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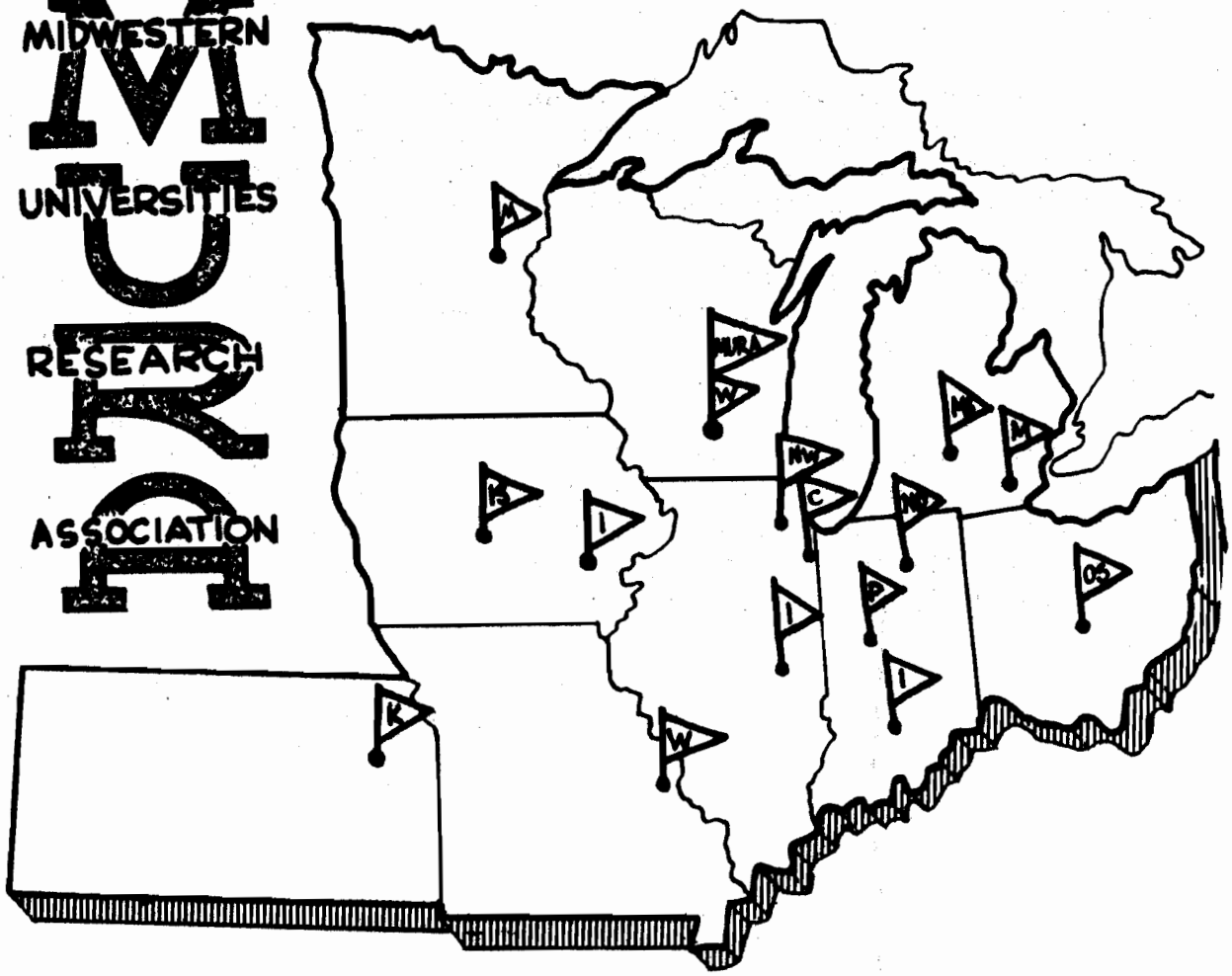

PREACCELERATOR COLUMN DESIGN

C. D. Curtis and G. M. Lee

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P.O. Box 6, Stoughton, Wisconsin

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ABSTRACT

The design of an accelerating column for proton beams of 200-400 mA requires special attention to space charge forces if distortions of beam emittance due to aberrations are to be avoided. A high gradient column design to accelerate a large diameter beam in a converging spherical field is presented. The re-entrant structure of titanium and stainless steel electrodes has good ion source accessibility and is designed to operate at 750 kV with a 30-cm accelerating gap. The ceramic column of 21-inch length resides in a pressurized atmosphere, which is contained by a filament-wound fiberglass vessel 3-1/2 feet in diameter and seven feet in length.

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I. Preinjector Intensity

The recent increases in existing and projected beam current capabilities of linacs require corresponding improvements in preinjector performance. Low emittance beams from ion sources in the intensity range of 200-400 mA are now considered necessary to match linac performance. A variety of sources[1] appear capable of giving the required beam. The duoplasmatron in particular has been tested with a plasma expansion cup geometry at several laboratories including Leningrad, Brookhaven, CERN, Argonne, and Oak Ridge. Measurements have shown that emittances of 5-10π mrad-cm for a 400 mA beam at 750 keV are possible.

The 200 MeV Argonne linac has a beam current design value of 100 mA. If one assumes a proton percentage of the preinjector beam of 80% and a buncher system which enables capture of 60% of the beam into linac synchrotron phase space, the minimum total beam current required from the source is approximately 200 mA. The linac acceptance is calculated to be 20π mrad-cm. From the above emittance figures currents greatly in excess of 200 mA will fit well within the acceptance.

II. Requirements

There are three principal requirements that we should like to meet in the design of a high current accelerating system. The first of these is that the undesirable effects on beam emittance by space-charge forces within the beam be removed or rendered very small. One approach to accomplish this is to use a Pierce-type field geometry to balance out the self-forces during acceleration of the beam. This balance can be achieved for a particular value

of beam current. Another approach is to provide a beam from the source which is initially large in diameter to reduce the self-forces and which can be accelerated very quickly to reduce the time for the forces to act. Both approaches lead to a high field gradient in the accelerating gap or column.

A second requirement is for reliability of operation without voltage breakdown. Because of the premium placed on a high field strength capability within the column, we wish, if possible, to design the over-all system so that the chance of breakdown due to conditions external to the accelerating gap is small. When we are successful in this, our principal concern will be limited to the voltage-holding properties within the column.

The third requirement is for good ion source accessibility. Under the assumption that servicing of the ion source is a major cause of downtime on a preaccelerator, it is important to provide for fast access and change capability. In particular, on an experimental facility where changes may be needed frequently, this is important. In the case of accelerator operation, the use of two preinjectors with one on standby should give increased reliability.

III. Electrode Design

To provide for a large diameter beam we have chosen to use the scheme of a plasma expansion cup attached to a conventional duoplasmatron source, following the example of Solnyshkov[2] and others. We propose that the extraction grid be the first electrode of the high gradient acceleration region as shown in Fig. 1. The beam, thus, will be accelerated quickly without the delay required in passing first through a focusing lens. The plan is to control the focal properties of the beam to some extent for any given

current intensity by simultaneous adjustment of the plasma density and the extraction voltage. A properly concave plasma surface will render the beam initially converging. Use of a fine mesh grid to shape the boundary would be a welcome addition, if successful. The source position is shown in Fig. 1. The exact configuration of the source cup and extraction grid are subject to experimental change. Although there is shown a duoplasmatron, which is at present undergoing tests, other sources could be adapted to the column.

Unless one uses an accelerating field of the appropriate shape to counteract the space-charge forces there will be some divergence of the beam. One can see the dependence of the divergence on beam size and field gradient by assuming a uniform accelerating field. If one further assumes a cylindrical beam of radius R and of uniform charge density, which remains uniform across the beam diameter, one can derive an expression for the divergence of the ion beam after acceleration through some difference in potential. This is given approximately for a particle at the edge of a long beam with neglect of end effects by

$$\theta = \frac{I}{ER} \sqrt{\frac{m}{-2\,ev}} \ \ln \frac{V}{V_o} \ .$$

The beam here is assumed parallel as it crosses the surface of potential V_o relative to the source. For a given final potential V one notes the divergence angle to be proportional to beam current I and inversely proportional to beam radius and to field strength E. For constant gradient and variable V there is

a maximum θ for $\ln \frac{V}{V_o} = 2$. As an example we may consider a beam of 4 cm radius accelerated through a column or gap of 30-cm length. If the initial potential of the parallel beam is $V_o = -50$ kV and the final potential V is -500 kV, the angle θ becomes 6×10^{-3} radians. If V is changed to -1000 kV, θ becomes 2.6×10^{-3} radians. This divergence is comparable with the spreading which results from thermal motion of the ions at the source but does not play the same role in determining beam emittance.

An initially homogeneous beam does not remain so in a uniform accelerating field. The potential hill in the center of the beam leads to a non-uniform charge distribution and consequently to a spherical aberration of the space-charge equivalent lens.[3] The emittance phase space of the beam becomes distorted as a result so that the effective emittance for the total beam becomes increased. In such a case, at least a portion of the angular divergence due to space-charge contributes to the effective emittance. It is important therefore either to eliminate this aberration or to keep it small.

When considering a short high gradient accelerating column, one is attracted to the idea of a single-gap two-electrode accelerator. If the field in such a gap were converging, it would tend to offset the beam divergence due both to space-charge forces and to the diverging aperture lens at the gap exit. An example of a simple converging field geometry, not of the Pierce type, is given by concentric spherical electrodes as shown in Fig. 2. The optics of the system is given by the formulas in the figure where f is the focal length of the exit aperture lens and F is the distance of focus from this aperture for a beam which, starting from rest, is accelerated radially

between the spheres. The drawing is for the special case of the sphere radii having the ratio of 4/3, which renders the beam parallel beyond the exit.

Aside from the question of adequate voltage insulation between the electrodes in vacuum, there is the problem of insulation at the boundary between vacuum and external pressure. One approach is to take the beam out through a grounded tube which passes through a high voltage bushing support for the high potential sphere. Another approach is to distort the electrode shapes to give a spherical field in the beam region when the grounded electrode is bent back to surround the high voltage electrode as shown in Fig. 2. The electrodes in this figure were determined in an electrolytic tank and give closely the required field shape. A similar geometry except for cylindrical electrodes is used successfully as an electron gun[4] on the MURA 50 MeV accelerator. In this gun the source leads enter through a high voltage bushing, which supports the high voltage electrode.

Of prime concern in such a two-electrode system for the 500 to 1000 kV range is the large area of the electrodes in vacuum. Through the "area effect", one can expect to hold less voltage for large than for small area. For small gaps between stainless steel electrodes withstanding of the order of 100 kV, the breakdown voltage varies with area[5] approximately as

$$\frac{V}{V'} \approx \left(\frac{A'}{A}\right)^{0.15} .$$

One way to reduce the electrode area required to gain a desired field distribution is the usual practice of a multi-electrode design to aid in distributions of the potential across the gap. The electrode area exposed to

the total voltage difference can now be greatly reduced. The "total voltage effect" whereby the breakdown voltage above 100 kV is approximately proportional to square root of electrode separation is not now so severe. A further benefit resulting from use of the intermediate electrodes should be a reduction in x-ray intensity.

In the interest of achieving a high gradient column with good accessibility to the ion source as well as to the exit beam, we considered it prudent for the present to use a multi-electrode design with a conventional arrangement of the ceramic insulators. This is the design of Fig. 1, which still retains a converging field having the optics of Fig. 2. The accelerating gap is 30 cm long. The thin spherical electrodes have supports which flare out to a longer ceramic column of 21-inch length having 14 sections. A variable extraction voltage is applied across the first two sections while the other sections divide the remaining voltage drop equally.

If the exit aperture in the last electrode is covered by a grid, the beam optics will, of course, be changed. The exit lens action is then removed and an otherwise parallel beam will converge, except for space-charge effects, toward a minimum at the center of the spheres.

Each intermediate electrode consists of a thin portion of spherical shape connected to a z-shaped portion which in turn is connected to a conical support. The required field was achieved in an electrolytic tank by John Spooner with only the top and bottom spherical electrodes in place together with the z-shaped portions of the other eleven electrodes. This means that one can

operate either without the spherical electrode portions or with these spherical parts placed along already existing equipotential surfaces. In the latter case, one can thereby hope that, with accurate placement, the thin electrode edges will not be prone to voltage breakdown and will offer only a small perturbation in the field distribution due to finite electrode thickness. The thickness of electrodes which have been constructed is 1/16 inch. In the event of voltage breakdown problems, edge thickening rings can be added.

The electrode material having the best voltage-holding properties in the 100 kV range that has come to our attention is a titanium alloy, Ti-7 Al-4 Mo.[5] Furthermore, since it has a thermal coefficient of expansion which closely matches that of the ceramic rings, it becomes a good ring spacer material. Certain voltage tests which we have carried out on 304 stainless steel and on Ti-4 Al-3 Mo-1 V indicate that stainless also may be suitable although not as good as the titanium alloy. These included tests of gaps up to 0.9 cm between a plane and the end of a thin-walled right circular cylinder of 10-inch diameter. A cylinder of 1/16-inch wall held dc voltages well beyond 100 kV without breakdown at a pressure of 10^{-5} Torr when the gap was paralleled with a 0.02 μf capacitor. In the column a voltage gradient of 75 kV per gap, where the minimum spacing is 1 cm, would give over 900 kV for the total accelerating voltage and a voltage gradient of 30 kV/cm. The tests also showed a lower x-ray level with titanium than with stainless, as expected.

The ceramic rings are 16 inches O. D. Each ring is one inch thick by 1-15/32 inches high and is recessed at the ends as may be seen in Fig. 1. This is to take advantage of any improvement in ability to hold voltage, as observed by others[6] when the cathode end is recessed. The rings have been vinyl sealed together with titanium spacers. A photograph of the column appears in Fig. 3.

In assembly the electrodes are inserted into the column through the high voltage end. A jigging arrangement permits accurate positioning of each spherical electrode with its attached z-shaped portion before it is connected to its conical support.

The equipotential surfaces in the column will be moved slightly by the presence of the beam. With a homogeneous proton beam of current I the potential on the axis will be increased by an amount

$$\Delta V = 6.5 \times 10^5 \left(2 \ln \frac{b}{a} + 1\right) \frac{I}{\sqrt{-V}}$$

where V is the undisturbed potential, a is the beam radius and b is the effective radius of the accelerating aperture. The potential difference between points on the axis and on the beam envelope is given by the second term within the parentheses. The beam diameter should therefore be large to reduce the radial gradient within the beam. Typically, ΔV will be a few hundred volts for a 0.2 ampere beam. With operating column gradients of $\gtrsim 20$ kV/cm, the equipotential surfaces in the beam will be displaced a few thousandths of an inch and flattened slightly. If one wishes, one can move the potential

surfaces around quite freely by varying the external voltages applied to the electrodes. In fact the present potential distribution is sufficiently close to that of a Pierce-type cylindrical geometry that potential adjustment to approximate this would not be difficult. To obtain the rectilinear flow which would match this Pierce geometry would then necessitate either higher beam current than we now require or a reduction in beam diameter.

IV. Pressurized Shell Assembly

In order to diminish the possibility of voltage breakdown outside the accelerator column, we decided to enclose the column in a pressurized atmosphere. A practical way to do this is to use a filament wound fiberglass vessel as shown in Fig. 1. Such items are made commercially in a variety of sizes for rocket motor cases and chemical tanks. The vessel we are using was wound by Brunswick Corporation onto end flanges machined at MURA. A photograph of the vessel is shown in Fig. 4. The wall thickness is 1/8 inch with an additional 1/16 inch rubber liner to seal the fiberglass for SF_6 up to 100 lbs/in^2. The finished product is 42 inches inside diameter and 84 inches long and was tested at 200 lbs/in^2.

There is a 17-inch diameter access channel to the source, which remains at atmospheric pressure. Bellows in this tube allow for some stretching of the pressurized tank. The column is under compression when evacuated and approximately neutral when up to air. Source changes are thus possible without disturbance of the tank pressure.

Each column electrode is connected to an external corona ring on the fiberglass shell as indicated in Fig. 1. A resistor string, not shown, divides the voltage here. The resistors can readily be changed if one should wish to alter the field distribution within the column. The position of the column within the tank can be changed, of course, from that shown by changing the electrode leads and the relative lengths of the source and beam exit channels.

Should one wish to test other electrode configurations, the tank should be capable of accommodating designs which vary greatly in electrode and insulator structure from that described here.

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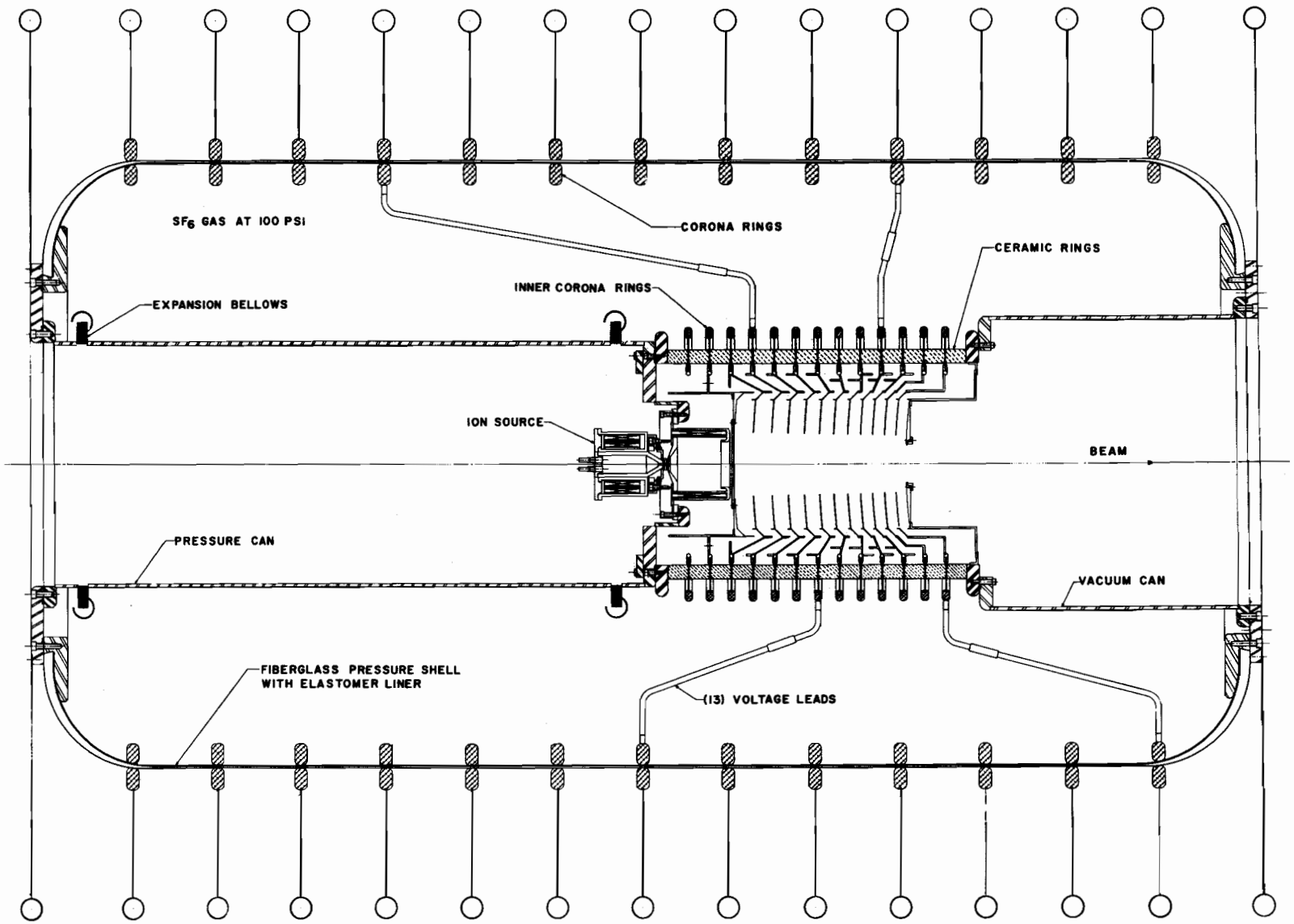
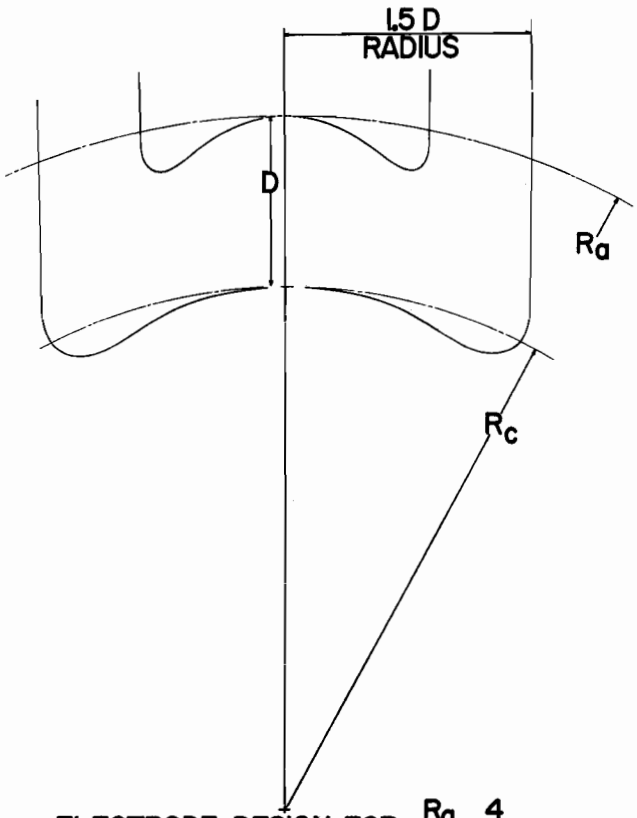

SF_6 GAS AT 100 PSI
CORONA RINGS
CERAMIC RINGS
INNER CORONA RINGS
EXPANSION BELLOWS
ION SOURCE
BEAM
PRESSURE CAN
VACUUM CAN
FIBERGLASS PRESSURE SHELL
WITH ELASTOMER LINER
(13) VOLTAGE LEADS

FIG 1



ELECTRODE DESIGN FOR $\frac{R_a}{R_c} = \frac{4}{3}$

$$\frac{1}{F} = \frac{1}{R_c} + \frac{1}{f}$$

$$\frac{1}{f} = \frac{\Delta E}{4V} = -\frac{R_a/R_c}{4(R_a - R_c)}$$

$$\frac{1}{F} = \frac{3R_a/R_c - 4}{4(R_a - R_c)}$$

FIG 2

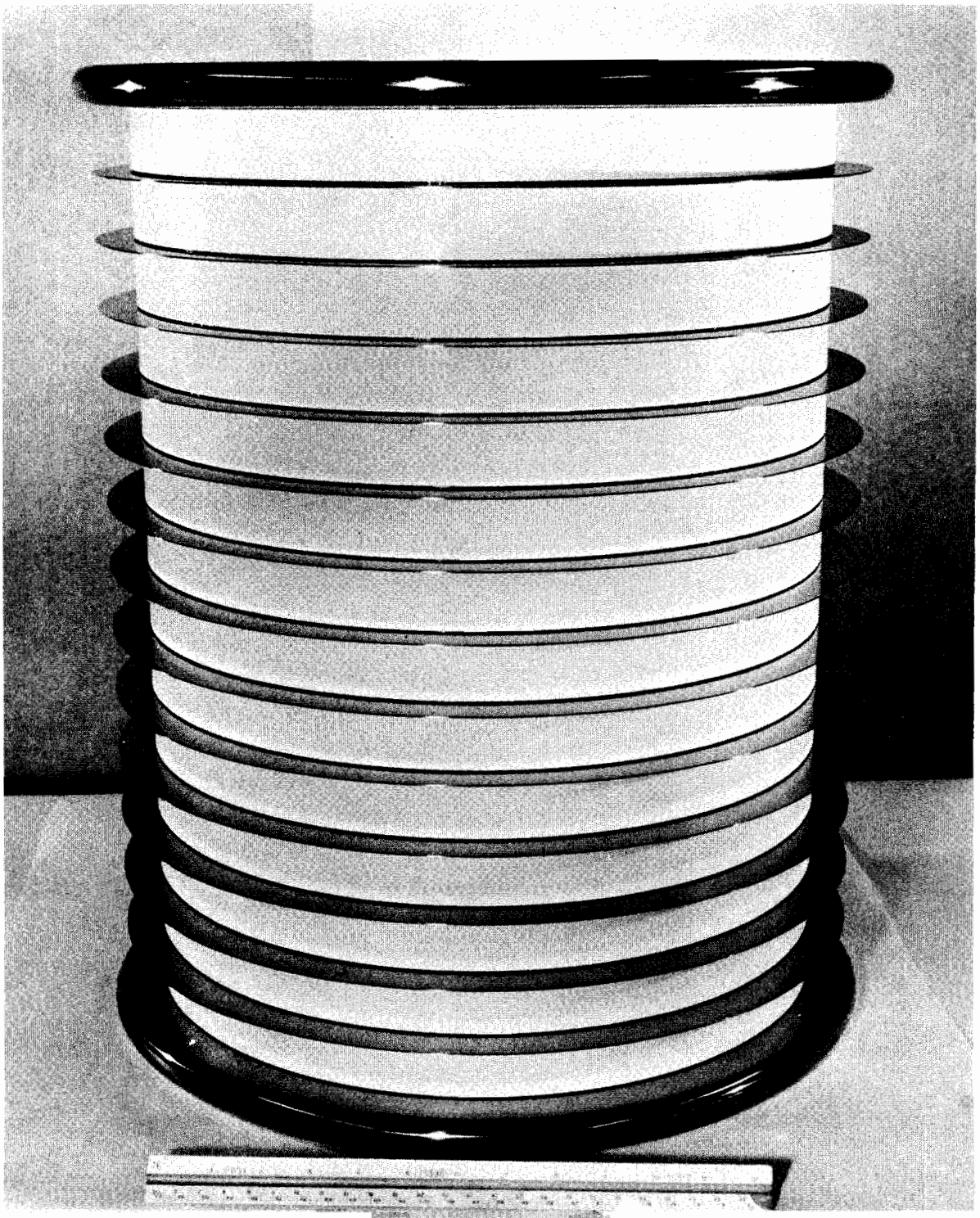


Fig. 3

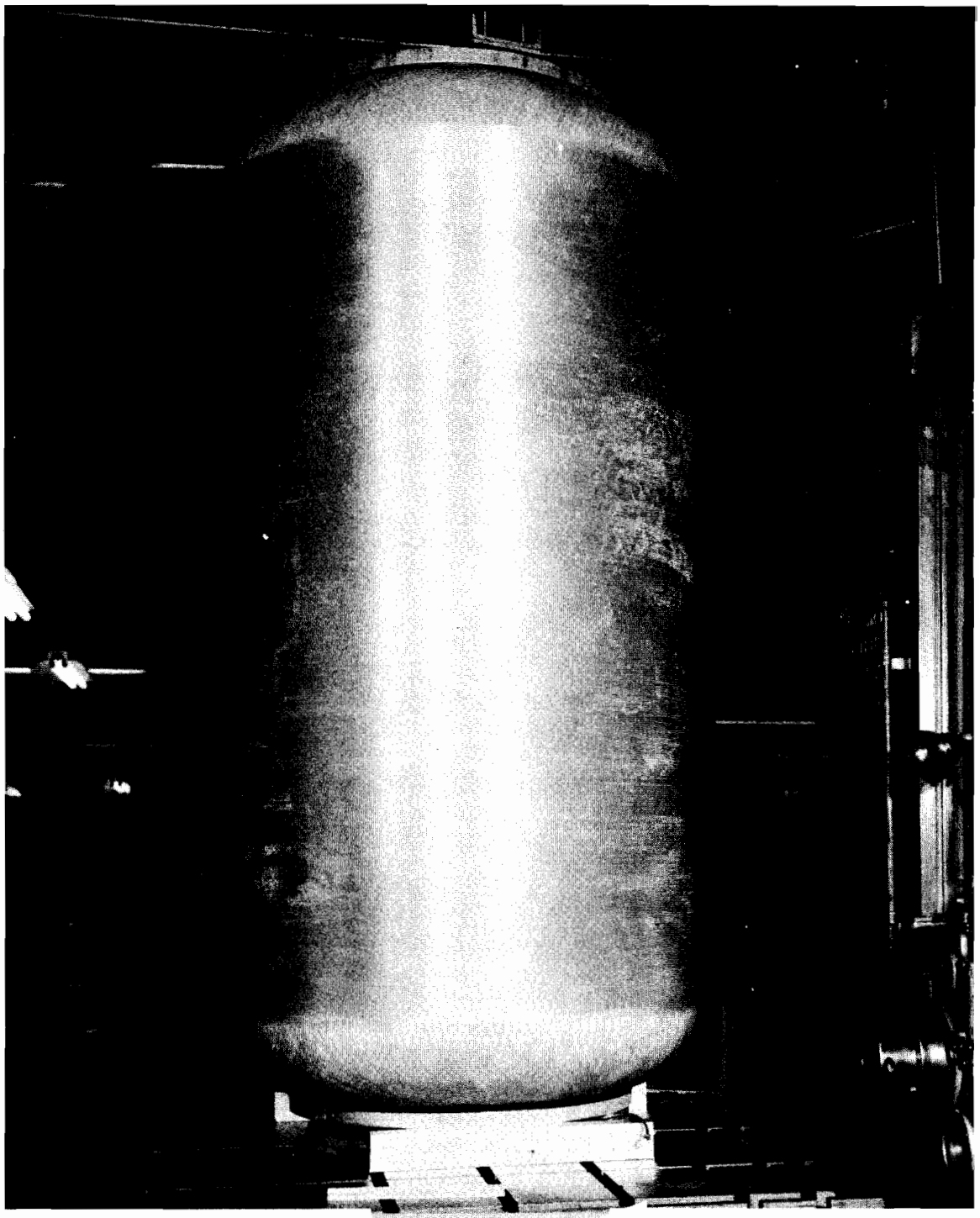


Fig. 4