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Tokamak Neutral Beam Heating Technology*

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ABSTRACT

Same as CONCLUSION with change in verb tense.

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Introduction

Attaining ignition temperatures in tokamak thermonuclear plasmas probably will require a heating system to supplement ohmic heating. A prime candidate for this task is neutral beam heating. Neutral beams are being used to heat present day tokamak devices and are planned for heating the next generation devices as well as future feasibility and burning tokamak experiments. The evolution of the neutral beam systems to satisfy the requirements of the future tokamak experiments should lead to reactor neutral beam heaters. This evolution from present systems can be catagorized into increases in time of operation, beam current and beam energy.

The first two ORMAK injection units at ORNL produce 125 kW of neutral power per injector at 25 to 35 kV with up to 200 msec pulse lengths. Eighty percent of this power is available for heating of the ORMAK plasma and has been successfully used to heat the ORMAK plasma. These units ARE BEING ~~have been~~ scaled up by a factor of two in current and power capability, with two such new units scheduled for installation on ORMAK in June 1974.

Further scaling towards more reactor-like injection systems is now being undertaken. This paper presents some initial design considerations for a 20 A, 150 kV D° injection system, which at this time seems to be the proper parameters for the ORMAK F/BX-2 tokamak concept illustrated in Fig. 1. This system will be based on neutralization of a positive ion beam. These energies and power levels are approaching those of reactor injection units and in fact equal those of some concepts, such as ~~ignition at small radius followed by expansion.~~ 2 meter radius tokamaks.

The initial design considerations include optimization and parameter studies of neutralizing cell lengths, neutral fractions, gas flow rates, total beam line lengths, divergence losses, the number of extraction system STAGES, power loading and power supply current drains. These design considerations are based on the technology, design experience and operating experience of the successful ORMAK neutral injection systems.[2-5]

Neutralizing Cell Lengths, Neutral Fractions and Gas Flow Rates

The heart of the ORMAK neutral injection system is the duoPIGatron ion source[6-8] shown in Fig. 2. The ion source and acceleration ~~In this concept of close-coupling~~ are used ~~as used with those injectors,~~ with a the gas cell which is fitted tightly to the last of the three electrodes of the accel-decel extraction system, shown in the lower part of Fig. 2. Hydrogen or deuterium which is not used in forming the ion beam must pass through the electrodes, through the gas cell, and a large fraction of it is then pumped in the gap beyond the cell.[4] This close coupling simplifies the pumping problem and minimizes the source-to-target distance, thus minimizing beam divergence losses. Alternatives to close-coupling appear to require discouragingly large pumping speeds and pumping capacities.

The neutral gas pressure in the ion source which corresponds to the optimum extracted current density, ~ 0.35 A/cm^2, is ~ 0.015 torr. These optimum values will hold also for scale-ups of this system. The pressure drops across the cell and the electrode system must then total this source pressure. The cell dimensions and gas flow rate are then not independent, as they must produce this pressure rise. So if the neutralizing effectiveness of the cell is dictated, the cell length and therefore its contribution to

the total beam line length have been determined, and the gas flow rate and therefore the pumping requirements have been determined.

Considering the gas conductances for cylindrical tubes and the multi-aperture electrodes, we find the cell length is given by:

$$\ell = \frac{(\overline{p\ell})}{p_s} + \left[\frac{(\overline{p\ell})^2}{p_s^2} + \frac{5.33\, N_E a^3}{g R_o^2} \left(\frac{T_c}{T_E}\right)^{1/2} \frac{(\overline{p\ell})}{p_s} \right]^{1/2} , \qquad (1)$$

Her $(\overline{p\ell})$ is the cell thickness or line density and is being used as a parameter, p_s is the source pressure, N_E is the number of extraction system electrodes and g their transparency, a and R_o are the radii of the gas cell and electrode system, and T_C and T_E are the absolute temperatures of the gas in the cell and extraction regions. The gas flow rate, in torr·liters/sec, is given by

$$Q = 61 \frac{a^3}{\ell^2} \left(\frac{T_c}{M}\right)^{1/2} (\overline{p\ell}) , \qquad (2)$$

where a is in cm, ℓ is the cell length in cm, T_C is in degrees K, M is the mass number, and $(\overline{p\ell})$ is in torr·cm. The beam neutral fraction, assuming an atomic-ion beam, is given by:

$$f_o = \frac{\sigma_{10}}{\sigma_{10} + \sigma_{01}} \left[1 - \exp\left(- \frac{(\sigma_{10} + \sigma_{01})(\overline{p\ell})}{k T_c} \right) \right] , \qquad (3)$$

where σ_{10} and σ_{01} are the cross-sections for neutralization and ionization of the atomic ions in cm^2, and $k = 1.0 \times 10^{19}$ torr/cm^3°K.

These relationships are shown in Fig. 3 for the 20 A, 150 kV D° system. The solid lines are for a cell gas temperature of 300°K and show that for this case a cell length of about 1-1/2 meters is desirable. The cold gas flow

rate is then equivalent to 20 A of atomic neutrals to go with the 20 A of extracted D^+, or a 50% source gas efficiency. Also shown in Fig. 3, by the dotted lines, is the decrease in cell length which can be obtained by cooling the gas to 90°K in the cell region. The desirable cell length is then about 50 cm and the cold atomic neutral flow rate is about 30 A, for 40% gas efficiency.

Divergence Losses and Beam Focusing

We have done studies of the beamlet profiles obtained with a single-aperture extraction system with varying extraction voltages, extraction gaps, pressures, and current densities. We have done extensive studies of beamlet angular displacements, as a function of these source parameters, caused by deliverate misalignment of the single apertures. These data fit very well the empirical equation $\theta = 18.4\ \Delta r/z$ degrees, where Δr is the translation, perpendicular to the beam, of the aperture in the source and z is the extraction gap. This empirical formula is in agreement with a model proposed by Green, which predicts $\theta = 19\ \Delta r/z$.

We combine this profile data and this angular displacement data with data on source plasma density profiles and therefore beam current density profiles to design multiaperture extraction systems. The design equation for aperture displacement thus obtained is

$$\Delta r = 3.11 \frac{R_0}{f} \left\{ z(0) \frac{r}{R_0} + \left[z(R_0) - z(0) \right] \left(\frac{r}{R_0} \right)^3 \right\} . \qquad (4)$$

Here Δr is the displacement of a single aperture at the radial location r on an electrode of radius R_o. f is the desired focal length of the extraction system, and $z(R_o)$ and $Z(0)$ are the values of the extraction gap at $r = R_o$ and $r = 0$. In general, $z(R_o) \neq z(0)$ because of electrode curvature done for

thermal stability and done to obtain optimum single beam optics given the source density gradient.

Electrode systems designed according to Eqn. (4) are used on the ORMAK injectors and provide up to 40% increases in the neutral beam power delivered, over systems which use no aperture displacement. A calorimeter scan of the current density for such a system, done approximately at the focal point, is shown in Fig. 4. Also shown for comparison is a scan for a source and extraction system identical in all respects except lacking the aperture programming of Eqn. (4).

When we examine programmed-aperture profile of Fig. 4 and consider our studies of the single-aperture profiles which comprise the total profile, we conclude the total profile can be represented accurately by a gaussian with a half width given by:

$$\theta_{1/2} = L\left(\tan\theta_s + \tan\theta_r + \sqrt{T_i/V}\right), \tag{5}$$

Here L is the distance from the extraction system to the target, T_i is a characteristic source ion temperature having the same units as V, the beam ion energy, θ_r is single-aperture gaussian half-angle divergence remaining after account is taken of the finite source ion temperature, and θ_s is additional gaussian half-angle spreading introduced by imperfect focusing or summing of the single-aperture beamlets.

The ORMAK injection units exhibit the values T_i = 0.5 eV, θ_r = 0.4° and θ = 0.6°. T_i is probably a characteristic of the duoPIGatron source and may be considered constant for future scalings. θ_r is the result of parameter studies and optimizations of both single-beamlets and total beams and may be very close to optimum, θ_s, however, indicates errors in aperture displacement

which are larger than basic data error bars and larger than can be accounted for by random machining errors. We feel θ_s is due to beamlet angular displacement caused by electrode curvatures and source density gradients. These effects have not been taken into account in the design Eqn. (4). More extensive single-aperture studies will be undertaken to include these effects in electrode design and therefore θ_s may be decreased in the future.

Integration of the gaussian profile gives the total current within a target of radius r:

$$I = I_s \left\{ 1 - \exp\left[-\frac{1}{2} \left(r/r_{1/2} \right)^2 \right] \right\} \tag{6}$$

where I_s is the total source current. This shows that if, as we contend, that programmed apertures allow $r_{1/2}$ to be constant as the source area and therefore I_s are increased, an arbitrary amount of current can be put onto a target of given radius. The penalties to be paid for having I_s large or $r_{1/2}$ large compared with r are large power supplies, increased gas flow, and wasted beam power to be handled.

Equation (6) has been combined with the previous considerations of cell lengths, neutral fractions and gas flows for the 20 A, 150 kV D° system. Using the attained values for T_i, θ_r and θ_s and using the length and size of the beam drift tube compatible with the access and stray fields of the ORMAK F/BX-2 system of Fig. 1, we get an optimum cell length as shown in Fig. 5. This is an optimum in nuetral power delivered to the plasma, given as the ratio of neutral current delivered to total source current, and comes about because increasing the cell length increases the neutral fraction as well as the divergence losses.

Extraction System Power Loading

We observe in our injection systems that extraction system power loading is directly proportional to the pressure in the extraction gap and is independent of aperture misalignment. We conclude from these things that the power loading may not be due to direct interception but rather due to ions and electrons in the extraction gap, produced by collision between the beam ions and the background gas, which are accelerated by the electric field of the gap. The ion incident on the extraction electrode then produce a power loading and also a significant number of secondary electrons, which are accelerated, along with the electrons from the ionizations, towards the source electrode, where they result in power loading.

Pressures in the extraction system are predicted for a particular system as described above, and along with the cross sections for ionization[10] and secondary emission[11] lead to predictions of power loading. These predictions, including source plasma loading, are shown in Table I for the ORMAK systems and for 20 A, 150 kV D° systems (called TCT in the table) which have up to three acceleration stages.

Table I

MAXIMUM ELECTRODE POWER LOADINGS, kW/cm^2

SYSTEM	PLASMA ELECTRODE	FIRST ACCEL ELECTRODE	SECOND ACCEL ELECTRODE	THIRD ACCEL ELECTRODE
ORMAK	0.5	0.08		
TCT ONE STAGE	15	3		
TCT TWO STAGE	5	5	0.5	
TCT THREE STAGE	3	2	2	0.3

The power loadings are given as kW per cm^2 of total extraction system surface and might be decreased by whatever fraction of the power passes through the apertures and onto the internal source structure, which is more amenable to power dissipation. However all this power must be handled by a power supply, and Table II shows these power loadings translated into current loadings of the supplies attached to the various stages. These are given as the basic beam current loadings plus an additional amount due to these extraction system interactions. These additions are per stage for the multistage systems. The 800 mA of additional loading calculated for the ORMAK system is in agreement with the actual loading observed.

Table II

POWER SUPPLIES

ORMAK	25 kV, 8 A + 0.8 A
TCT ONE STAGE	150 kV, 20 A + 12 A
TCT TWO STAGE	150 kV, 20 A + 8 A
TCT THREE STAGE	150 kV, 20 A + 6 A

According to the model presented, the power loadings are given by approximately by

$$P \approx (\bar{\gamma} + 0.5)(\Delta V)\, j\, z\, \bar{\sigma}\, \rho \tag{7}$$

where $\bar{\gamma}$ is an averaged secondary coefficient, ΔV is the acceleration-stage voltage drop, j is the beam current density, z is the acceleration-stage gap, $\bar{\sigma}$ is an averaged ionization cross section, and ρ is the background gas density. For our copper extraction electrodes, $\bar{\gamma} \approx 2.5$ and therefore secondary emission is the dominant contribution to the power loading.

Because of this, we will undertake a program to reduce the secondary emission by using coatings or electrode materials other than copper.

The extracted current density is a function of the voltage drop and the ap size according to the Childs-Langmuir law:

$$j = C \frac{(\Delta V)^{3/2}}{M^{1/2} z^2} \tag{8}$$

where $C = 5.44 \times 10^{-8}$ for ΔV in volts, M in A.M.V. and z in cm. Also the gas flow rate and therefore the gas density is proportional to the extracted current density. Combining these we find:

$$P \propto j^{3/2} \tag{9}$$

So we see that backing off in current density and compensating by increasing the source and extraction system radius is a way of decreasing the large power loadings of Table I and II.

Tables I and II also indicate that power loadings per stage can be decreased by increasing the number of stages, thus making the total power easier to handle. If the voltage is divided equally between stages, we have $\Delta V \propto 1/n$, where n is the number of stages, and from Eqn. (18), $z \propto (\Delta V)^{3/4}$. Combining these gives

$$P_{\Delta V} \propto n^{-7/4} , \tag{10}$$

illustrating the gain to be obtained by increasing the number of stages.

We will be obtaining design values for the allowable power loadings by pushing our systems to whatever limits appear while monitoring calorimetrically and electrically the electrode power loadings. We expect the intensive beam-extraction system interaction to cause electrode destruction and/or voltage

breakdown. This latter effect may already have been noted by Culham[12] who report breakdown at a voltage given empirically by $V_B = 6 \times 10^4 z^{1/2}$, with z in cm and V_B in volts. If we set $V_B = \Delta V$ and combine Eqns. (7), (8), and (9), we get

$$V_B = \left[\frac{MP}{1.71(\bar{\sigma} + 0.5)\bar{\sigma}} \right]^{1/4} z^{3/4} \tag{11}$$

This $z^{3/4}$ scaling along with the variation in $\bar{\sigma}$ as a function of V_B produces good agreement with the Culham data. If we then use our system parameters, which we expect to be similar to those of Culham, we get $P \approx 30$ kW/cm^2 at breakdown.

Conclusions

Initial design considerations for a 20 A, 150 kV D° neutral injection system, based on neutralization of positive ions, have been presented. This design has been and will be based heavily on the technology, design experience and operating experience of the successful ORMAK injection systems. Some results of optimizations and parameter studies of the neutralizing cell lengths, neutral fractions, gas flow rates, total beam line lengths, divergence losses, extraction system power loading and power supply current drains have been presented. Substantial extraction system power loadings and the resultant power supply current drains indicate a potential problem area. This potential problem area is being approached through experimental tests of system power handling capabilities and tests of the basic concepts underlying the predictions. Approaches in the near future will include tests of multistage extraction systems and tests of various electrode materials and coatings to control secondary emission. Plans are being laid for test stands and power supplies capable of full scale testing of the 150 keV D° injection system which evolves.

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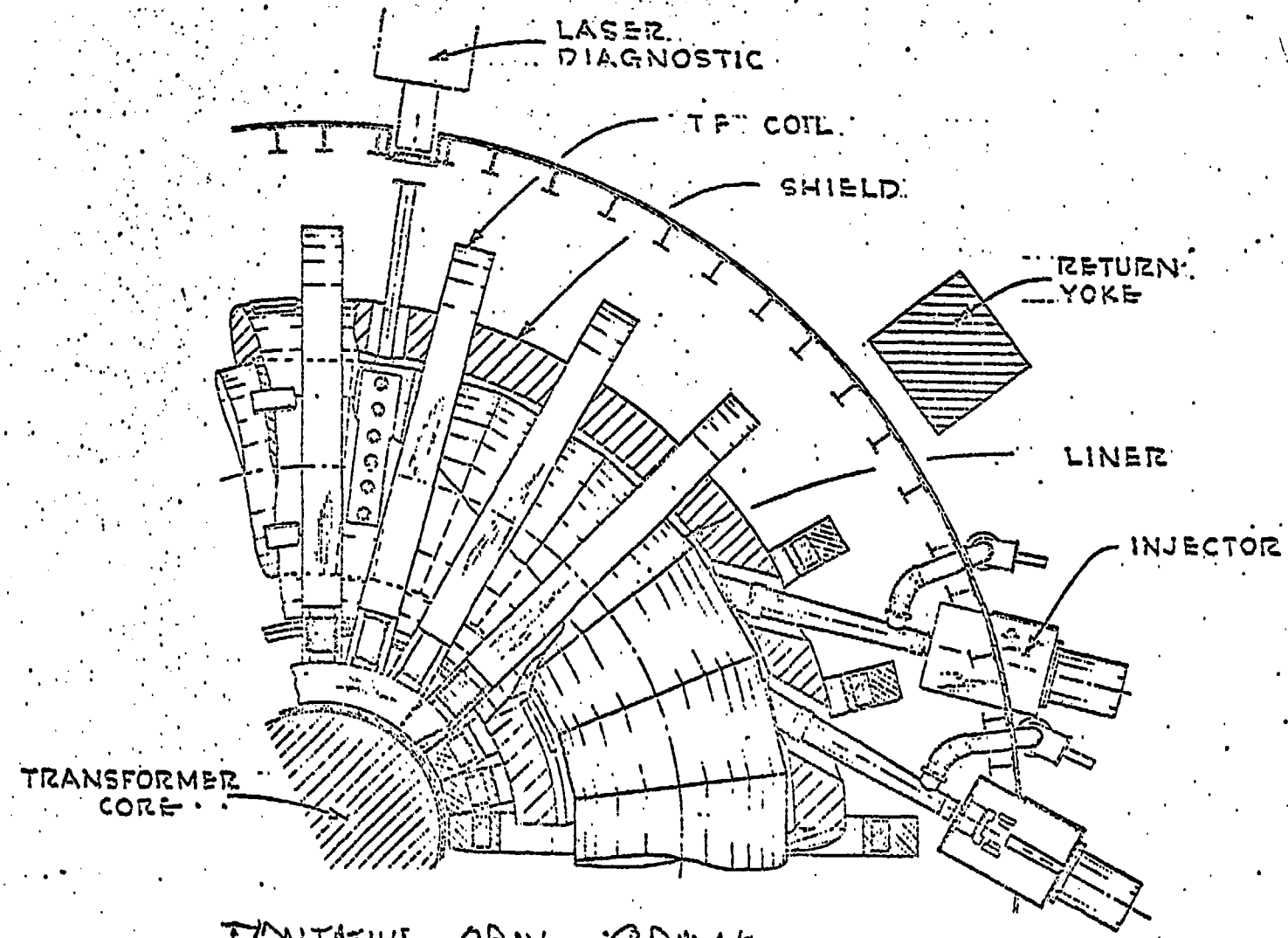
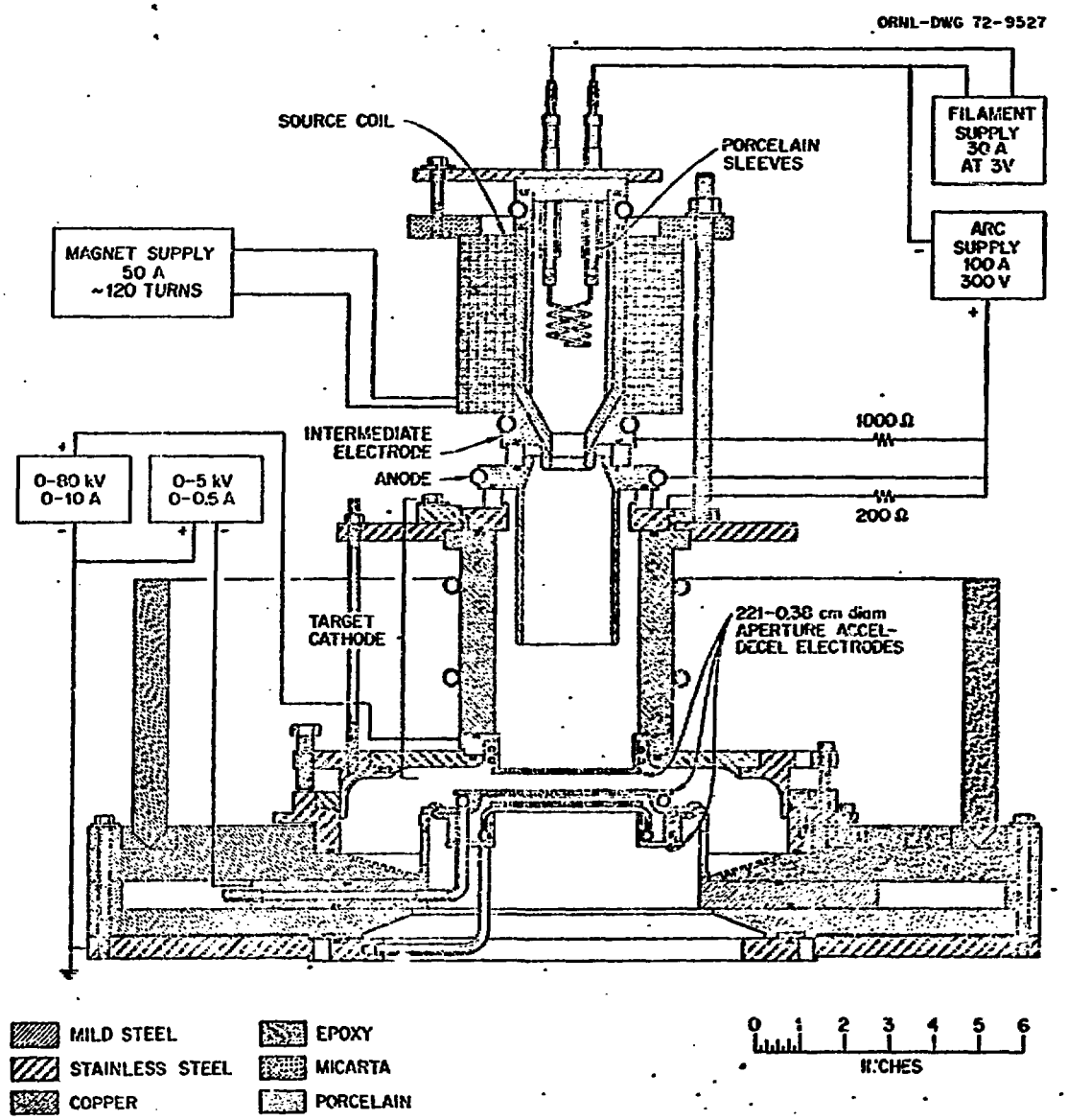
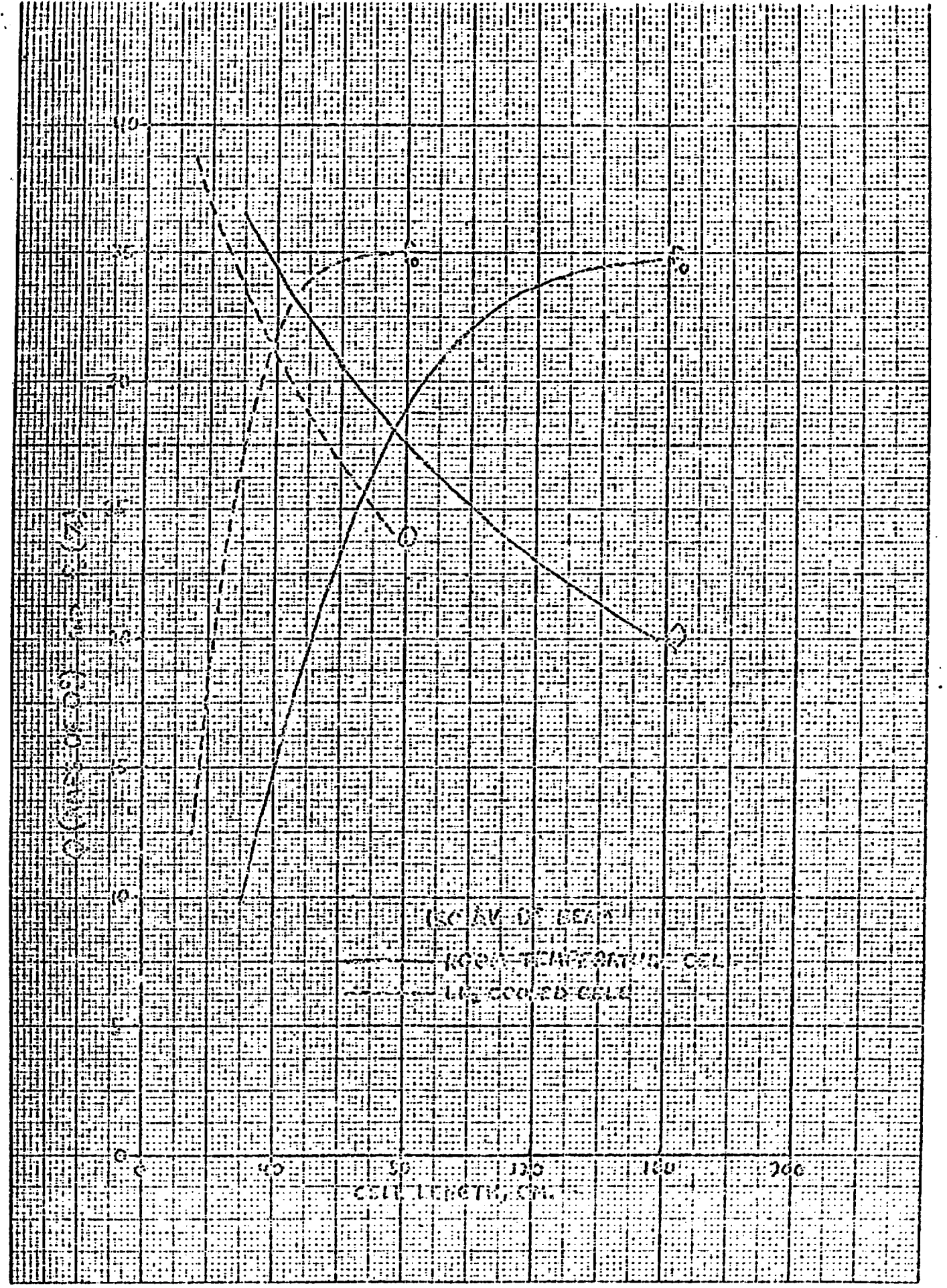


TENTATIVE ORNL ORMAK
F / BX - 2 REFERENCE DESIGN

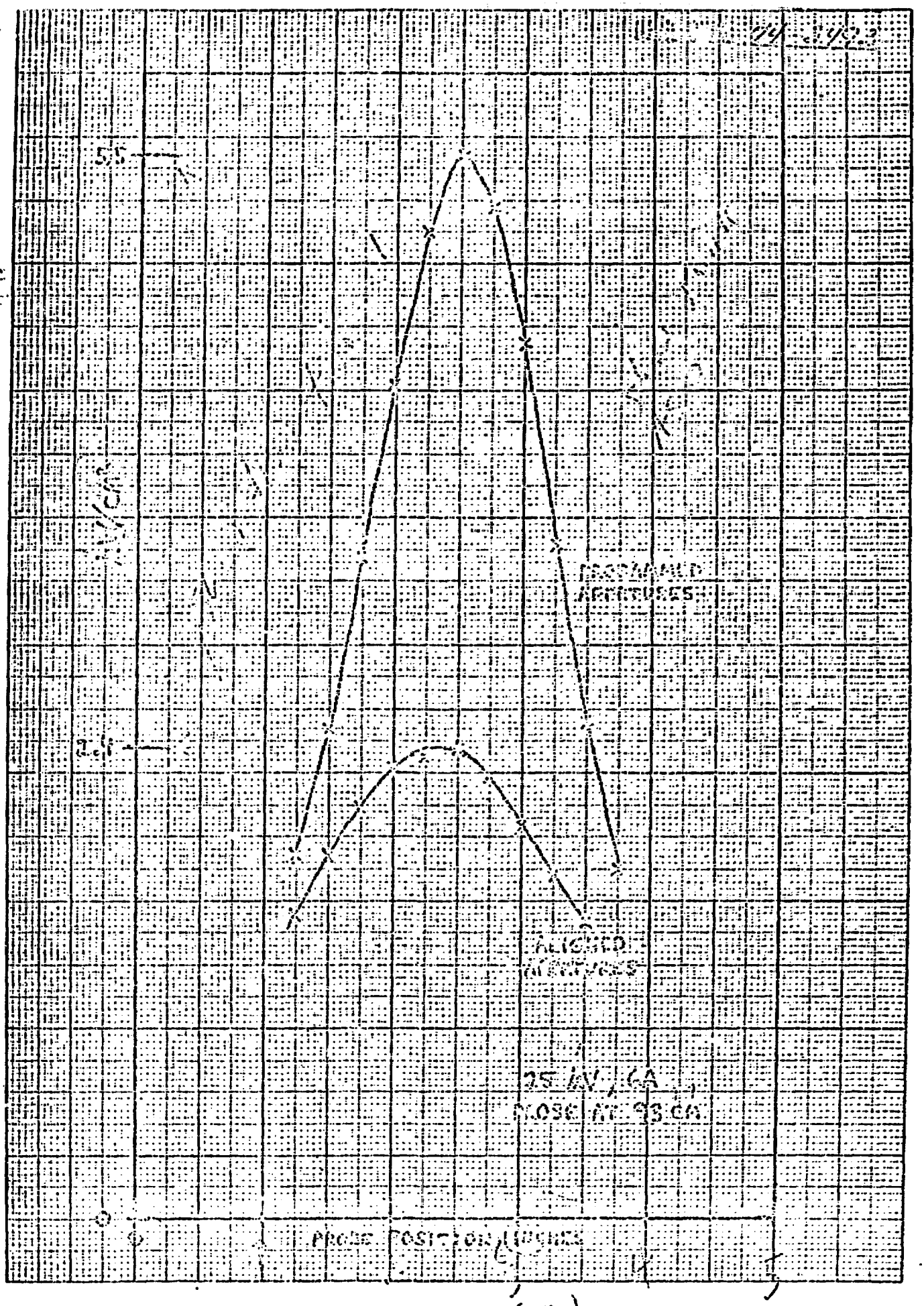
0 1 2 3 4 5 6
METERS



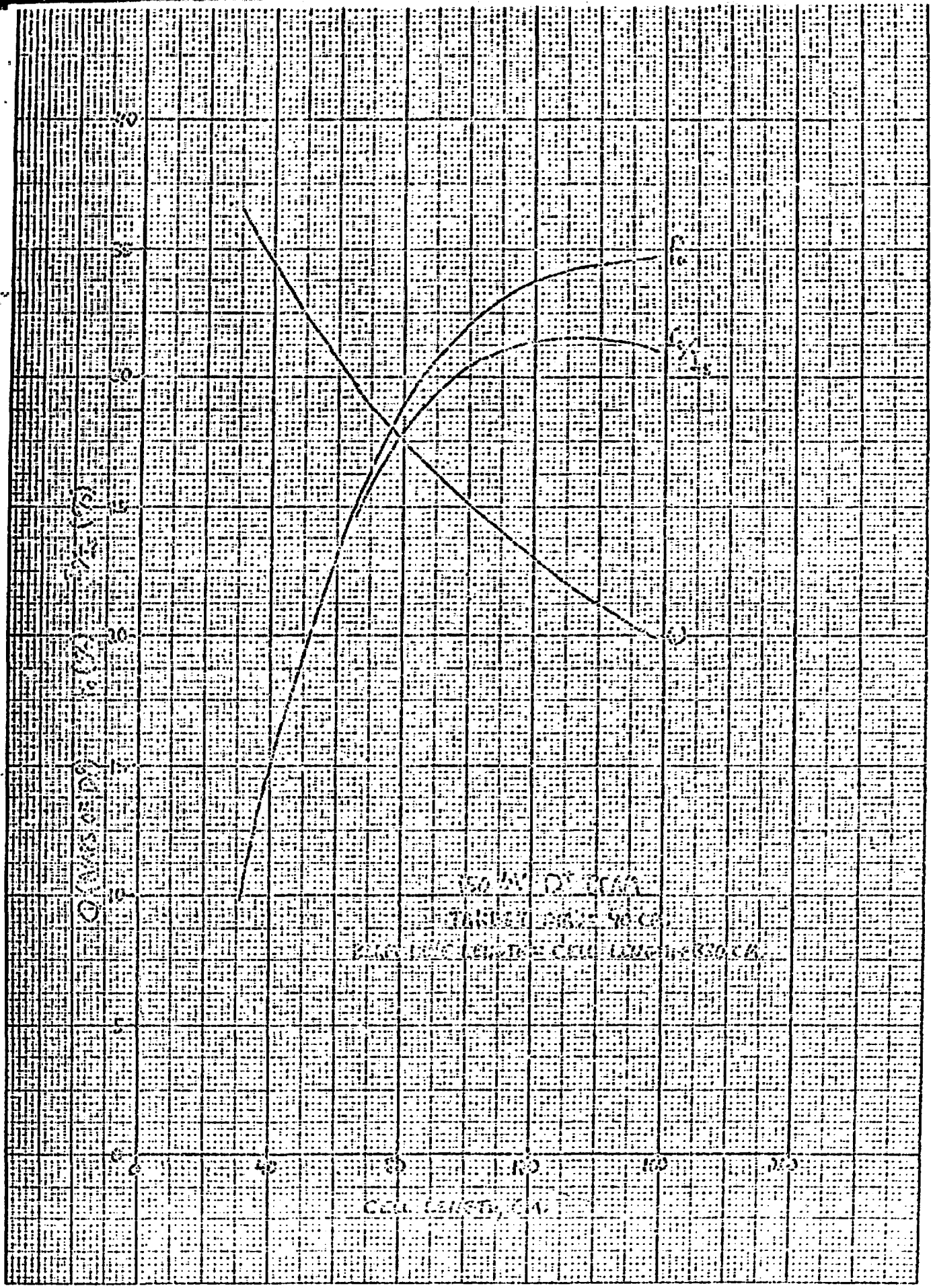
DUOPIGATRON ION SOURCE



ISO AV. DE BEAM
ROOM TEMPERATURE CELL
LN2 COOLED CELL
CELL LENGTH, CM.
0
40
80
120
160
200
10
20
30
40
50
60



5.5
2.4
PROBE POSITION (INCHES)
(in.)



40
35
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25
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120
160
200