ratio being approximately one-tenth of ambient temperature with an accuracy satisfying practical requirements.

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