A Regulated High Voltage Supply for the Electron Microscope

Thesis by

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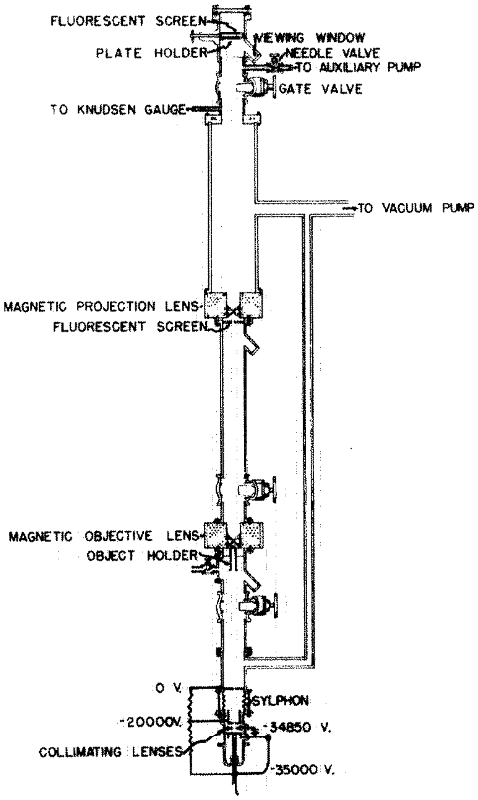
ABSTRACT

The errors of magnetic electron lenses are discussed, particularly with respect to the ultimate resolving power of the electron microscope. A regulated high voltage power supply using frequency modulated carrier system has been constructed which contributes considerably to the operation of the electron microscope at high magnifications. The errors of the magnetic lenses due to poor lining up and centering have been reduced considerably by operation at lower magnifications. A resolving power of about 150 Å has been obtained. Some pictures of clays, calcite and rouge are presented.

INTRODUCTION

The electron microscope which is the subject of this thesis was constructed by Prof. W. V. Houston during the past few years. Hugh Bradner and J. Earl Thomas have also done some work on this instrument. As shown in the diagram below it consists of an electrostatic condensing lens followed by two magnetic lenses. The instrument is about 2 meters long and is operated at a pressure of about 10^{-5} mm. of Hg. The photographic plate and the object can be changed without losing the vacuum by means of the various gate valves. Objects are usually prepared from a liquid suspension of the substance being investigated. A drop of this liquid is placed on a small disc of fine mesh screen which supports a very thin film of collodion. This is then placed in a desiccator until the water has evaporated, placed in the object holder and a picture taken. The high voltage power pack consists of two voltage doublers in cascade.

The mathematical theory of magnetic and electrostatic electron lenses is treated in detail in many places, a good review of the subject being found in the thesis of J. H. Bradner (C. I. T. 1941). The practical use of such lenses however is not so well known and will be treated here. A typical magnetic lens is shown in Fig. A. The errors of this kind of lens make it imperative that a very small aperture be used, and common practice is to use a lens with a speed of about .005. In order to have as small a focal length as possible the pole shoes are placed as close together as possible and a magnetizing current used which will not cause excessive saturation at the pole tips. The aperture used is usually less than $\frac{1}{2}$ the diameter of the hole in the pole shoes in order to keep away from any



Electron Microscope.

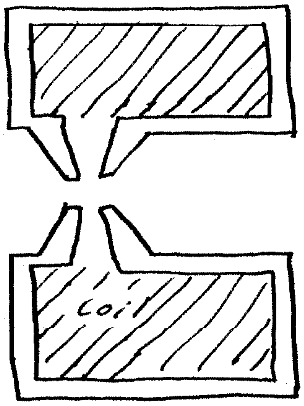


Fig.A Typical Magnetic lens.

local inhomogeneities in the iron. It is not possible at present to construct magnetic lenses with a focal length of less than 2 or 3 mm. The use of such a small ratio of lens diameter to focal length results in a rather large depth of focus. At a resolving power of 10 Å the depth of focus may be as much as .5 μ. The magnification of a single magnetic lens as normally used is about the same as that of an ordinary light microscope. This is a very convenient feature of an electron microscope as the first lens can be arranged so as to give an image on a fluorescent screen, while the small numerical aperture of the second lens requires only a small hole in this screen to let the electrons through. Thus interesting objects can be picked out using only the first lens, and detailed observations made with the two lenses.

The errors of thin magnetic electron lenses can be treated just like the optical errors in light systems with a few exceptions. The magnetic lenses rotate the image. Thus the simple astigmatism of light optics is replaced by a more complicated phenomena. There is also a mutual repulsion in electron rays which is not present in light rays, which is classified under the heading of space charge effects. The scattering of electrons is of course different from that of light. The following errors are of importance in electron optics:

1. The diffraction of electrons due to their de Broglie wave length.
2. Space charge effects.
3. Errors due to the finite aperture of the lenses.
4. Chromatic aberrations.
5. Errors due to the rotation of the image.
6. Scattering of electrons in the object.
7. Stray magnetic fields.

The errors due to the diffraction of the electrons due to their de Broglie wave length areimportant due to the very small numerical apertures used. The wave length of 50 kv. electrons is only about .05 Å but with a numerical aperture of .005 the resolving power is

$$R.P. = \frac{\lambda}{2a} = \frac{.05}{.01} = 5 \text{Å}$$

Numerical apertures considerably smaller than this are quite often used. The limit of resolution of course increases as the numerical aperture decreases.

Space charge effects are of little consequence in electron microscopes due to the small current densities and high voltages used. They become of importance only in the so-called immersion lenses used in cathode ray tubes and to some slight extent in the other lenses of cathode ray tubes as used in television.

The errors due to the finite aperture of the lenses can be considered as if they are independent and similar to those of light optics. These errors are:

1. Spherical aberrations.
2. Coma
3. Astigmatism
4. Curvature
5. Distortion

Of these errors the last two do not affect the definition of the image, but merely the position of the various points of the image. They do not seem to be important in electron optics. Coma and astigmatism can be reduced to a negligible amount by lining the lenses up correctly. Spherical aberration is the only error which occurs with on axis objects, and is the main error of magnetic lenses.

The diameter of the circle of least confusion(10) is given by

$$d = C\left(\frac{D}{f}\right)^3 f$$

where D = the diameter of the lens, f is the focal length, and C is a constant depending on the geometry of the system. It is seen that this error is proportioned to the cube of the numerical aperture and hence is greatly reduced by reducing the numerical aperture. The aperture used is often as small as 20 μ , and hence the construction and accurate positioning of such a small hole is quite difficult. The errors of spherical aberration and diffraction set the limit of resolving power for present electron microscopes. For if the numerical aperture is further reduced to lessen the spherical aberration, the error due to diffraction increases. The theoretical limit, determined by the experimentally observed spherical aberration for large apertures and extrapolated back to small apertures, and the error due to diffraction is about 6 Å. The best pictures published sometimes show an observed resolving power of about 20 Å.

There are several types of chromatic aberrations. For a well lined up microscope the only type of importance is the change of focal length with the change of velocity of the electron beam. This change of velocity can occur due to the following causes:

1. The accelerating potential may change.
2. Changes in the initial velocity of the electrons on leaving the source of electrons.
3. Changes in velocity due to variable energy loss of the electron beam in traversing the film which supports the object or in traversing the transparent portions of the object.

The diameter of the circle of least confusion, due, due to a varying velocity of the electron beam in a well centered system is

$$d = K D \frac{\Delta V}{V}$$

where K is a constant, D the aperture of the lens, and V the acceleration ~~in~~ voltage. If the objective lens is 10 μ in diameter, ~~and~~ $V = 10^5$ volts and the resolving power required is 10 Å, then the voltage must be kept constant to ± 10 volts at least. The changing of the accelerating voltage is taken care of in this microscope by the voltage regulator to be described in another section of this thesis. v. Ardenne finds a saturating core type of AC regulator and a filter system using large condensors satisfactory. The RCA microscope probably uses a degenerative type regulator in which the amplitude of the oscillations of the oscillator which supplies the high voltage rectifier with radio frequency power (at 175 kc.) is corrected so as to keep constant output voltage on the microscope. Batteries or very well regulated DC power packs must be used to supply the current for the magnetic lenses.

The error from the different initial velocities of the electrons ~~are~~ is negligible if a tungsten filament is used, but ~~are~~ is serious if the electrons are made by positive ion bombardment or some other similar method.

The change in velocity due to the supporting film at the object becomes serious if the film is much more than .1μ thick. Fortunately it is quite easy to make and use films about 500 Å thick, so this error is rather small.

If now the lenses are not well lined up and centered, other errors come in to existence. For instance, the circle of least confusion increases rapidly if the beam is off center from the lens by much more than the diameter of the aperture. Also variable rotation occurs as is discussed in another section of thisthesis.

The remaining error of importance is that caused by stray magnetic fields. As is shown by the calculations of the magnetic field required to deflect the image in another section of this thesis, the electron beam is very easily deflected by very small magnetic fields. A reduction of at least 25:1 is necessary to make this error negligible. One or two iron or permalloy shields will usually accomplish this.

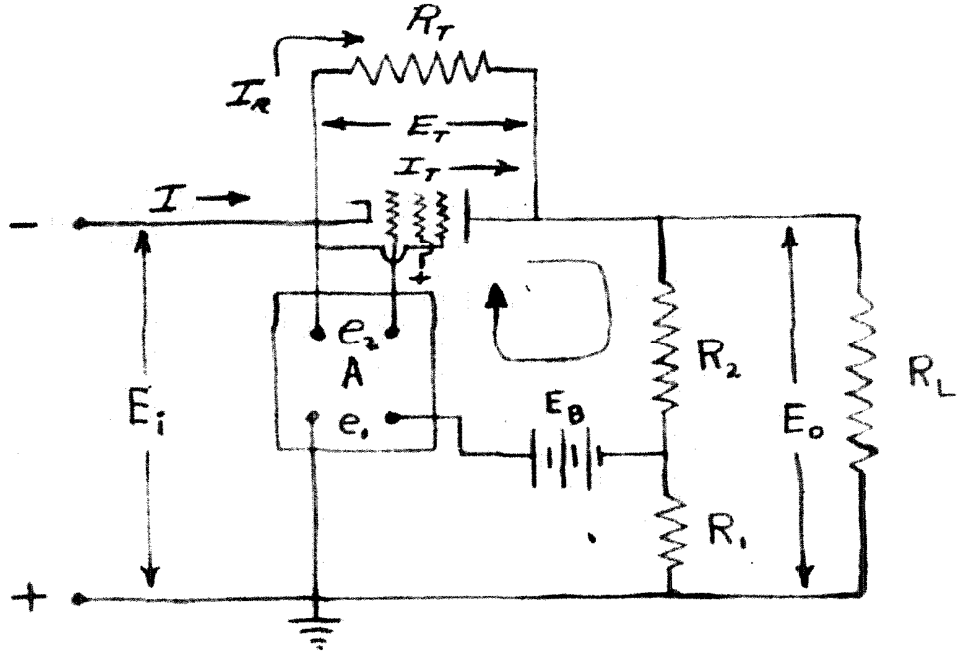
The High Voltage Regulator

In October, 1941, Professor Houston suggested that I take over the job of building a regulator for the high voltage supply of the electron microscope. For some time the microscope had seemed to be in good condition except for a random and slow moving of the image. Professor Houston had correlated this motion of the image with variations in the 110 volt AC line. Since the high voltage supply was the only part of the microscope which was operated by 110 volts AC, he was led to the conclusion that changes in the electron accelerating voltage were causing the moving about of the image. The reasons for this shifting about of the image as a function of the high voltage will be taken up in another part of this thesis. This section will have to do only with the means adopted to keep the high voltage constant.

Degenerative regulators

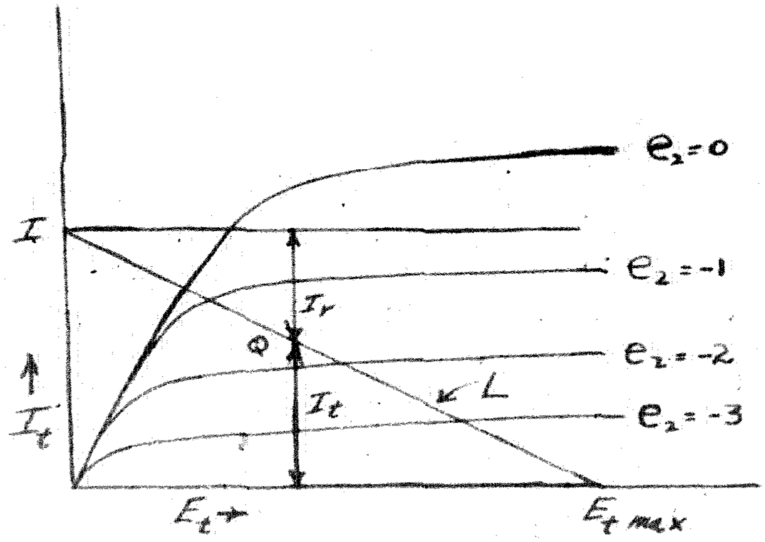
In 1939 Hunt and Hickman(1) published a paper describing many new and old types of electronic voltage regulators. Almost any type of regulator can be found under one of their general classifications. Many of these regulators are balanced affairs, giving infinite regulation for only one output voltage or load resistance. However, the type of regulator recommended by them for general use is the degenerative type, and indeed degenerative regulators have found use in many problems of physics(2). The analysis of degenerative regulators given here will be slightly different from that of Hunt and Hickman, as it was found necessary to use a screen grid tube as a regulator tube, and to shunt the tube with a protective resistor. The general scheme is shown in Fig. 1.

In Fig. 1, R_L is the load resistance, and for the purposes of analysis



R_T
I_R
E_T
I_T
I
−
+
e_2
A
e_1
E_B
R_2
R_1
E_i
E_o
R_L

Fig. 1.



$e_2=0$
I
$e_2=-1$
I_r
Q
$e_2=-2$
I_t
L
$e_2=-3$
I_t
E_t →
E_t max

Fig 2.

it will be assumed that $R_L < R_1$ or R_2, so that all the current I goes through R_L. The fraction of the output voltage fed back to the DC amplifier A will be called β and is equal to $\frac{R_1}{R_1 + R_2}$. β will be of the order of .01 in practice, and hence E_B will be about 350 volts in order to obtain a reasonably small voltage for the input of the DC amplifier (2 or 3 volts are needed as grid bias for the input stage). The action of the pentode and its protective resistor is shown in Fig. 2. Since $I = I_r + I_t$ at all times, it is seen that varying the grid voltage of the pentode will shift the operating point Q along the line L, and hence will change the division of the current I between R_t and the tube. This will result in changing the value of E_t. In fact it is seen that if e_{co} is the cut-off voltage (that voltage for which the plate current is reduced to zero) then

$$I_t = g_m (e_2 - e_{co}) \tag{1}$$

where g_m is the mutual conductance of the pentode. The maximum voltage across the tube is $E_{t\,max}$ and is equal to IR_t. Since $E_{t\,max}$ is the range over which regulation will obtain it should be made as large as possible. In the usual course of operations, I runs around 300 μ amps, and the range of control desired is about 1500 volts. This makes $R_t = 5$ megohms. The reason for the use of R_t at all is to limit $E_{t\,max}$ to a safe maximum. For if R_t were not present and for some reason e_2 went negative and beyond cut-off, about 35,000 volts would appear across the tube and destroy it. The reason why a pentode is used is that it was impossible to obtain any cut-off with a triode at the small currents and high voltages encountered. The plate current of a well shielded RF pentode however is determined almost solely by the grid and screen voltages, and is practically unaffected by any changes in plate voltage.

Returning to Fig. 1:

Let $\beta = \frac{R_1}{R_1 + R_2}$ and $R_L < R_1 \text{ or } R_2$

Also let A be such that $e_2 = \mu e_1$

Then:

$$E_o = E_i - E_t \tag{2}$$

But

$$E_t = I_R R_t \text{ and } I_R = I - I_t$$

$$I_t = g_m e_2 \text{ (absorbing } e_{co} \text{ into } e_2\text{)} \tag{1}$$

$$\therefore E_t = R_t I_R = R_t (I - g_m e_2) = R_t (I - g_m \mu e_1)$$

$$E_t = R_t (I - g_m \mu \beta E_o - g_m \cancel{R} \mu E_B) \tag{3}$$

Hence, from (2), since $I = E_o / R_L$

$$E_o = E_i - E_o \left(R_t / R_L - g_m \mu \beta R_t \right) - g_m R_t \mu E_B \tag{4}$$

$$E_o = \frac{E_i - R_t g_m \mu E_B}{1 + R_T / R_L - g_m \mu \beta R_T} \; \# \; \cancel{\frac{1}{-g_m R_T \mu \beta}} \tag{5}$$

$$\frac{dE_o}{dE_i} = \frac{1}{1 + R_T / R_L - g_m \mu \beta R_T} \simeq \frac{1}{-g_m R_T \mu \beta} \tag{6}$$

This last expression can be written as "$\frac{1}{\mu\beta}$", where "$\mu\beta$" is the round trip gain in the direction of the curved arrow of Fig. 1. Thus it is seen that this type of regulator is similar to a DC amplifier with degenerative feedback. Here the constant voltage E_B is amplified by the circuit to a value E_o, the "plate supply" being E_i. In this case variations in the plate supply appear in the output reduced by a factor of $\mu\beta$. In the regulator constructed $\mu\beta$ is of the order of 1000, so that changes in the input voltage appear in the output reduced by a factor of 1000. For ± 1% variation in line voltage, this means that the output voltage is constant to about ± .35 volts.

The DC Amplifier

It is seen from the above discussion that it is advantageous to have as much gain as possible in the DC amplifier. Since the largest convenient value of E_B is about 350 volts or so, β is at most about 10^{-2} for a 35 kv. power supply. Hence in order to obtain a $\mu\beta$ of 10^3, it is necessary that the gain of the DC amplifier be about 10^5. This is an uncomfortably large gain to try to get with the usual direct coupled type of DC amplifier. If there are any phase shifts in the many stages needed, as always occur at high frequencies due to the input capacitancesof the tubes, the whole system may become regenerative instead of degenerative and break into oscillation at a frequency where the round trip phase shift is 180° out of phase with that indicated in the previous section (i.e. μ may be a negative quantity instead of a positive one). One way to stop this is to short the output of one of the stages with a large condenser, thus making the maximum phase shift 90° at medium frequencies, which will not usually cause oscillation, but which will reduce the gain at high frequencies so that oscillation will not occur in this region. Another cause of oscillation in a multistage DC amplifier is coupling between the output current and some grid near the input through the common impedence of the plate supply. This coupling may have a regenerative effect and cause oscillations. These considerations all point to the desirability of a DC amplifier with high gain, negligible phase shift, and uncritical adjustment. These characteristics all seem to be contained in a frequency modulation carrier system which will be described in the next section.

The Frequency Modulation Carrier System

The classical paper of Major Armstrong(3) gives clearly the advantage of frequency modulation over amplitude modulation for normal short range broadcast service. However we are not interested in such things as quality of reception, interference between adjacent channel stations, etc., in this case. All we want here is lots of gain with negligible phase shift over a wide frequency band. A reasonable amount of amplitude distortion may even permitted in the DC amplifier as long as there is no phase shift, and as long as the amplification is always large. Hence, in describing this system only those advantages of frequency modulation that are used in this regulator will be mentioned.

The basic method of the FM (frequency modulation) carrier system is as follows:

1. The DC input signal is impressed on the grid of a reactance tube, changing, in effect, the DC voltage into a reactance whose value changes as the DC input signal changes.

2. This varying reactance is connected to the tank circuit of an oscillator in such a fashion as to change the frequency of oscillation as the reactance varies. Normally the reactance tube is connected directly across the tank circuit, thus acting as a condenser or inductance which is added in parallel to the tuned circuit.

3. A voltage of this frequency, varying a few percent in frequency as the DC input signal is changed, is amplified considerably, eventually arriving at the limiter tube, which is merely a completely overloaded amplifier. This gives a square wave output voltage with an amplitude independent of everything except the DC plate and screen voltages of the limiter tube.

4. This amplitude limited but frequency modulated voltage then goes to the discriminator which changes a voltage which varies in frequency back into a DC voltage, which varies as the original DC voltage.

It is seen that the overall amplification of this system depends on three factors:

1. The change in kc. of the oscillator frequency for 1 volt applied

to the grid of the reactance tube.

2. The level at which the limiter operates.

3. The changein DC volts output of the discriminator for 1 kc. change in oscillator frequency.

A block diagram of the elements in this amplifier is shown in Fig. 3.

It is interesting to note that although the experimental realization of all the advantages of FM was obtained by Major Armstrong, the circuits that he used to modulate and demodulate a FM system have to a large extent been discarded. The circuits now used were developed at the RCA Laboratories at about the same time that Armstrong was working on FM, but were used for automatic tuning of superheterodyne receivers. In superheterodyne reception the signal beats with a local oscillator to produce a beat frequency, usually about 450 kc. The major partof the amplification then takes place at this intermediate frequency (IF) in a sharply peaked amplifier called an IF amplifier, after which the signal is demodulated in the usual way. Considerable distortion results if the beat frequency, formed by the combination of the signal and local oscillator, isnot very close to the frequency at which the IF amplifier is peaked. This will result from imperfect tuning or from oscillator drift. Hence it was suggested by Travis(4) that the frequency appearing at the output of the IF amplifier be fed into a discriminator, thus giving a DC voltage which increased or decreased as this frequency increased or decreased. This DC voltage wasthen fed to the grid of a reactance tube which was connected across the tank circuit of the local oscillator in such a way as to correct the original mismatch between the output of the IF amplifier and the frequency at which it was peaked. Of course perfect correction was not possible, but it was quite feasible to obtain a correction factor of about 100:1 (i.e. an original mistuning or oscillator drift of 10 kc. could be reduced to a mismatch of only 100 cycles,

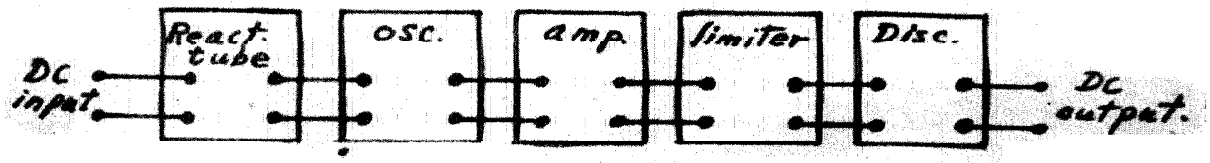


Fig. 3

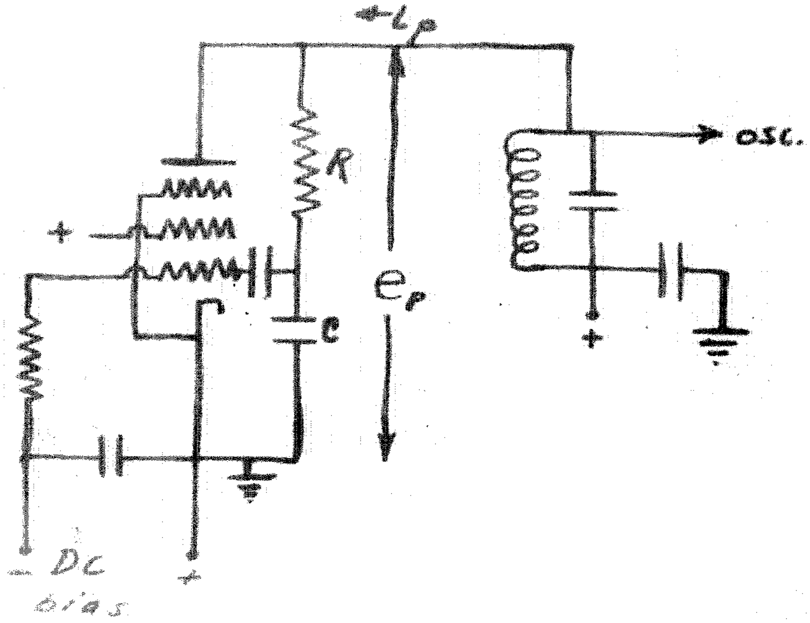


Fig. 4.

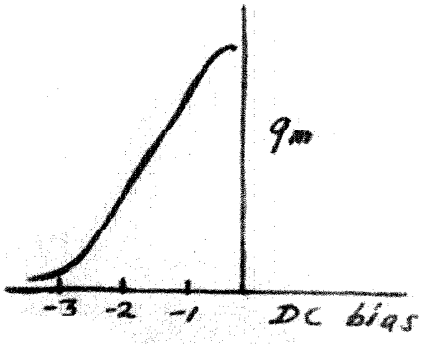


Fig 5.

which was considered quite satisfactory).

The Reactance Tube

The reactance tube circuit is similar to that of Travis$^{(4)}$ and Foster and Seeley$^{(5)}$, and is shown in Fig. 4. If R is large compared to the working impedence of the oscillator tank, and if the reactance tube is a pentode, then the current drawn from the oscillator tank will depend only on the grid voltage of the reactance tube. If now this grid voltage is made to be proportional to e_p, but 90° out of phase with it, i_p will be 90° out of phase with e_p, and the reactance tube will seem like a reactance to the oscillator tank. In particular if

$$R \gg \frac{1}{\omega C} \tag{7}$$

the current drawn by the tube is

$$i_p = g_m e_g \tag{8}$$

But

$$e_g = e_p \frac{-j/C\omega}{R - j/C\omega} \simeq e_p \frac{-j}{RC\omega} \tag{9}$$

$$\therefore i_p = -j \frac{g_m}{RC\omega} e_p \tag{10}$$

$$\text{or } z_{tube} = \frac{e_p}{i_p} = \frac{RC\omega}{j g_m} = j\omega\left(\frac{RC}{g_m}\right) \tag{11}$$

Hence the impedance of the tube seems to the oscillator to be just like an inductance of value

$$L = \frac{RC}{g_m} \tag{12}$$

The value of this inductance is a function of the mutual conductance, g_m, of the tube, and since g_m varieswith the DC bias of the tube (see Fig. 5) it is seenthat the value of this inductance is a function of the DC bias.

The Oscillator Section

The oscillator used is quite normal, being merely a triode hooked up in a standard "tickler coil" circuit. However, the method of coupling the reactance tube to the tank circuit is quite unusual. Instead of connecting the reactance tube directly across the oscillator tank, it is connected across a tuned circuit which is very loosely coupled to the oscillator tank. By this means, it will be shown, a considerable change in oscillator frequency can be effected with a vanishingly small change in the reactance of the reactance tube. This gives, of course, infinite amplification for the whole system. Since the reactance tube merely changes the tuning of the loosely coupled circuit, the analysis will be given for the case of an oscillator which has, coupled to the tank, a loosely coupled resonant circuit which can be tuned to various frequencies. This idea is an old one, and was used in the old days of radio to compare accurately two wavemeters. The theory is presented by Chaffee(6), but the details given here are from a course which I once took from Professor Chaffee.

The circuit is shown in Fig. 6. Oscillations will just occur when the lossesof the circuit as seen by the grid and filament are zero. The function of the tickler coil is to reduce the effective resistance of this circuit to zero, permitting oscillation. The frequency of oscillation is that frequency for which the reactance is zero (i.e. parallel resonance between grid and filament in Fig. 6, or series resonance as seen from E in Fig. 7). Consider now Fig. 7.

$$E = Z_2 I_2 + j M \omega I_1 \tag{13}$$

$$0 = Z_1 I_1 + j M \omega I_2 \tag{14}$$

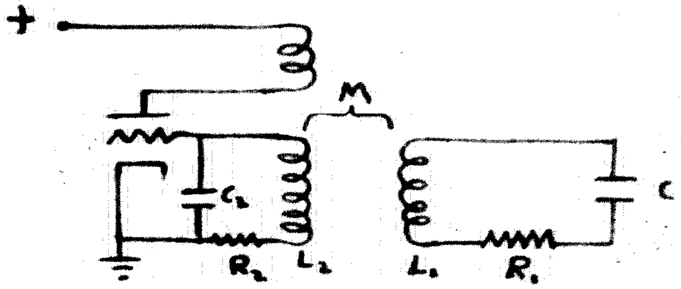


Fig. 6.

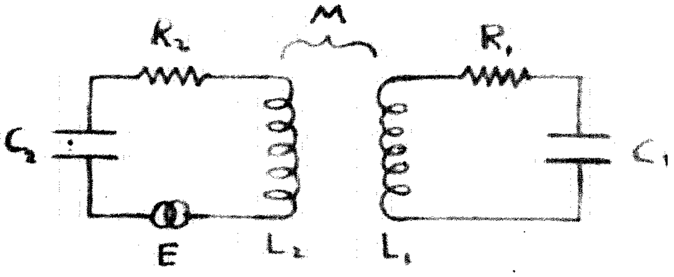


Fig. 7.

where $$Z_2 = R_2 + j\omega L_2 - 1/\omega C_2$$

and $$Z_1 = R_1 + j\omega L_1 - 1/\omega C_1$$

Hence

(15) $$I_1 = -jM\omega I_2 / Z_1$$

(16) $$\therefore E = \left(Z_2 + \frac{M^2\omega^2}{Z_1} \right) I_2$$

Hence the impedence looking into the circuit from E is

(17) $$Z_{21} = Z_2 + \frac{M^2\omega^2}{Z_1} = R_2 + j\overline{X}_2 + \frac{M^2\omega^2}{R_1 + j\overline{X}_1}$$

$$= \left(R_2 + R_1 \frac{M^2\omega^2}{R_1^2 + \overline{X}_1^2} \right) + j\left(\overline{X}_2 - X_1 \frac{M^2\omega^2}{R_1^2 + \overline{X}_1^2} \right)$$

$$= \quad [R] \qquad + j \quad [X]$$

Oscillations will occur when $Z_{21} = 0$. The vanishing of $[R]$ is taken care of by the tickler coil. The vanishing of $[X]$ determines the frequency of oscillation. Hence for frequency of oscillation:

(18) $$\overline{X}_2 = \overline{X}_1 \frac{M^2\omega^2}{R_1^2 + \overline{X}_1^2}$$

or $$\omega L_2 - \frac{1}{\omega C_2} = \frac{(\omega L_1 - 1/\omega C_1) M^2\omega^2}{R_1^2 + (\omega L_1 - 1/\omega C_1)^2}$$

let $$\omega_1 = \frac{1}{L_1 C_1}, \quad \omega_2 = \frac{1}{L_2 C_2}, \quad \eta_1 = \frac{R_1}{\omega L_1}, \quad \eta_2 = \frac{R_2}{\omega L_2}, \quad \tau = \frac{M}{\sqrt{L_1 L_2}}.$$

Then (18) reduces to

(19) $$1 - \left(\frac{\omega_2}{\omega} \right)^2 = \frac{\left[1 - \left(\frac{\omega_1}{\omega} \right)^2 \right] \tau^2}{\eta_1^2 + \left[1 - \left(\frac{\omega_1}{\omega} \right)^2 \right]^2}$$

Let $$\theta_1 = \frac{\omega_0}{\omega_1} = \frac{\lambda_1}{\lambda_0}, \quad \theta_2 = \frac{\omega_0}{\omega_2} = \frac{\lambda_2}{\lambda_0}, \quad \theta = \frac{\omega_0}{\omega} = \frac{\lambda}{\lambda_0}$$

where ω_0 is some fixed frequency, and λ_0 the corresponding wave length.

(19) then becomes

(20) $$1 - \left(\frac{\theta}{\theta_2} \right)^2 = \frac{\tau^2 \left[1 - \left(\frac{\theta}{\theta_1} \right)^2 \right]}{\eta_1^2 + \left[1 - \left(\frac{\theta}{\theta_1} \right)^2 \right]^2}$$

θ_1 + θ_2 are seen to be proportional to the tuning of the two circuits. θ is proportional to the frequency of oscillation. If now θ_2 is set equal to 1, and only θ_1 is varied, (20) reduces to

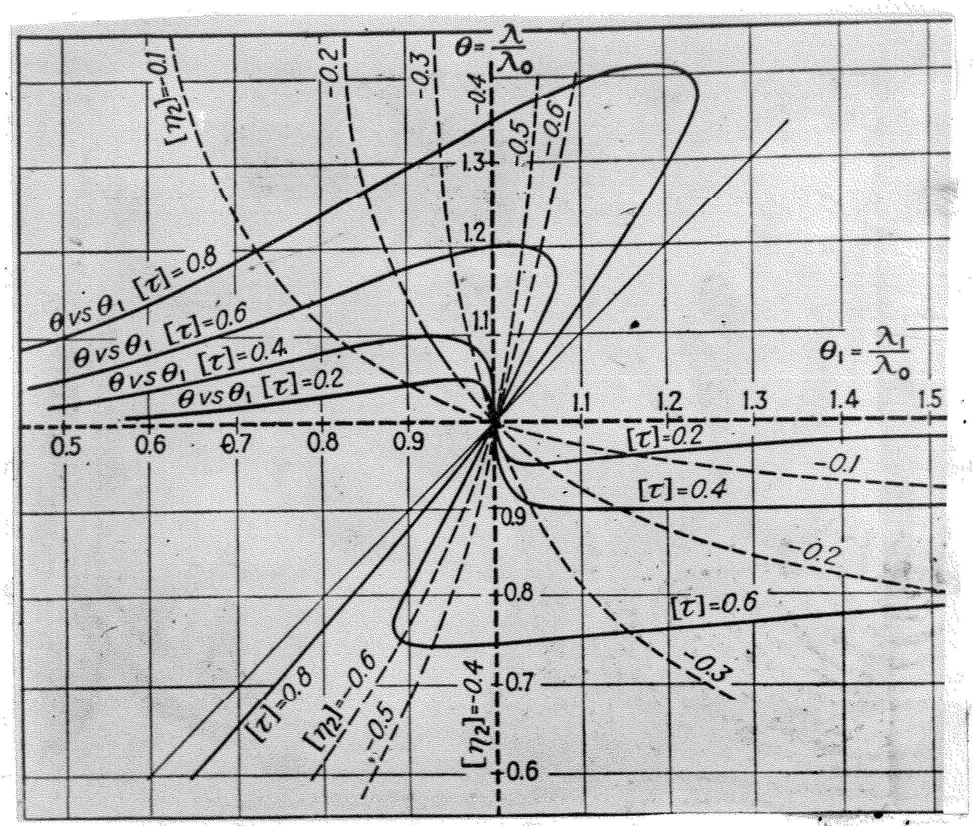
$$1-\theta^2 = \frac{\tau^2\left[1-(\theta/\theta_1)^2\right]}{\eta_1^2+\left[1-(\theta/\theta_1)^2\right]^2} \tag{21}$$

(21) is seen to be rather complicated, but Chaffee has plotted it for $\eta_1 = .4$, and it is shown in the full line curves of Fig. 8,which is taken from Chaffee's book.

(21) givesthe frequency of oscillation of the system, but does not tell whether oscillation actually occurs. An analysis, similar to the above, can be carried out for $\left\{ R \right\} = 0$, and this will give the dotted curves of Fig. 8. These dotted curves show where oscillation just occurs. With more positive feedback oscillation will of course occur, the amplitude of the oscillations increasing until the tube is overloaded. The $[\eta_2]$ shown in Fig. 8 are negative, as they include the effective negative resistance introduced by the tickler coil. These dotted lines are therefore the dividing lines between regions of oscillation and non-oscillation. It is seen that if sufficient positive feedback is employed ($|\eta_2|$ large), oscillations will be sustained over the whole tuning range. It is easily seen now how the "infinite amplification" occurs. If τ is set equal to .4 and θ_1 set in the region $\theta_1 = 1$, then the rate of change of oscillator frequency with the tuning of the coupled circuit (θ_1), is very large. The condition for infinite rate of frequency change is that $\tau = \eta_1$, as will now be shown. The condition for this particular coupling is that with $\theta_1 = 1$ there will be just one root of (21). Hence:

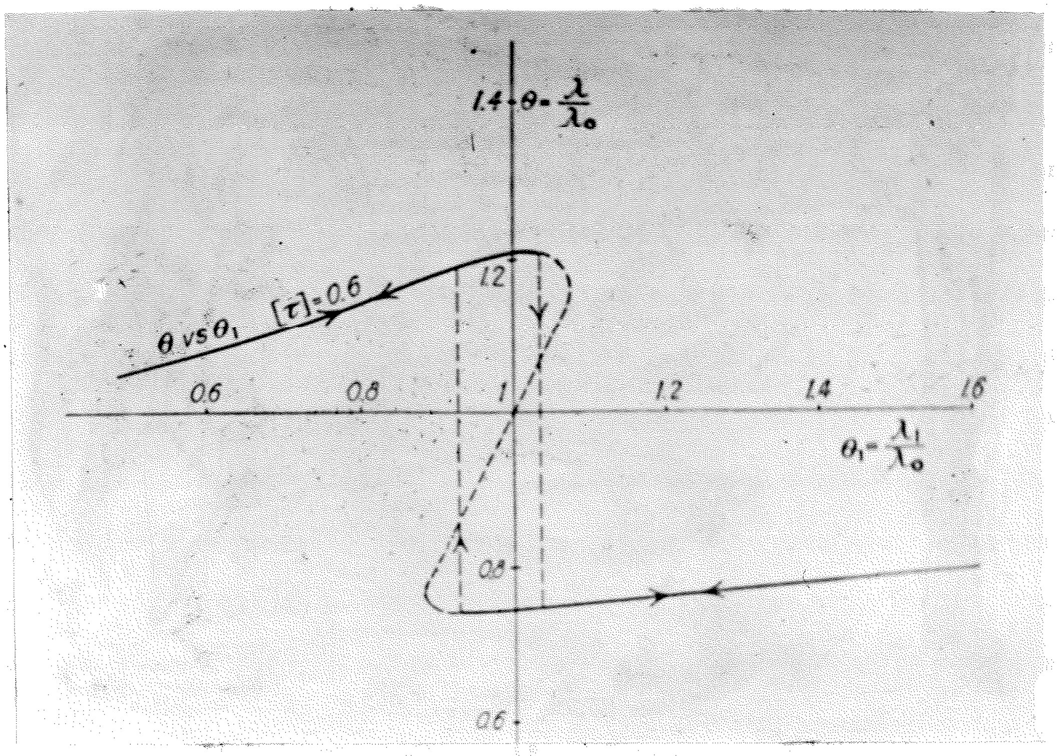
$$1-\theta^2 = \frac{\tau^2(1-\theta^2)}{\eta_1^2+(1-\theta^2)^2} \tag{22}$$

$1-\theta^2$ can be cancelled as there will always be a root at $\theta = 1$.



θ = λ/λ₀
θ₁ = λ₁/λ₀
[η₂]=-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
1.3
1.2
1.1
0.9
0.8
0.7
0.6
0.5
0.6
0.7
0.8
0.9
1.1
1.2
1.3
1.4
1.5
θ vs θ₁ [τ]=0.8
θ vs θ₁ [τ]=0.6
θ vs θ₁ [τ]=0.4
θ vs θ₁ [τ]=0.2
[τ]=0.2
-0.1
[τ]=0.4
-0.2
[τ]=0.6
-0.3
[τ]=0.8
[η₂]=-0.6
-0.5
[η₂]=-0.4

Fig. 8.



1.4
θ = λ/λ₀
1.2
θ vs θ₁
[τ]=0.6
0.6
0.8
1
1.2
1.4
1.6
θ₁ = λ₁/λ₀
0.8
0.6

Fig. 9.

Hence:

$$\eta_1^2 + (1-\sigma^2)^2 = \tau^2 \tag{23}$$

It is seen by inspection that if $\tau = \eta$, that there is just one root of this equation. If $\tilde{\tau} > \tilde{\tau}_{prot}$ then changing θ_1 will not give a continuous change of θ, but θ will change abruptly from the top part of the curve to the lower, as σ is in this case a multivalued function of θ_1. This gives rise to the "drag loop effect" shown in Fig. 9, but this is of no interest here as operation here is unstable.

The Limiter.

Many of the advantages of FM are tied up with the use of the limiting amplifier. Usually a limiter is just a screen grid tube, which normally operates with an input voltage of a few volts, operated in this case with an input voltage of about 50 volts. Thus on the positive swings the grid draws current, and if the tube is fed from a high impedence source, can only be driven slightly positive. On the negative swings the grid is driven way beyond cutoff. The result is that for a sine wave input the plate current is a square wave, the amplitude of which is independent of changes in the amplitude of the input signal. In fact, the only characteristic of the input signal that arrives at the output is its frequency. If the input signal is larger than some interference such as static, the signal to noise ratio will be considerably increased by the action of the limiter. As used in this DC amplifier the main advantage in the use of the limiter is that the oscillator need not be stabilized for constant amplitude output, and no special precautions need be taken to insure that changing the reactance across the oscillator tank does not change the amplitude of oscillations. The carrier frequency presumably has at all times an amplitude large compared with the noise due to corona, etc.

Hence an additional advantage is obtained, for in FM the signal to noise ratio is larger than in other systems as long as the frequency deviation is large compared to the highest frequency contained in the signal. This applies of course only to noise picked up between the oscillator and the discriminator.

The Discriminator.

A discriminator is a circuit that changes variations in frequency back into variations of a direct current, discriminating between positive and negative deviations from the mean frequency. It plays the same role in FM that the detector plays in amplitude modulation. Almost any frequency selective network, such as an inductance followed by a rectifier, will perform this function. However, to obtain linearity, range, and sensitivity a circuit originally invented by Riegger in Germany in 1920, and rediscovered by Foster and Seeley(5) in 1937 was used. The complete theory of this circuit is described by Roder(7) and is very complicated. However, a simple explanation of how it works will be given here. Consider Fig. 10, which is a diagram of the circuit used. It is seen that there are two diode rectifiers connected so that the net DC output is proportional to the difference between the absolute values of the alternating currents present in each diode circuit. Present in each diode circuit is the voltage across the radio frequency choke (RFC) which is the voltage across the primary of the discriminator transformer since the coupling condenser has very little impedence at the carrier frequency. In addition there is present in each diode circuit a voltage which is induced in the secondary of the discriminator transformer by virtue of the coupling M to the primary. Since the voltage appearing on one side of the centertapped winding is 180° out of phase with that appearing on the other side, the voltages

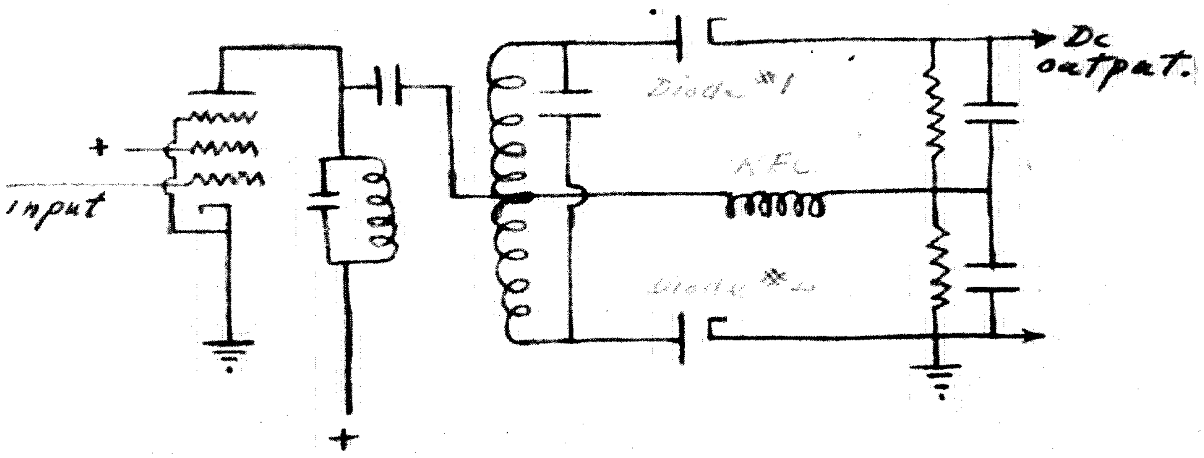


Fig. 10.

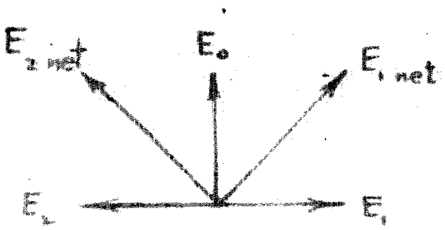


Fig. 11.

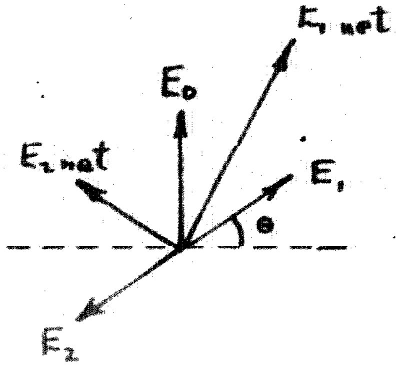


Fig. 12.

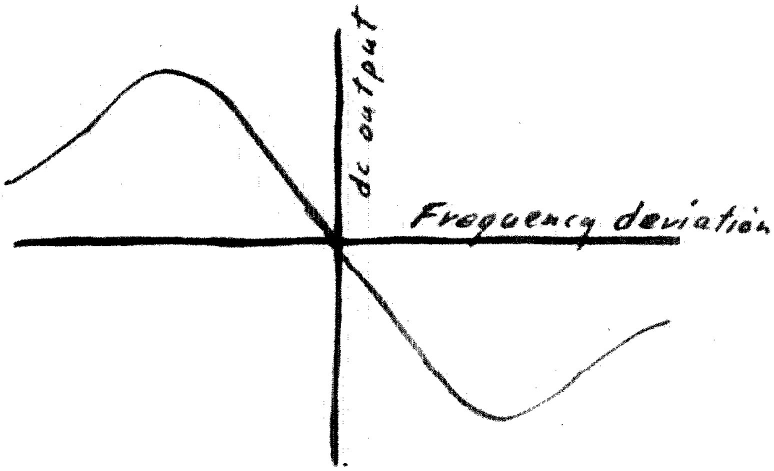


Fig. 13.

appearing in each diode circuit from this cause are 180° out of phase with each other. From (15) it can be seen that at resonance the voltage across the secondary is 90° out of phase with the primary voltage. Hence, if E_o is the AC voltage appearing across the RFC and E_1 and E_2 the voltages appearing across each diode circuit due to M, then the relationship between these vectors is that given in Fig. 11. E_1 net and E_2 net are the net AC voltages appearing in each diode circuit. It is seen that when the input frequency is in resonance with the secondary that these two vectors are equal, so that no DC voltage appears at the output. However, if the frequency deviates from this value the voltage induced in the secondary will no longer be 90° out of phase with the primary voltage due to Z_1 contributing some phase shift. Thus the situation in Fig. 12 arises. It is seen that E_1 net is no longer equal to E_2 net so that a DC voltage appears at the output whose sign is dependent on the sign of the frequency deviation because the sign of changes as Z_1 introduces a positive or negative reactance. The complete theory shows that the characteristic obtained is that given in Fig. 13.

Construction and operation.

In Fig. 14 is seen the hook-up of the DC amplifier as finally used. The only difference here from what has gone before is the method of coupling the reactance tube to the oscillator. This was made capacitative coupling instead of inductive so that it could be easily varied. The capacity needed is very small, of the order of $5 \mu\mu F$ or so, and had to be specially constructed. The frequency chosen for operation was about 2000 kc. At this frequency the coils used are not too large (about 60 turns on a 1½" coil form) and capacity effects are not too troublesome. Another reason for choosing this frequency was that there was available a Hazeltine oscillator in this frequency region

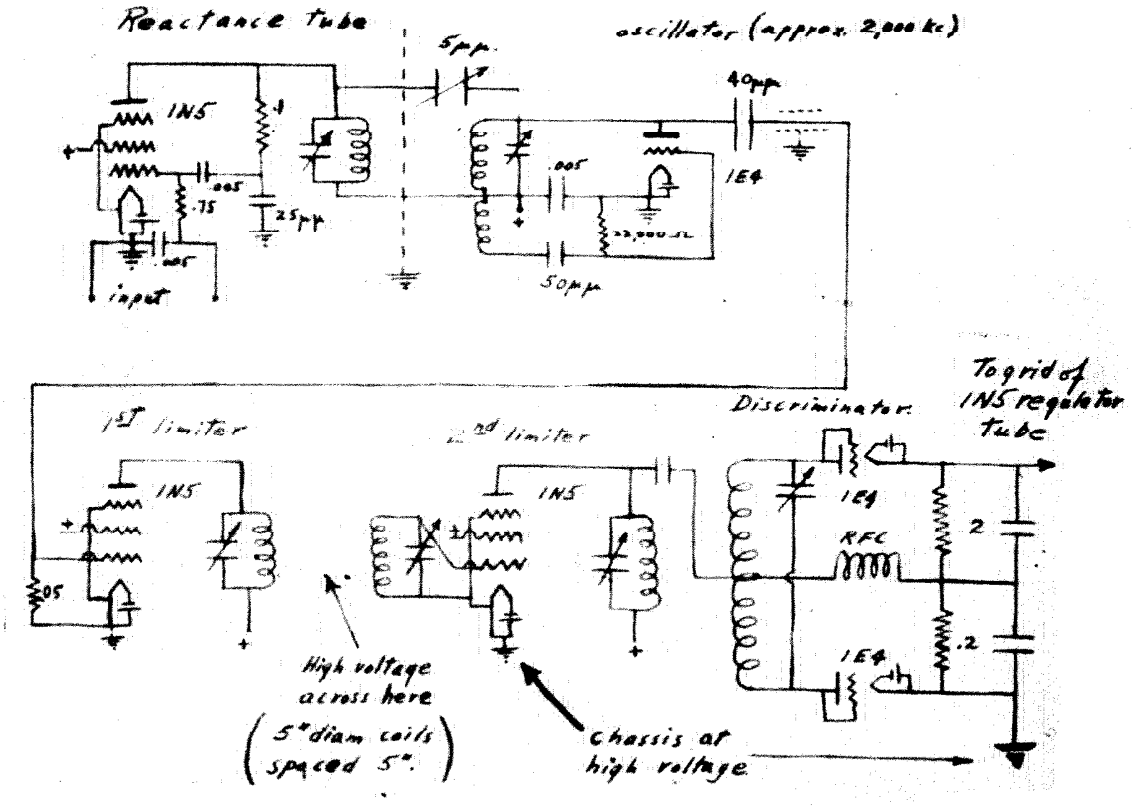

Reactance tube
1N5
.1
.005
.75
25μμ
.005
input
5μμ
oscillator (approx. 2,000 kc)
40μμ
.005
1E4
22,000 Ω
50μμ
1st limiter
1N5
.05
2nd limiter
1N5
Discriminator
1E4
RFC
2
.2
1E4
To grid of 1N5 regulator tube
High voltage across here
(5" diam coils spaced 5".)
Chassis at high voltage

Fig. 14.

which was very useful in lining up the system. The procedure in lining up the system is as follows:

Using the Hazeltine oscillator, the discriminator, the two limiters, and the oscillator were tuned to the same frequency. A great help in this was a simple one tube infinite inpedence detector which was used as a vacuum tube voltmeter. In doing this the input to the limiter must be kept low enough so that limiting action does not take place, for otherwise the tuning is very broad. The regulator tube was then connected up to the discriminator but the plate circuit was replaced by a 90 volt battery in series with a 0-100 volt meter. The reactance tube was then connected in with very loose coupling. By placing a reasonable bias on the reactance tube such as 3 volts, tuning a very small vernier condenser in the reactance tube tank circuit will give an output voltage curve similar to that shown in Fig. 8 for $\tau < .4$. The coupling between the reactance tube and the oscillator is then slowly increased until the amplification becomes extremely large. The amplification is measured by inserting a few millivolts in the grid circuit in addition to the 3 volts bias. The limiters are then checked to see that they are properly overloaded and the output connected up as in Fig. 1. The phasing throughout the whole system is such that the tap on the voltage divider should go to the grid of the reactance tube for degeneration. For a final line up a 3 volt battery is connected between the grid and filament of the reactance tube, the high voltage turned on and the vernier condenser on the reactance tube tank set at such a value that the output voltage is 50% maximum. The constant source of voltage and the voltage divider are then hooked up and the regulation obtained.

When this circuit was originally conceived I was rather worried about the frequency stability of a normal oscillator. When the feed back is disconnected small changes in the oscillator frequency do give large variations in the output. However, when the feed back is connected the vernier on the reactance tube tank can be varied over a large range without appreciably changing the output voltage. This can be understood if one thinks of this regulator as a DC amplifier with negative feed back. It can be shown in this case that variations in the output due to disturbance in the amplifier section are reduced by a factor $\mu'\beta$ where μ' is the gain from the input to the place where the disturbance is introduced. Thus in this case there must be considerable "gain" in the reactance tube alone, and hence frequency stability is no great problem.

It has already probably been noticed that there is one piece of design work in this system that is almost fantastic. This is the use of a 1N5-GT as the regulator tube. As are all tubes in this regulator, the 1N5 is a small $1\frac{1}{2}$ volt filament type tube of the kind often used in portable radio receivers. Its rating is 100 volts maximum on the plate. In normal use in this regulator it often has 1500 volts on the plate, yet this tube has never failed during a period of operation of over half a year. A glance at Fig. 2 will show, however, that when the tube has high voltage across it the current drawn through the tube is only a very small portion of the total current to the load, which is at most 300μ amps. Thus, the fact that the tube will take 1500 volts with ease during normal operation merely means that the insulation inside the tube is very good. The tube is protected with a flash over device which consists of a double thickness of notebook paper between two metal spring supports, the whole being connected across the tube. This protective device seems to go over at about 2500 volts. When flash overs occur in the microscope, as happens quite often after changing filaments, the regulator tube may pass as much as 300μ amps at 2500 volts for a very short time before the paper punctures. Just why the tube does not become gassy after such treatment is not understood.

The source of constant potential is another regulated power supply giving constant output in the range from 200 to 400 volts. It was thought at first that eventually this would have to be replaced with a battery but this was not found necessary. The use of this regulated power supply introduced some ripple into the input, probably due to its not being grounded. To cure this ripple a condenser was placed across the input of the DC amplifier. This made the high voltage regulator insensitive to fast changes in the output voltage, so a condenser was placed across the load so that no fast changes could occur across the load. The net result of all this was that the ripple in the output increased from about .2 to .5 volts when regulation was established. The regulation was tested by connecting a 7500 ohm resistor (approximately the impedence of the output condenser) in series with the output condenser, and observing the variations of the voltage across this resistor with an oscilloscope. With no regulation the output voltage was seen to jump up and down 20 or 30 volts in a random fashion. As soon as the regulation was established, however, the pattern on the oscilloscope stayed steady to within a few tenths of a volt, which was all that the oscilloscope would show.

There are several advantages to the above system. At no time has there ever been any trouble from regeneration. Once lined up, the system is never touched except to replace a filament battery every few months. It is very convenient to have the important controls at ground potential. The simplicity of the system can be seen from the space which it requires. The reactance tube and oscillator are in a 5x5x5" metal box. The first limiter is on a small board near the high voltage power supply. The second limiter, the discriminator, and the regulator tube are all on a chassis 3"x5"x10". The only large piece of equipment is the voltage divider which is 40 10-megohm resistors mounted on a pieceof bakelite about 3' long. A 0-200 microammeter is included in this line as a voltmeter. The only attention that need be paid to the regulator during normal operation is to check every ten minutes or so that the range of regulation has not been exceeded. The total cost of parts in the regulator is probably only about ten dollars, excluding meters and batteries. The only failure that has occurred has been in the reactance tube. If the high voltage supply is turned off and the regulator tube left on connected to the 300 volt constant voltage supply, the grid is driven slightly positive. Since thereis no DC load in the plate supply, the plate current may amount to 10 ma. or more. This current, added to the filament current of 50 ma. will sometimes blow the filament. The solution to this difficulty is to turn off the reactance tube filament.

Operation of the Electron Microscope

One unfortunate feature of the electron microscope is its lack of flexibility. The two magnetic lenses are bolted to the main frame of the instrument and they cannot be moved with respect to each other or the electron gun. This means that the microscope must be lined up once and for all when constructed, and not changed thereafter. It is felt that if extensive changes are made in this instrument that each magnetic lens should be mounted between sylphons and that the electron gun be moveable laterally.

The method of testing the line-up of the system depends on the rotation of the image as the current through the magnet coils is varied. The rotation of the image of a magnetic lens is given by (8)

θ = ∡ of rotation
V_0 = elect. acc. volt.

$$(24) \qquad \theta = \sqrt{\frac{e}{8 m V_0}} \int_{z_1}^{z_2} H(z)\, dz$$

As H is changed the image rotates. The axis of rotation is the axis of symmetry of the lens. Hence the lenses should be arranged so that changing the current in a magnet coil rotates the image about its center. In the present microscope the image movespractically linearly as the current in the magnetic lens is varied, indicating a center of rotation a large distance away from the instrument. Earl Thomas tells me that when this microscope was first constructed it was lined up quite well, so something must have shifted in the instrument in the last year or so.

Consider now a single magnetic lens which is lined up correctly. From (24) it is seen that

$$(25) \qquad \theta = k_1 \, I / V_0^{1/2}$$

where I = current thru coil.
V = electron voltage.

But

$$(26) \qquad \frac{1}{f} = \frac{e}{8 m V_0} \int_{z_1}^{z_2} H^2 dz = k_2 \frac{I^2}{V_0}$$

Since $\frac{1}{f} \simeq M$ when m >> 1, M = magnification.

(27) $$M = K_3 \theta^2$$

Hence from (25) the rotation due to a change in V_o is

(28) $$d\theta = -\tfrac{1}{2} K_1 \frac{I}{V_o^{3/2}}\, dV = -\tfrac{1}{2}\theta \frac{dV_o}{V_o} = K_9 \sqrt{M} \frac{dV_o}{V_o}$$

Hence it is seen that the angular deviation due to a fractional change in voltage increases with the magnification. If now two pictures are taken with different magnifications but with the same $\frac{dV_o}{V_o}$, and after being taken are enlarged optically to the same net magnification, then the picture with the larger electron microscope magnfication will have a larger $d\theta$ and hence will seem to have jumped at the edges. In this electron microscope, the axis of rotation lies at quite a distance from the center of the picture so that the whole picture seems to move in a line when the voltage is changed (see Fig. 15).

If now the microscope were perfectly lined up and if further the object could be placed at different distances from the first lens, then all rotations due to changes in voltage could be eliminated. A glance at (24) and (26) will show that while the sense of rotation of the image changes when the current through the magnetic lens is reversed, the magnification is not changed. Hence if both magnetic lenses were similar and operating at the same current, but poled so that the second lens rotated the image in a direction opposite to the rotation produced by the first lens, then there would be no net rotation of the image at any voltage. In order to work at different magnifications it would be necessary to change the position of the object. Focussing could still be accomplished by changing slightly the current through the first lens. This method, of course, will not eliminate all sources of error due to changes in voltage, but would at least eliminate

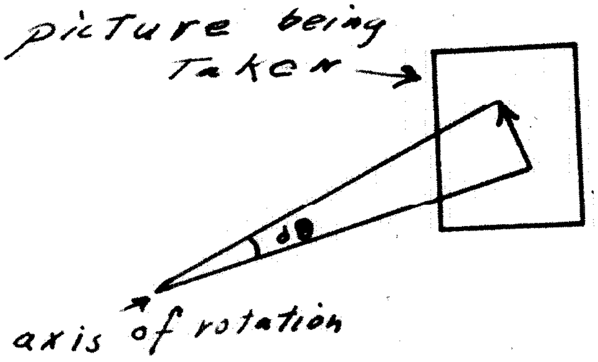

picture being taken
$d\theta$
axis of rotation

Fig. 15.

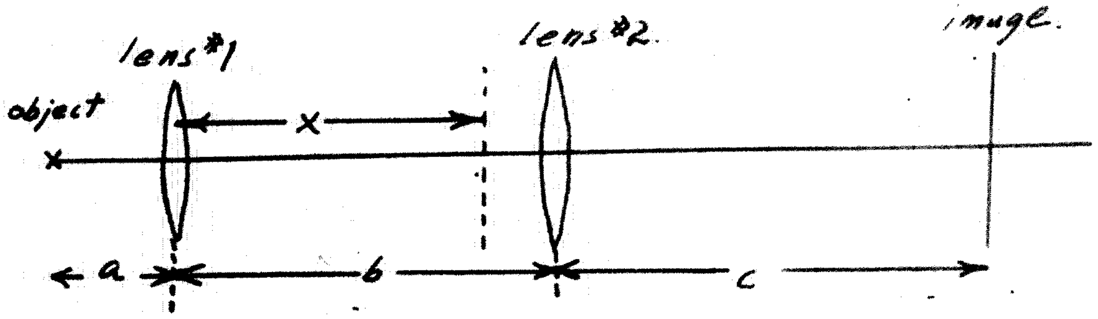

lens #1
lens #2
image.
object
x
a
b
c

Fig 16

one source of error.

The effects of this rotation and other errors that may occur due to the lenses not being lined up, such as astigmatism and coma, presumably change with the magnification. However, these changes are hard to evaluate in the present apparatus because of the use of a set of auxiliary deflecting coils between the two lenses. The present method of lining up the microscope when a new filament is installed is to aim the electron gun at the object holder. The resultant image is then aimed at the aperture of the second lens by means of the auxiliary deflecting coils. These operations are made possible by the presence of some fluorescent material in front of each lens. The resultant image should be in the center of the fluorescent screen at the top of the microscope, but usually it is displaced a few cm. Now different magnifications require different deflecting fields to properly set the image on the second lens. Thus the angle of incidence of the electron beam on the second lens changes with the magnification in a manner not directly connected with the magnification. These auxiliary deflecting coils may be needed not only to correct for original misalignment but also to correct for some residual magnetism in the magnetic shields between the two magnetic lenses.

The variations in the position of the image as the voltage changes is taken care of by the voltage regulator. After the voltage regulator was installed, the image never jumped around unless the range of regulation was exceeded. However, there still seemed to be some error in the system. After taking many pictures at high magnification this error (a fuzzing of the image in one direction) was thought to be due to improper lining up of the instrument. No double images were observed so it was not jumping of the image. When the magnification was reduced this trouble seemed to go away. This is shown in plates 615, 616 and 617. This solution of the problem seemed to be quite satisfactory. There are other reasons why low magnification is an advantage which will be treated later.

The simple theory of the focusing action of this electron microscope will now be presented. Referring to Fig. 16 it is seen that

(29) $$\frac{1}{a} + \frac{1}{x} = \frac{1}{f_1}$$

(30) $$\frac{1}{b-x} + \frac{1}{c} = \frac{1}{f_2}$$

(31) $$m_1 = \frac{x}{a} \quad . \quad \text{From (30)}$$

(32) $$\frac{1}{b-x} = \frac{c - f_2}{c f_2}$$ If now b and c $>> f_1$ or f_2 or a

(33) $$x = b - \frac{c f_2}{c - f_2} \cong b - f_2 \simeq b$$

(34) $$\therefore \quad m_1 = b/a$$

(35) $$m_2 = \frac{c}{b-x}$$

(36) $$\therefore \quad m = m_1 m_2 = \frac{bc}{a} \times \frac{1}{f_2}$$

Thus it is seen that if the image is in sharp focus that the magnification depends mainly on the focal length of the second lens. This assumes that the magnification of each lens is large compared to 1. Focusing is carried out by setting the focal length of the second lens for the magnification desired, and then varying the focal length of the first lens for the sharpest image on the fluorescent screen. That the magnification is independent of f_1 is seen from the fact that the current in lens #1 does not change appreciably when the magnification is changed from 500 to 10,000 by changing the current in lens #2.

The lens system in this microscope is stopped down in such a fashion

that the size of the stop in the last lens limits the size of the image for magnifications under about 2000, while for magnifications about 2000 the size of the image is limited by the gate valve just in front of the photographic plate. Thus the field of view is limited at magnifications above 2000, and this is one reason for working at low magnifications. Another reason for working at low magnifications is that the lens errors are very much reduced, as mentioned above. Still another reason is that with low magnifications the same field is imaged in a rather small area. This permits shifting the image laterally by means of a magnetic field $\perp$ to the direction of the beam and placed between the last lens and the plate. This allows several pictures to be taken on one plate. In practice 7 pictures are taken, each picture being slightly under ½" in diameter. The magnification is about 600. This system did not introduce any noticeable distortion.
It can easily be shown (see Fig. 17) that the deflection W of an electron beam by a magnetic field H extending for a distance L is

$$W = \frac{DL}{R} \tag{37}$$

where D is the distance of the screen from the magnetic field and R is the radius of curvature of electrons in the field H. R is given by

$$R = 3.36 \frac{\sqrt{V_0}}{H} \quad (\text{volts}/\text{gauss}) \tag{38}$$

In this system D = 37 cm., L = 5 cm., and W = 1 cm. Hence

$$R = \frac{DL}{W} = 185 \text{ cm}$$

and

$$H = 3.4 \text{ gauss.}$$

This field was easily obtained with a double coil, each coil containing about 50 turns of wire and each coil mounted on opposite sides of the electron microscope barrel. Two such double coils were used so that the image could be moved in two directions. Using such a set of coils the image can be moved to 9 positions as follows:

Switch Position	Current in coil #1	Current in coil #2	Deflection
1	0	0	undeflected
2	I	0	→
3	-I	0	←
4	0	I	↑
5	0	-I	↓
6	I	I	↗
7	I	-I	↘
8	-I	I	↖
9	-I	-I	↙

Actually a 2 deck switch was used which could get 7 of these positions. Using a 4 deck switch all 9 positions could have been reached. The hookup is shown in Fig. 18. The resultant picture is shown in the contact print of plate 702. Before this coil system wasinstalled, the beam was deflected by hanging some permanent magnets about the plate chamber so as to get the desired deflection. However these fields were not uniform and often distorted the image from a circle to an ellipse. This method has been of great use in increasing the output of the electron microscope. Where about seven pictures of each object are taken, this method speeds up the microscope by about a factor of seven. This was actually the case in the work done ~~for the NDRC project~~.

Since the beginning of June, 1942, the microscope has been operating at the rather low magnification of 600, instead of about 10,000 as was the usual practice before that time. Several of the pictures taken since that time were taken without the regulator operating due to a flash over which blew out the paper in the protective device. These pictures seemed to be just as good as those taken with the regulator working. Presumably this is due to the overall better operation of the microscope at low magnifications. The regulator seems to make the most difference at high magnifications. Another reason why the pictures taken with no regulation and at low magnifications are better than those taken with high magnifications is that at low magnifications more intensity is available, and hence exposures are only 1 second long instead of 5 or 10 seconds as at high magnifications. Thus, with the very long time constant of the filtering system, changes in the 110 volt line cannot produce large changes in the output voltage in the short period of one second, but can in 5 or 10 seconds.

One of the best pictures taken with this electron microscope was one of some precipitated calcite (see plate 702). In this picture the supporting collodion film seems to have been torn away, probably due to too strong an electron beam. Thus there is no chromatic aberration due to variable loss of energy of the electrons on traversing the collodion film, and only particles clinging to the wire screen were observed, preventing them from charging up and deflecting the electrons slightly as they pass by. A few of the edges of the crystals seem to be fuzzy, but this fuzziness seems to be distributed randomly over the picture both in direction and location, and hence is thought to be due to insufficient depth of focus. Since the depth of focus is about 1 μ and since these crystals are several μ long, this is quite reasonable. Observation of the sharp boundary outlined in the enlargement of plate 702 in an ordinary microscope shows that the transition complete darkness to complete brightness takes place in about 10 μ. This corresponds to about 160 Å in the object. Whether this is the ultimate resolving power of the instrument is not known, for it may be that this is also the limit of resolution of the plate. The plates used (Process plates) are good to about 12 μ using light. The grain size is 1 μ or less so this resolution seems to be determined by the scattering of light in the emulsion. Just how the scattering of light is different fromthe scattering of electrons in an emulsion is not known. However, no problems where a resolving power of lessthan 150 Å was needed have arisen, so this problem has not been fully investigated.

Various Problems on which the Electron Microscope has been used

Clay and rouge

Prof. W. E.Williams brought around some samples of clay which he had received from the American Optical Co. In attempting to find a substitute for rouge, they had taken x-ray powder pictures of clay calcined at various temperatures. These are shown in Fig. 19. On the evidence of the lack of linesof those clays calcined around 1500° F. they tried this clay and found it satisfactory for polishing. It is now being used by them commercially. Prof. Williams was interested in finding out if there was anything that the electron microscope could show which would explain why this certain clay was the best. The pictures shown (plates 668, 616, 684, 669 and 674) show a gradual trend up to 1700° F. and then a sudden change in formation between 1700° and 2600° F. In order to try to interpret these pictures, I asked Roger Hayward for some rouge samples from some work he was doing at Mount Wilson. These are shown in plates 700, 708, 710 and 714. They are of unused rouge, and of rouge which has been used for various lengths of time. It is seen that the clays around 1500° do show the one typical characteristic of rouge -- lots of small holesin the particles. The usual interpretation of these small holes is that they are the result of many small particles coming together to make one large particle, the small spaces between the particles seeming like holes. Some of the rouge pictures seem to indicate that this is not the case, and that having lots of small holes is a property of the single rouge particles. The used rouge pictures probably have some wax in them fromthe tool. One characteristic of the clays that persists up to 1700° is the long rod-like structures which gradually diminish in number as the temperature is increased. Rouge does not seem to have this type of particle. In general it is seen that the clay particles seem softer and rounder as the temperature is raised, excluding the clay calcined at 2600°, which seems to be an entirely different substance. It is rather strange that the x-ray lines that are just beginning to appear at 1700° are found in the raw clay spectrum rather than in the 2600° spectrum. This indicates that the material responsible for some of the lines in raw clay becomes mushy or of very small size around 1500°, but that it can be reformed after heating to 1700°.

Calcite

Some pictures of various forms of calcite were taken for Professor Zwicky in an attempt to observe the planes predicted by him. Some calcite was strained almost to the crushing point and then ground up in a mortar. The resultant powder was then allowed to settle in water and objects made of the fine particles which stayed in suspension. These gave particles which seemed to exhibit no crystal structure at all. In an attempt to get some small calcite crystals, Mr. Ronald Rau made some very pretty calcite objects by precipitation from very dilute solutions of CaCl and Na_2CO_3. These are shown in plates 701 and 702. Most of this work was done by Mr. Rau and is included here merely to show the rather pretty pictures that resulted. The ground up calcite pictures are shown in plates 711 and 671.

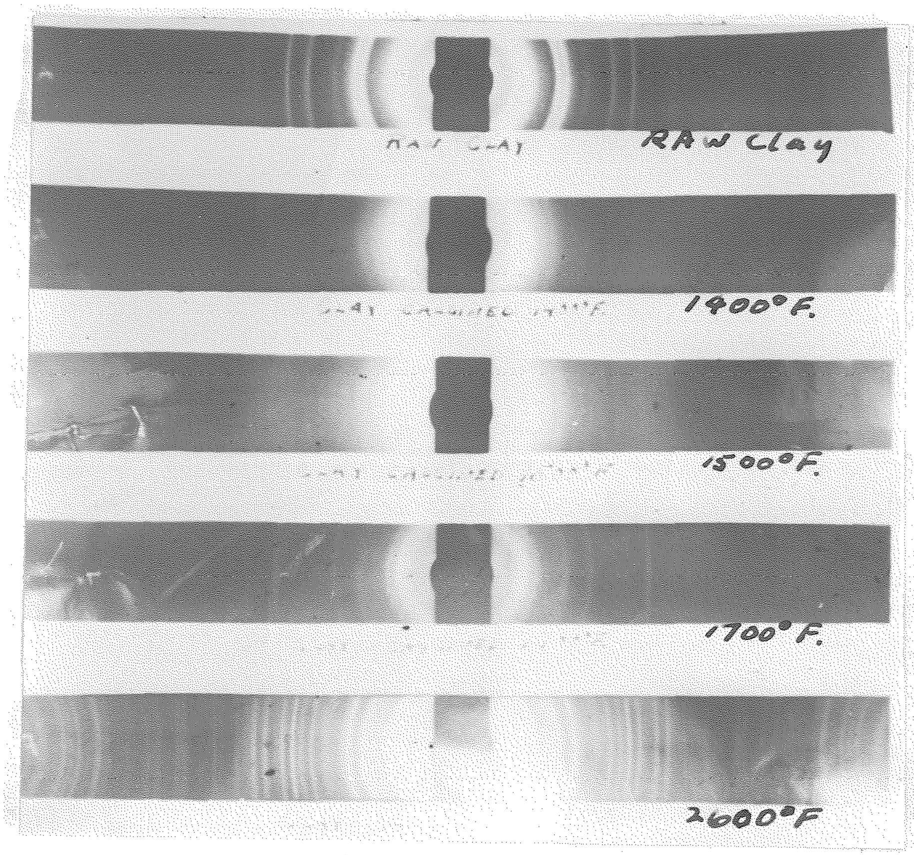
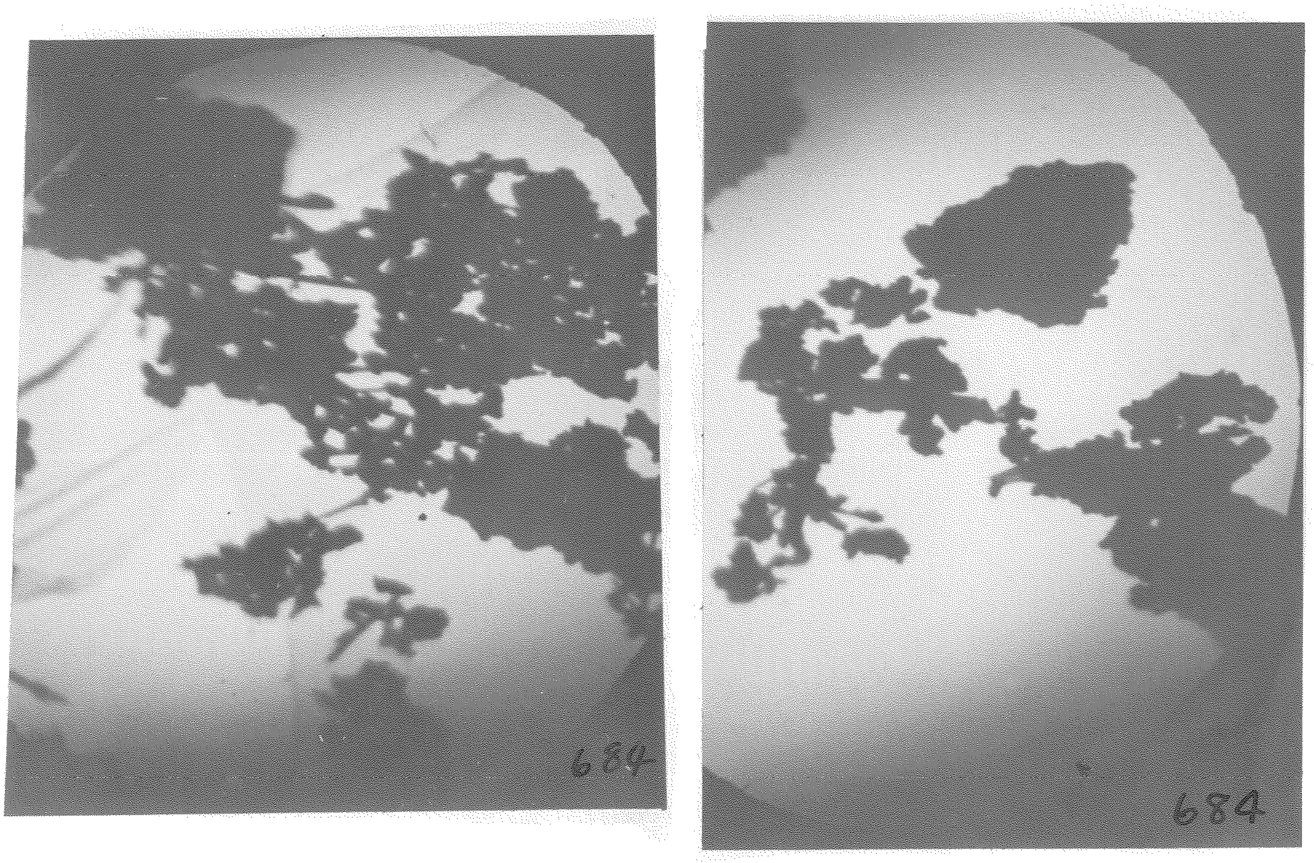


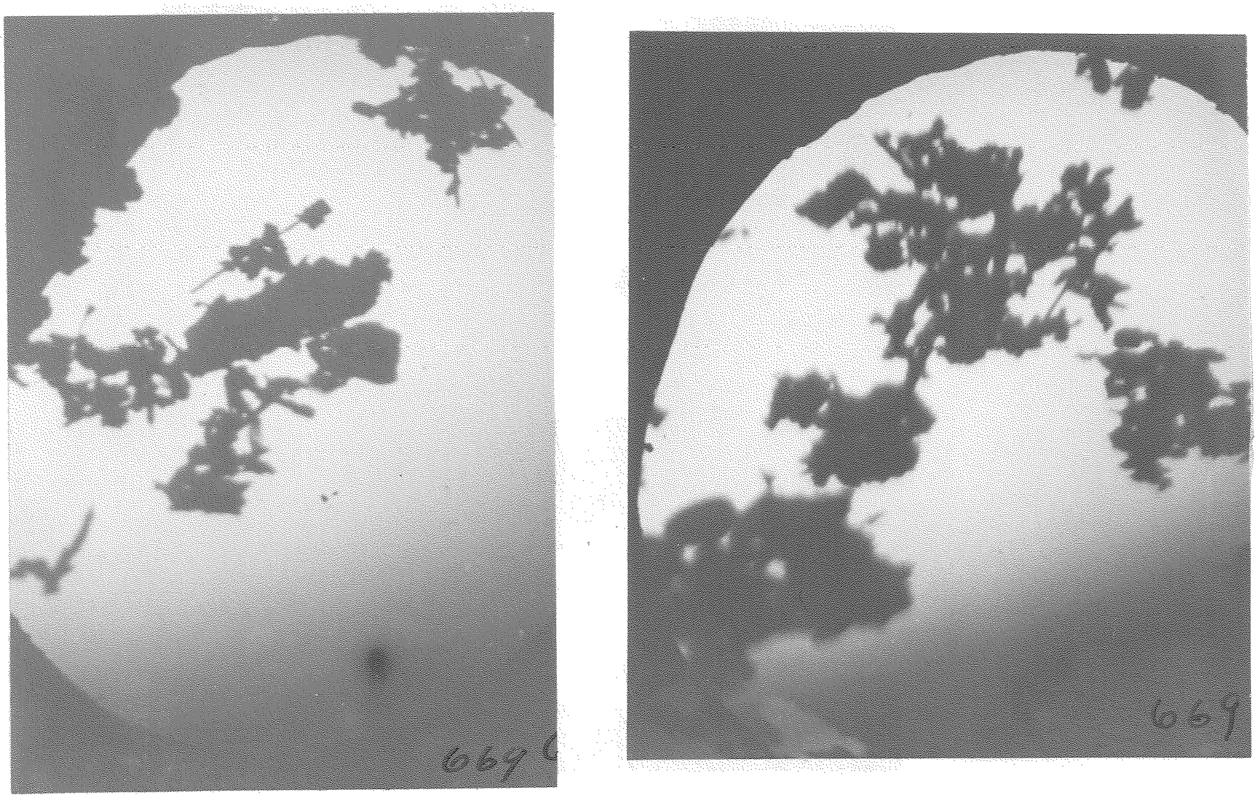
Fig. 19.

668 Clay (raw)

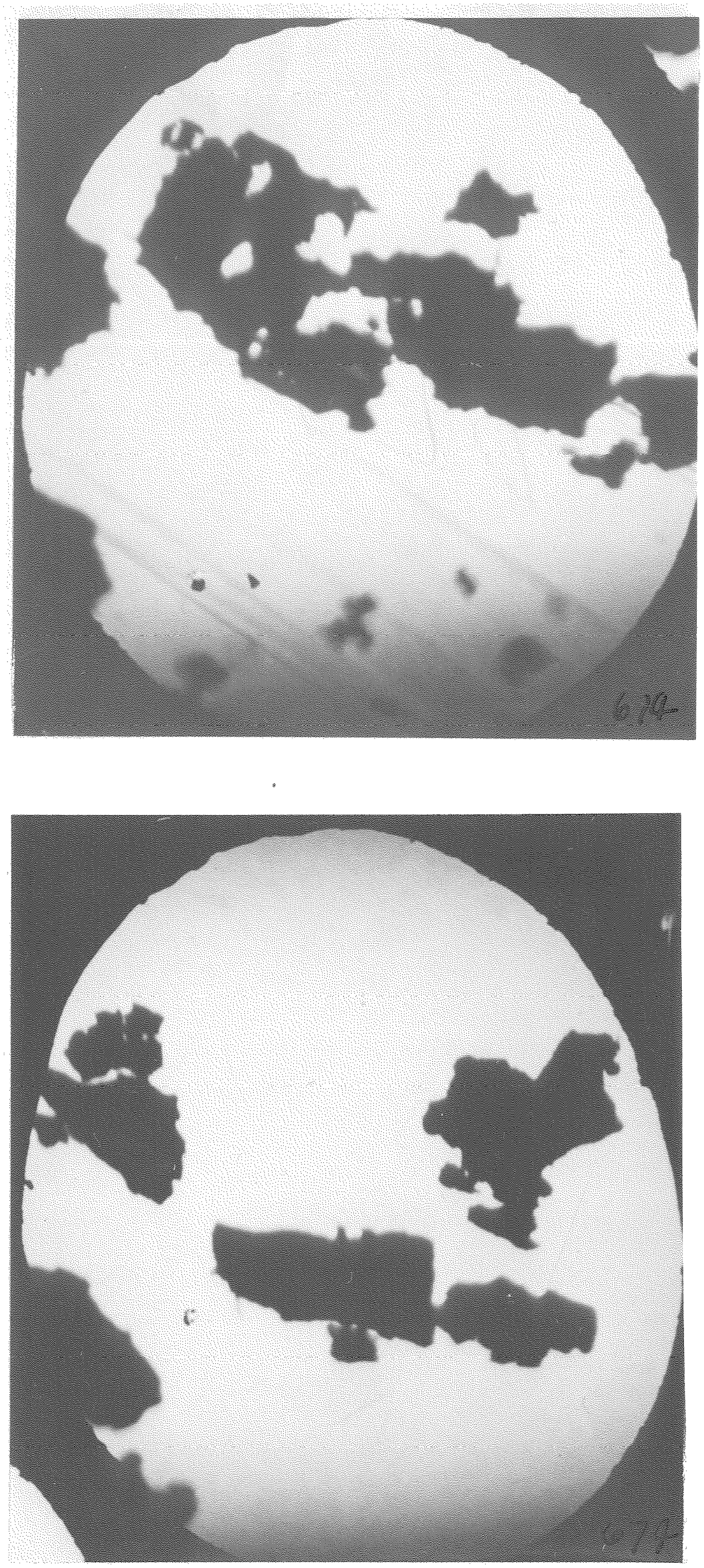
616 Clay (1400°)



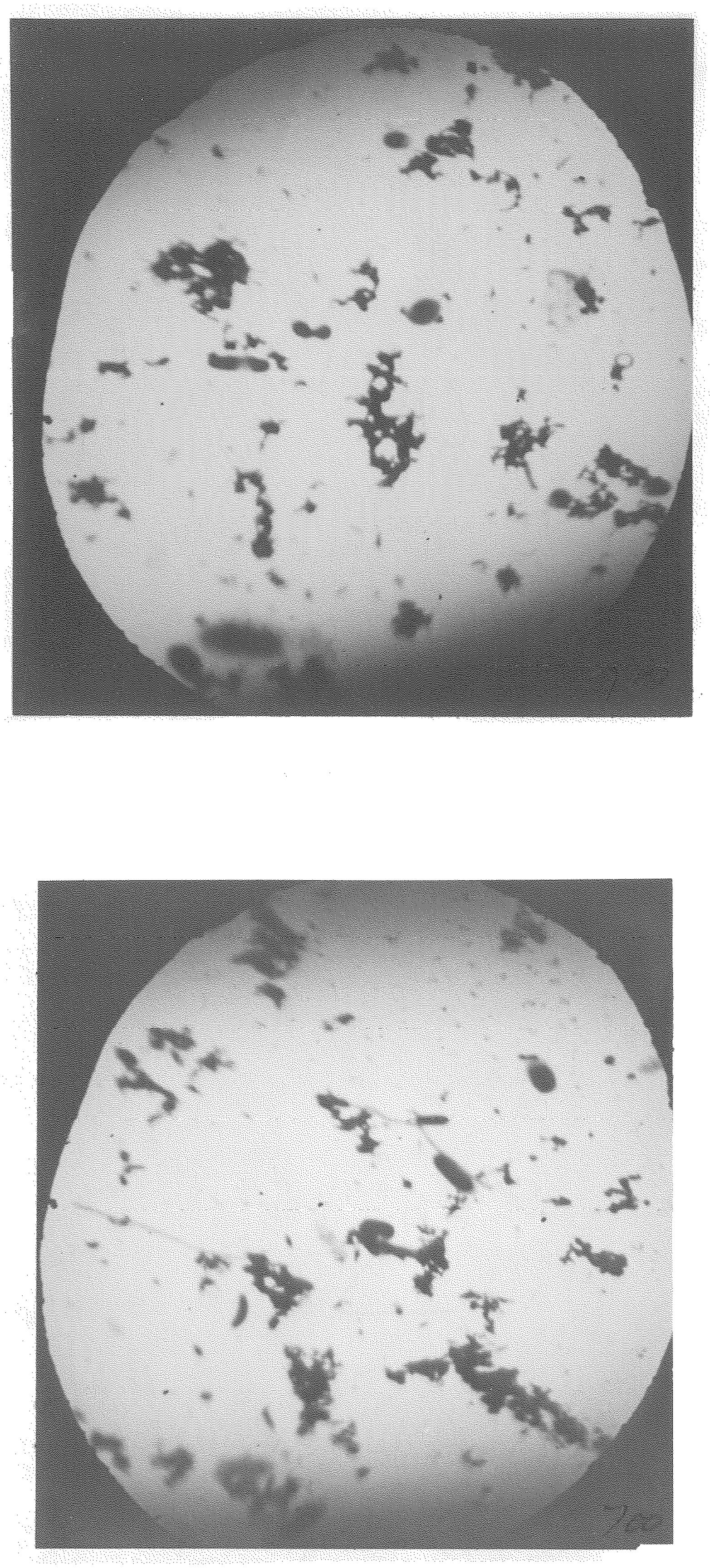
684. Clay (1500°)



669 Clay (1700°)

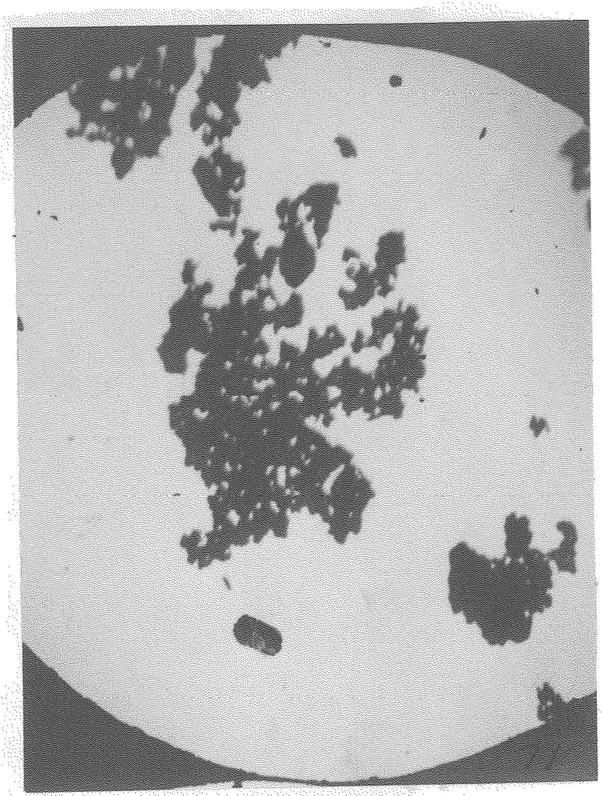


674. Clay (2600°).

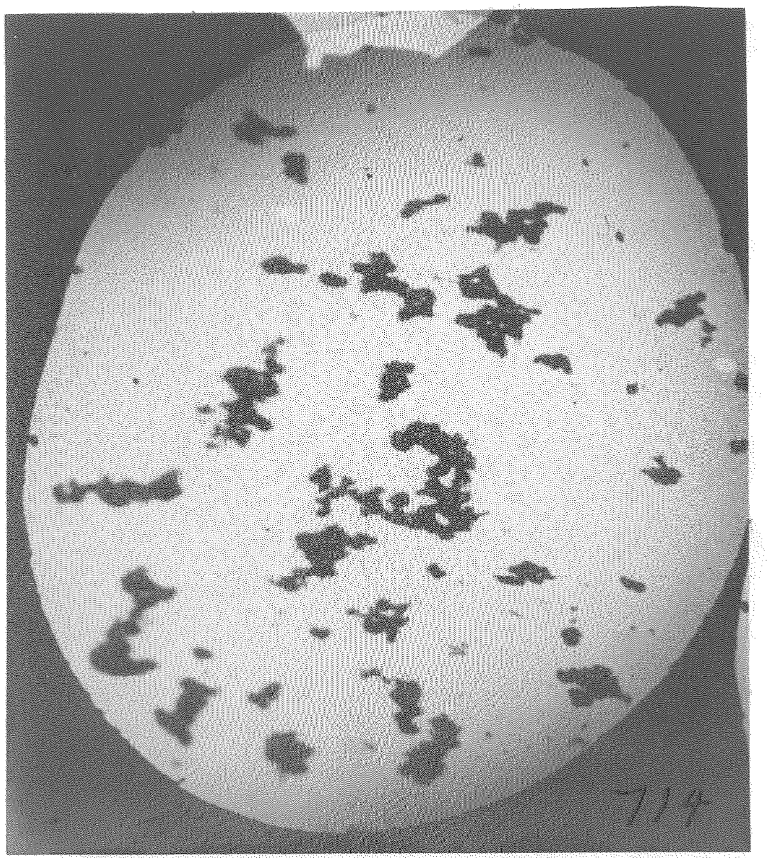


700. Used Rouge (from R.H., marked "F")

708. Unused Rouge.



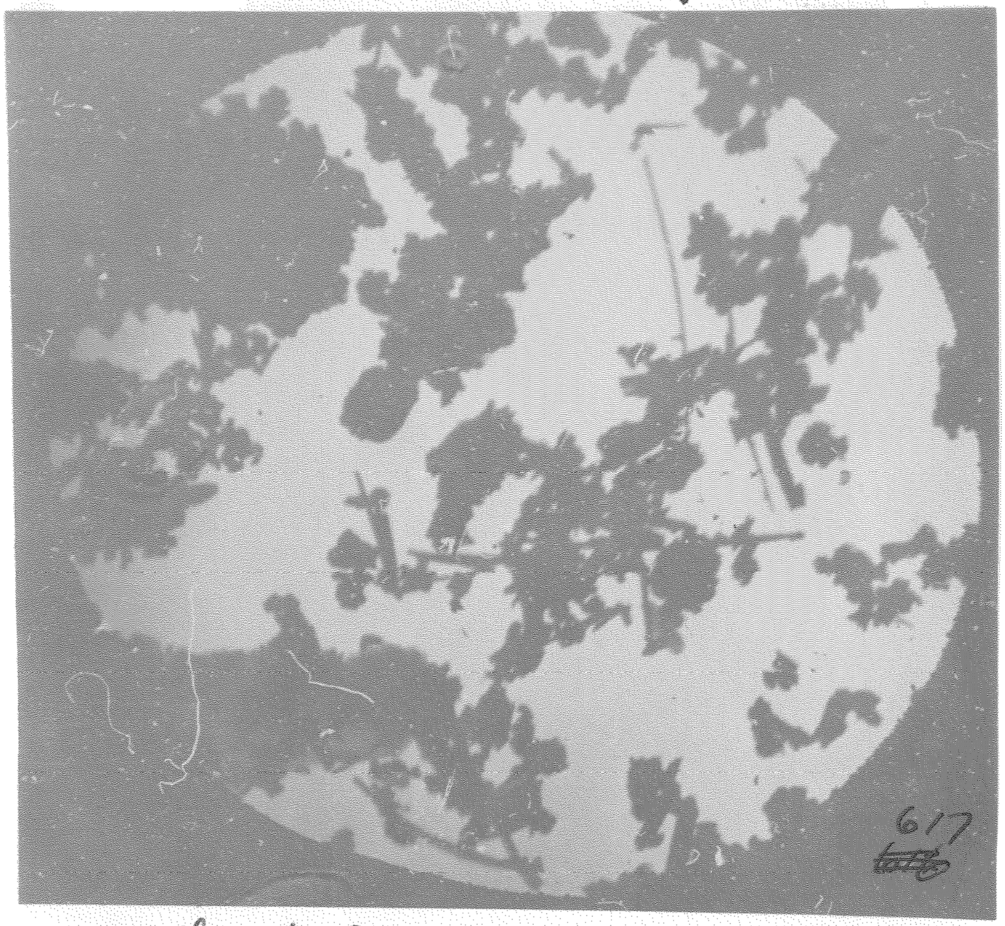
710. Rouge used 3hr.



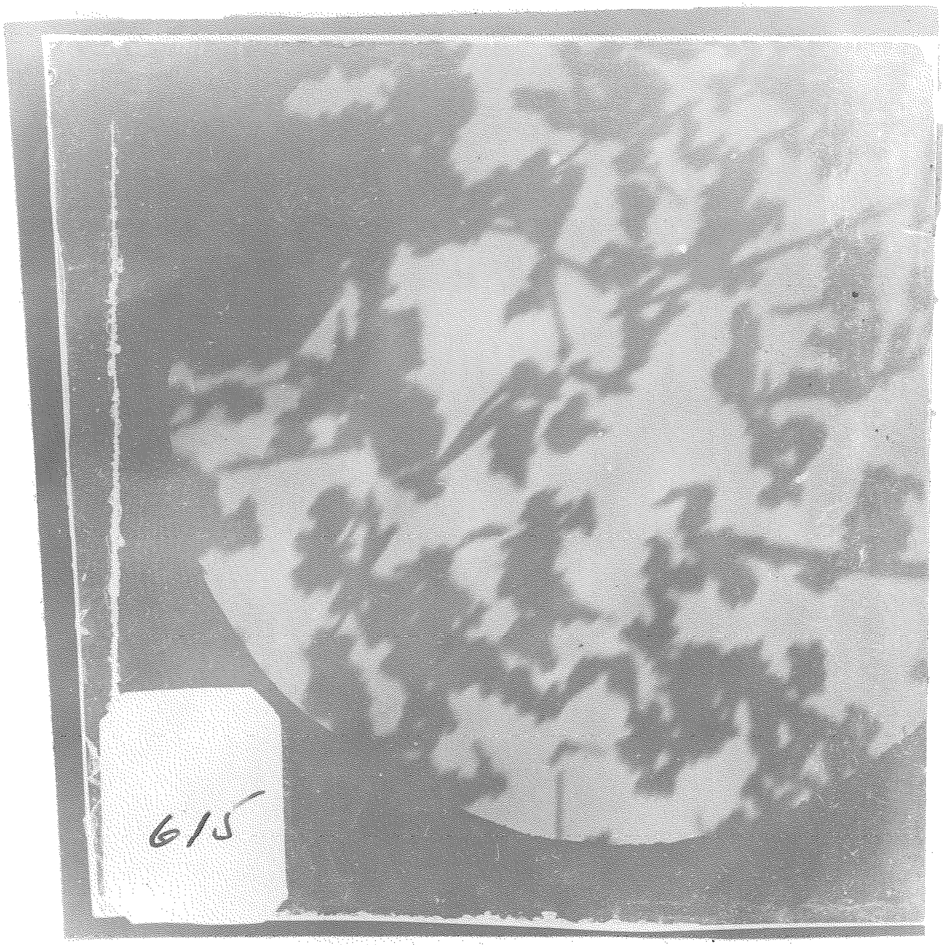
714. Rouge used 8 hr.

Note: The rouges
on These pictures
are from a single
polishing operation.

616 Clay 1400°. optical enlargement 14x.



617. Clay 1400° optical enlargement 8x



615. Clay 1400°. Optical enlargement 2.2 x.

Arrows indicate an object which appears in all three pictures.

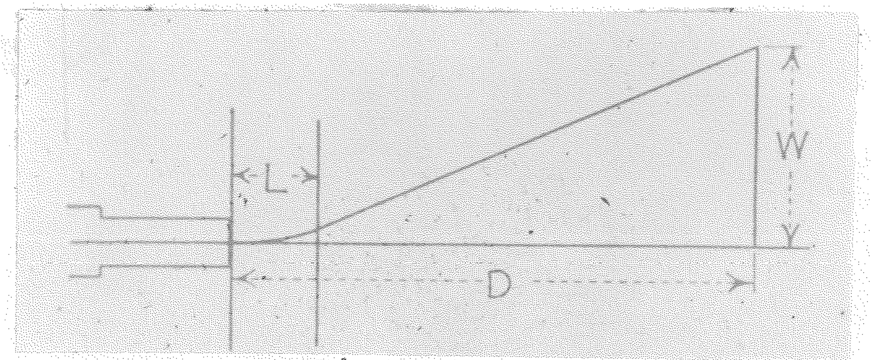


Fig 17.

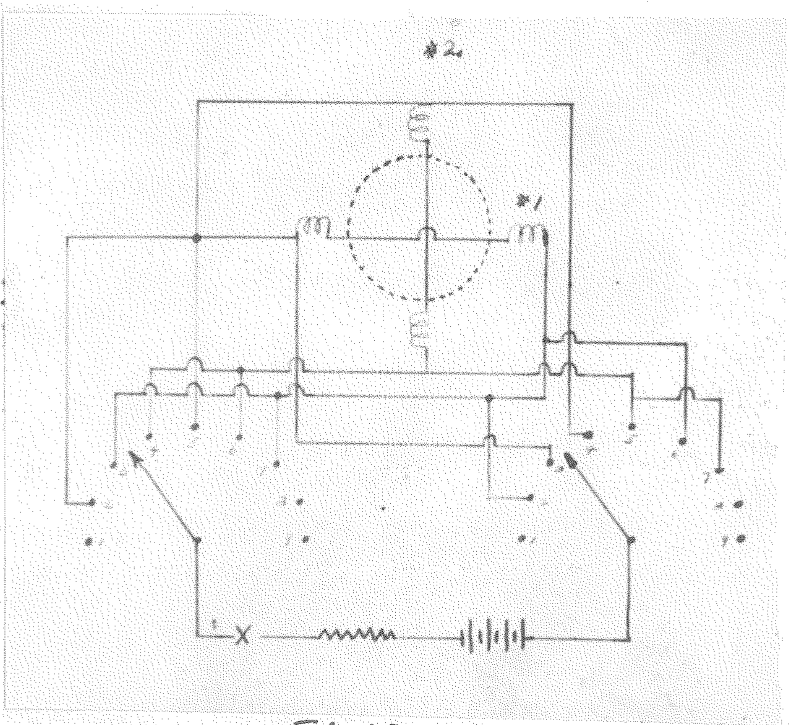
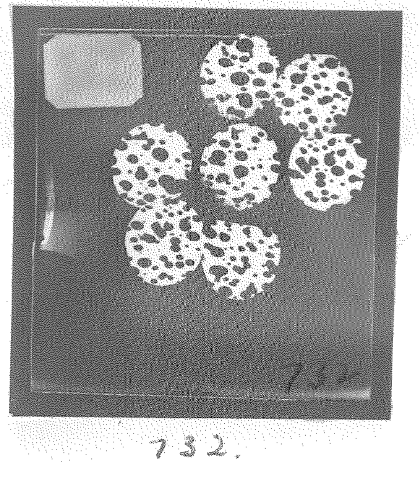
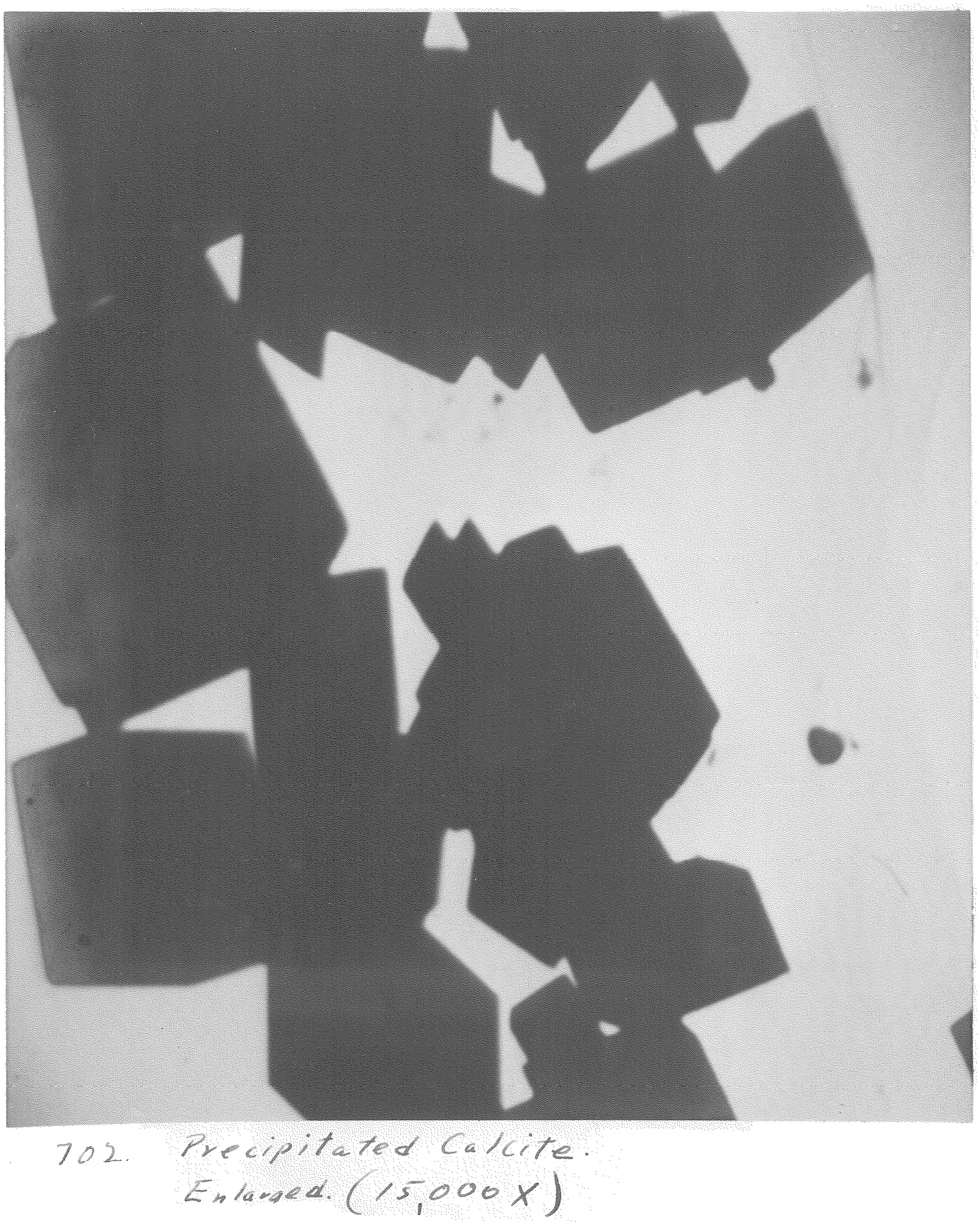


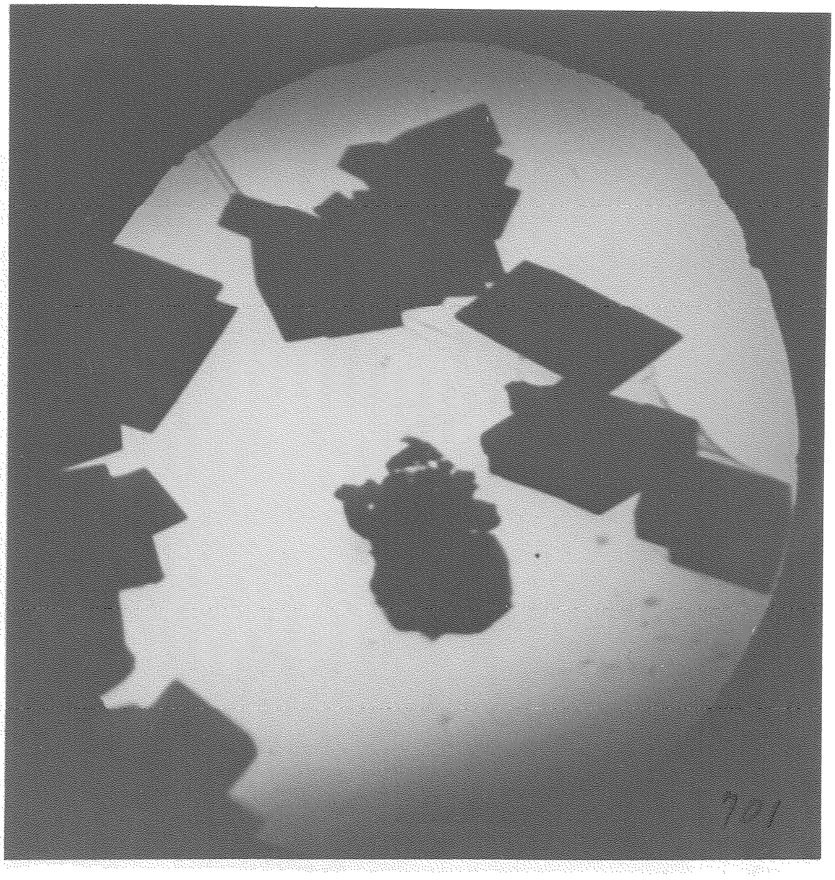
Fig 18.



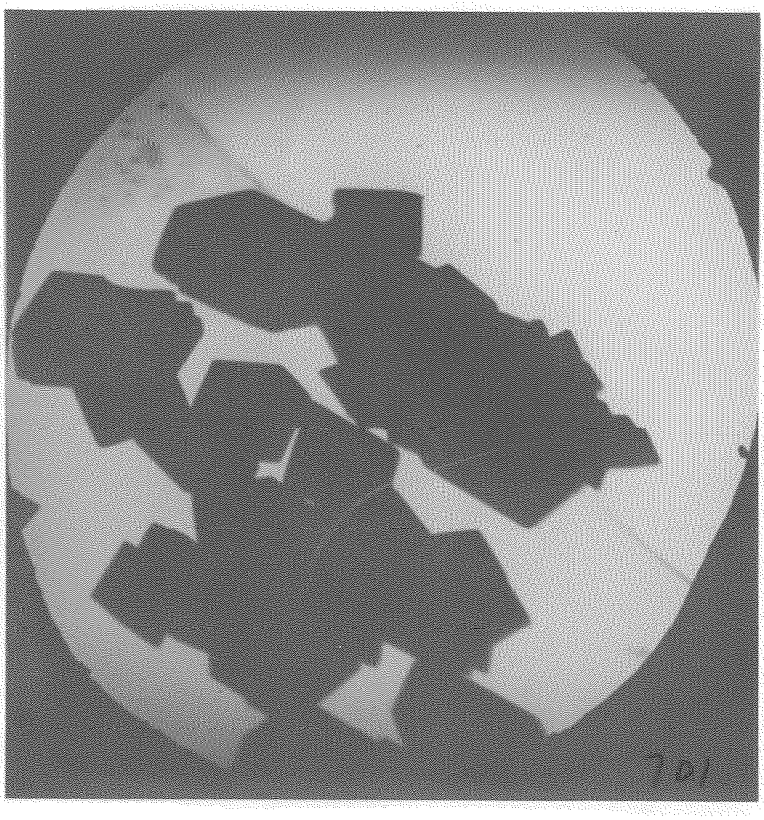
732.

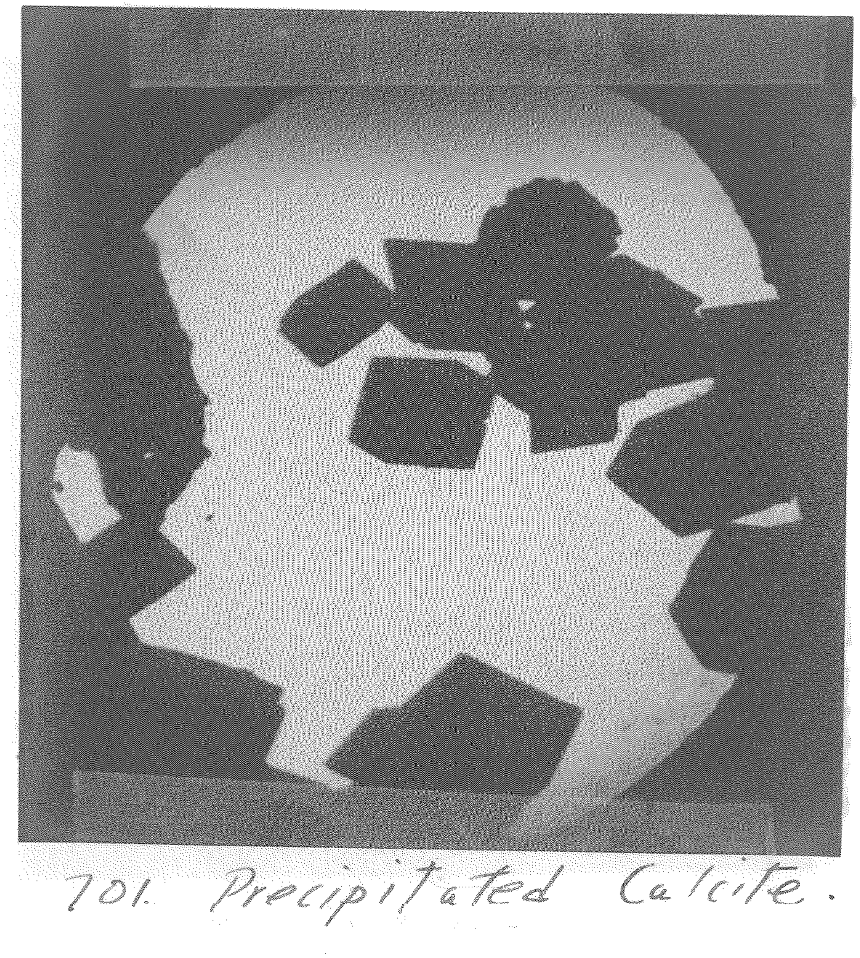


702. Precipitated Calcite.
Enlarged. (15,000 X)

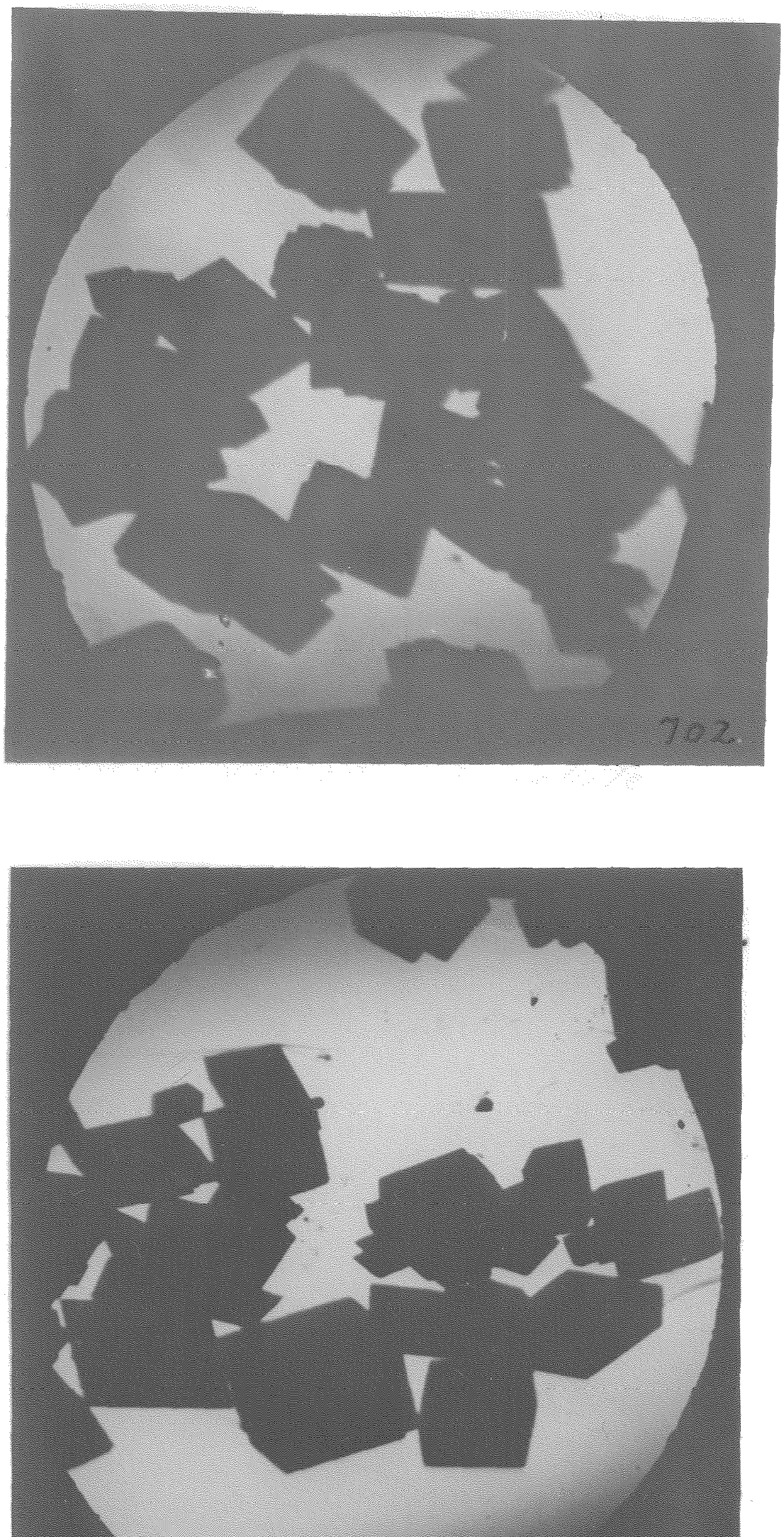


701. Precipitated Calcite.

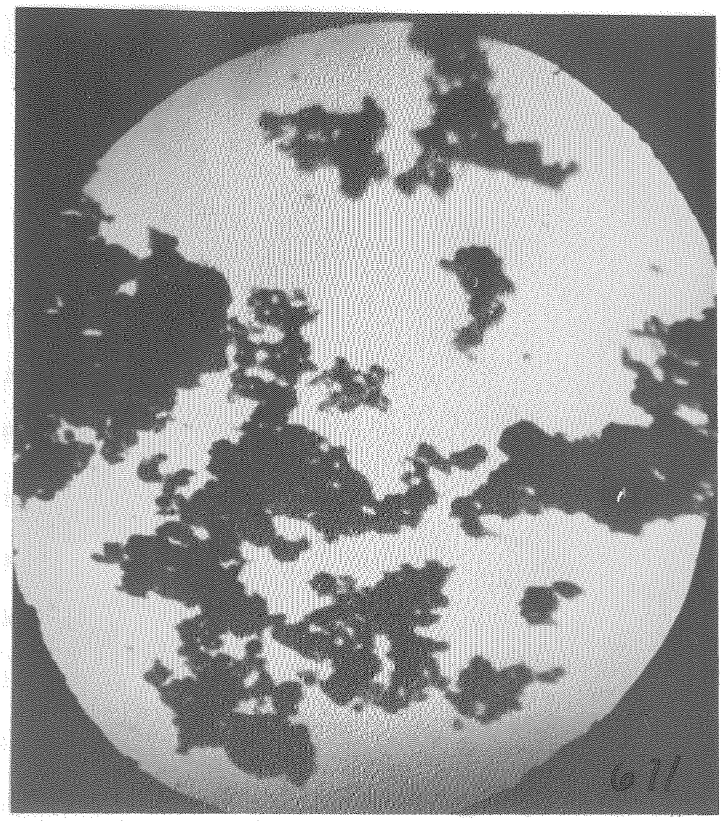




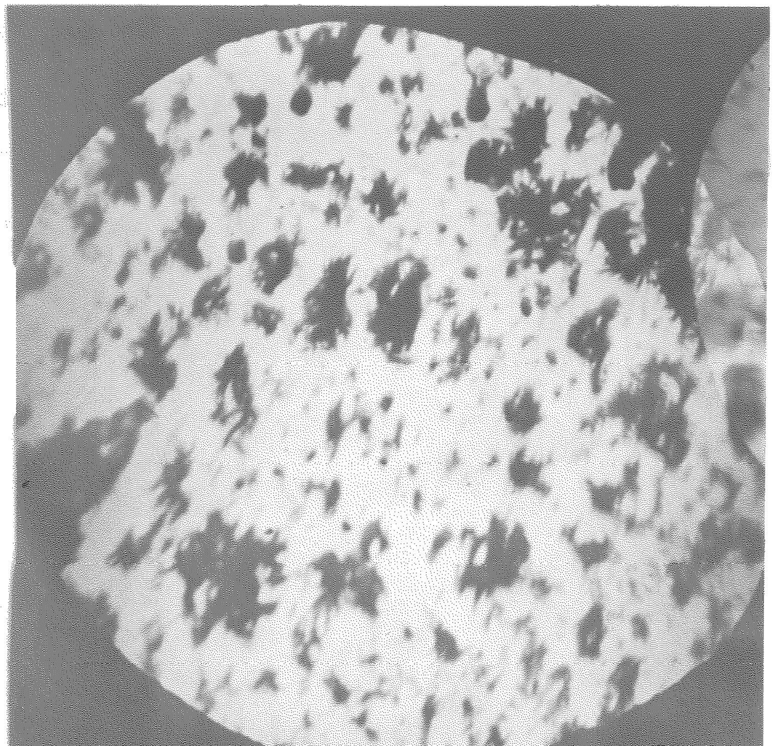
701. Precipitated Calcite.



702. Precipitated calcite.



671. Ground-up calcite.



711. Calcite precipitated from concentrated solutions of $CaCl$ and Na_2CO_3

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(2) See for instance "Procedures in Experimental Physics" by John Strong, Prentice-Hall, 1938, Page 294.

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(8) Maloff and Epstein, "Electron Optics in Television", McGraw-Hill, (1938) Page 156.

(9) Reference (8), Page 192.

(10) The most useful reference for the general theory of electron microscopes is M. v.Ardenne, "Elektronen-Übermikroskopie," Julius Springer, Berlin, (1940). The publications of the R.C.A. in the RCA Review are of little use as they give no details and are merely about the results obtained with the R.C.A. electron microscope.

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