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ELEMENTARY CALUTRON ARC THEORY

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ELEMENTARY CALUTRON ARC THEORY

Abstract

Calutron plasma phenomena are described and correlated with their causes, from a most elementary point of view. Ion motion, electron motion, ion formation and distribution, potential distribution, light ion requirement, and magnetic field effects are qualitatively discussed and unified in a simple but comprehensive description of the calutron source plasma.

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INTRODUCTION

The calutron arc is a plasma composed of neutral particles and equal numbers of positive ions and electrons. Neutral gas is fed into one side of the arc and the ionic and gaseous products pass through the other side and enter the calutron ion acceleration region. The way in which the arc performs its function of producing ions for electromagnetic separation has been the subject of a great many experiments and is the subject of this report. The general purpose is to present for the practical experimenter a somewhat detailed discussion of how the arc functions. A reasonably accurate picture of experimental results can be anticipated. The procedure will be to describe the fundamental motions of electrons and ions and from these motions to deduce the various processes inside the arc. These processes result in the formation of a uniform high flux of positive ions moving into the acceleration region of the ion source unit. This procedure permits the correlation of many phenomena and processes that have been observed in calutron operation and thus may contribute toward gains in ion output and in design simplicity. Emphasis will be placed, however, on gaining a working understanding of arc processes. The concepts developed below are considered fundamentally sound because a number of predictions made from them have proven true.

PLASMA PHENOMENA

Arc Particles and Particle Motions

The particles present in the arc are: electrons, uranium tetrachloride molecules, and the disintegration products of uranium tetrachloride in all stages of decomposition and ionization. The discussion below will emphasize the presence of electrons, positive ions of both uranium and chlorine, and the neutral gas particles.

The particles in the arc move in different ways depending on their masses and degree of ionization. Neutral particles move as if the magnetic field (required for electromagnetic separation of ions) were not present. Ions, on the other hand, are able to move perpendicular to the magnetic field only in circular paths. Their motion parallel to the magnetic field is not affected. The result is that as soon as atoms or molecules, moving in straight lines through the arc, are ionized they stop linear motion and start moving slowly along a tiny helix or screw-like paths parallel to the magnetic field. The radius of this circular motion perpendicular to the magnetic field is found from the fact that the centrifugal force on the ion is equal to the opposed magnetic force. The formula is:

$$\frac{Hev}{c} = \frac{mv^2}{r}$$

where m is the mass of the ion (gm.),
r the radius (cm.),
v the velocity of the particle (cm/sec)
H the magnetic field intensity (oersted)
e the charge of the particle (e.s.u.),
c the velocity of light (cm/sec).

When electrostatic fields are present the motion will be changed from a circle to a cycloid. The ion can move for great distances perpendicular to the magnetic field following a given potential line. The average velocity of this motion (the drift velocity) is obtained by the formula:

$v = c\,\frac{E}{H}$ where E is the electrostatic field intensity in e.s.u.

To the motions described above there will be an added motion that is completely random in character when the particles collide with other particles. This added motion will make a group of ions diffuse through the magnetic field as they would if the field were absent except that they will move with a much greater reluctance. The reason for this is that, unlike particles moving in the absence of a magnetic field, they do not move in straight lines between collisions, but in circles, and so cannot move from the immediate vicinity of the collision except along the magnetic field. If an electric field perpendicular to the magnetic field is also present, the cycloidal motion perpendicular to the magnetic field will also be present. This will result in the flow of ions in a stream perpendicular to the magnetic field and also perpendicular to the electrostatic field. All of these motions are present in the arc, so the above motions must be thoroughly understood. A simple picture can be visualized if one can see the flow of particles across the face of the arc like the surface of a river over-flowing dykes at its sides. The river streams along in the direction perpendicular to the electric and magnetic fields with its surface on an equipotential surface and moving with the ion drift velocity. The overflow on its sides is the motion parallel to the magnetic field, and the collisions of the atoms are like the random motion of the river water. The electrons and ions flow in the same direction with the same velocity. Diffusion of ions out of the arc into the beam is similar to steam arising rapidly from the surface of the river.

Arc processes will be deduced from the simple motions described above, with the added assumption that ion flow in the arc must be uniform, not varying rapidly in direction or in density with time. This is forced by the fact that the beam of positive ions from the arc is separated according to the constituent masses in a magnetic field. Space charge forces in this beam, due to the fact that the ions all have positive charges, must be neutralized to permit magnetic focussing. The neutralizing negative charges cannot follow rapid variations in beam density, so these variations must be slow, or absent. This is the basis for the arc stability requirement.

<u>Electrons in the Arc</u>

Electrons in the arc ionize the gas particles and permit the formation of a high intensity plasma. Understanding of the electron motions and limitations to plasma processes resulting from electron motions is essential to the understanding of arc processes.

Electrons are introduced into the arc with a given energy. They are traveling with a very high velocity along the magnetic field and very slowly normal to it, so most of the collisions they make occur along a straight line parallel to the magnetic field from the point on the cathode where they were first released. For this reason, the important processes in which ions are formed occur in what is called the collimated arc. Inside the collimated arc, electrons, making a great many collisions, move relatively slowly toward the anode. They lose some energy with every collision, so the average energy of the electron is reduced somewhat on going from the cathode to the anode end of the box. Upon reaching the anode end of the arc they will be lost to the anode if the energy of the electron is high enough to cross the plasma potential barrier there.

The plasma potential is set up as a result of the fact that the electrons in the arc move much more rapidly than the positive ions they form. The electrons can cross the arc length a number of times while the positive ions cross it once and so should be lost to the ends of the box containing the arc. When more electrons than positive ions leave, the net surplus of positive ions immediately set up a potential on the arc periphery. This potential holds back all the electrons having insufficient kinetic energy to cross it. The net result is that all the low energy electrons are held and the high energy ones escape at the ends of the arc. This is a second reason for non-uniformity of the arc near its ends.

The electrons move not only along the magnetic field, but also in circles perpendicular to it. If there is an electrostatic potential in the arc perpendicular to the magnetic field, the electrons can move along cycloids perpendicular to both. An electrostatic potential must be built up inside the arc due to the fact that because of their higher mass the positive ions can move out of the arc in a direction normal to the magnetic field much more easily than can the electrons. This difference in ease of motion between electrons and positive ions sets up an electrostatic field inside the arc that must be most negative at the center (because of the loss of positive ions). This field permits the electrons to move across the magnetic field along equi-potential lines. The net motion of the electrons is thus both along the magnetic field and in a stream around the center of the arc in the same direction as the motion of the positive ions.

The relative numbers of electrons of different energies can be estimated. The arc density is about 10^{13} ions and electrons per cc. The number of electrons coming directly from the filament is only about 10^{10} per cc. From this it follows that 99.9 percent of the electrons in the arc did not come directly from the cathode. The average energy will therefore be relatively low, perhaps a few electron volts, since a large fraction of the electrons are separated from neutral particles by the ionization process. All of these electrons have low energies.

Ionization and Neutralization

The UCl_4 vapor entering one side of the arc is very violently attacked by the electrons in the arc. The effective temperature of the arc is many thousands of degrees centigrade, and the probability of a UCl_4 molecule going through without being broken down and ionized is indeed small. The picture is modified by the fact that the pressure in the arc chamber is only about five microns, so the body of the arc is a fairly good vacuum. It is this fact that makes it impossible to use the usual formula for ionization rates and chemical equilibrium. Instead, one must associate ease of ionization and ion density with ionization potential and mass and must use the cut-and-try method for results.

Once ionized, there is a strong tendency for the particles in the arc to be neutralized and so lost as far as use is concerned. The best situation, of course, is for all but the desired ion to be neutralized, so that the accelerated ion current is all the desired ion. This is partly what is accomplished by controlling arc current, voltage, and temperature. A ratio of 1 to 4 for uranium to chlorine in UCl_4 is reduced to approximately 1 to 1, with a third portion consisting of the other associated ions, such as U^{++}, UCl_3, etc. In general, one can say that a light, easily ionized atom associated with the uranium in the arc should increase the output of U^+. This will be discussed in more detail below.

If one can neglect the desire to produce a small fraction of non-useful ions in the ion current from the arc, it is evident that a high effective arc temperature extending up to the meniscus, from which ions are drawn into the accelerating region, is best. It is true, however, that the higher the arc temperature the higher the fraction of U^{++} and Cl^+ in the beam.

Positive Ion Distribution and the Ion Current Limit

The distribution of the various positive ions must, for the steady arc mentioned above, be of uniform density and temperature. A lack of stability of the arc results in what is called "hash". Fundamentally, hash is plasma oscillations, or variations in neutralization of the ions in the arc, with a consequent formation of fluctuating potential gradients. These potential gradients move positive ions contained in their vicinities along cycloidal paths in a direction parallel to equipotential surfaces when the ions considered are accelerated in directions perpendicular to the magnetic field. This results in penetration of fluctuations into other volumes adjacent to the original fluctuation. Because of the extremely rapid re-establishment of the normal Maxwellian distribution, assisted by the high fields (nearly 800 volts/cm) between ions in the plasma, all oscillations are normally damped out very quickly. For arc density values of interest here, the inertia of the ions plays an important part. Plasma oscillation characteristics of the natural frequencies of the ionic masses and of the plasma density are present.

The upper limit of the accelerating potentials on any area of the arc has a natural value depending upon the rate of supply of the positive ions to the area. There is a characteristic acceleration voltage for each set of lower charge consumption rates and lower plasma densities accompanying lower magnetic fields. The complete picture regarding emission limits for a hash-free or stable plasma is not extremely straight-forward and must be determined empirically. There is an interplay of electrodynamic forces due to the drain currents out of the plasma that is clearly subject to easy disturbance. The extreme sensitivity to variation of any of the controls is commonly observed in calutron operation.

Plasma Potential Distribution

The potential distribution in the plasma is conditioned by two things: first, by the distribution of the relatively immobile positive ions, and second, by the requirement that electrons must drain out of the body of the arc at the same rate as the positive ions. These two factors are not independent. Small potential gradients radically change ionic motion since the average ionic kinetic energy in the plasma is very small (of the order of .01 ev). The collimated arc is the energy source, so the potential gradients in the collimated arc decrease rapidly from the center to the outside. The potential distribution is set up by electron drain requirements. There is in addition, the requirement that there be a small potential gradient in the arc in the direction of the magnetic field due to the rapid loss of positive ions to the cathode and anode. This potential gradient is of primary importance when some understanding of plasma phenomena in the region of the collimating slot and anode is of interest. In particular, the elementary picture of neutral particle density distribution in these regions is not valid because of this gradient.

Geometric considerations not mentioned here are also of great importance because of their effect on vacuum pumping speed at the plasma meniscus and at the ends of the plasma and thus on the pressure distribution in these areas. For this reason acceleration-slit geometry changes will change the ion output from the arc. A lot of neutral particles pour out of the arc into the accelerating region. High pumping speed in this region is important.

Secondary Electrons

The calutron arc is unlike other electron scattering and absorbing media in that ionization cross section, gas pressure, and electron temperature are mutually dependent in this case. A small increase in primary electron current or voltage will change the average electron temperature, the average ionization cross section, the positive ion density, the ratios of the different positive ions in the plasma, the pressure, and the mean-free path of the electrons and atoms in the arc. These variations, usually small for small changes in primary electron current values, can result in large changes in production of U ions and in arc stability, particularly if a change occurs in mode of loss of electrons or in mode of formation of U^+ from UCl_4. The changes observed on the meters during manipulation of arc controls are averaged over the surfaces of the arc (at the cathode, anode, and meniscus) and consequently are much smaller than actual changes in small sections of the arc.

Electrons in the plasma depend on fields inside the plasma for forces to drain them to ground, and these fields must be strong and steady to avoid building up plasma hash which will make the ion beam useless for isotope separation. It is these fields that result in one limit to the efficiency and output of the calutron for isotope separation. Small modifying fields, such as those applied by probes, can change the plasma potentials and thus the mode of dumping of electrons in a radical fashion, producing low useful beam intensity, plasma oscillations (hash), and a non-uniform ion distribution.

Light Ion Requirement in the Arc

A separable ion beam current must be uniform and constant in time. The positive-ion-space-charge-neutralizing electrons are formed slowly in the beam region, and any reduction in beam intensity causes the same reduction in electron density. These electrons are then lost to the tank walls, and are not recovered. The recovery of the original beam intensity demands, for space charge neutralization, the formation of more secondary electrons. These are formed slowly, and during this period of formation the non-neutralized space charge forces of the positive ions spread the ion beam. A focussed beam requires a stable source.

A stable ion beam current requires a stable plasma or arc source. This source, for maximum production, must be quite dense. This requirement, along with a large source area to permit maximum total current for a given emission per unit area, can be met because of the relative immobility of ions moving across the magnetic field. These ions circulate around the arc until neutralized or moved out of this region by a number of collisions with other ions. The result of this motion is a rapid increase in ion density when the arc is first struck because of the retention of all the ions formed until the density is increased to the point where loss by collisions (diffusion) becomes important. The arc can be most dense for the smallest neutral gas influx when the rate of loss by diffusion is least. The rate of loss by diffusion is smallest for the lightest ions, so light ions, accompanying heavy ions whose rapid diffusion into the acceleration region is desired, are best for the support of a stable arc.

An additional factor of importance is the character of the electron stream coming from the cathode. These electrons make all of their ionizing collisions with neutral gas molecules on a direct line from where they are released from the cathode. A uniform plasma therefore requires uniform electron emission. This emission will be uniform only if the plasma sheath at the cathode is uniform and constant. This sheath is composed of positive ions coming from the plasma and moving to the cathode. Ions that easily diffuse out of the plasma region will not reach the cathode in sufficient numbers unless the pressure is proportionately high. High pressure is thus required for heavy ions. Light ions can not diffuse out of the plasma easily and so satisfy the cathode sheath requirements at proportionately low pressures. It is certainly true, however, that light ions that are lost rapidly by neutralization are not desirable as light ion components. They would give the same lack of sheath uniformity as the heavy ions.

The last factor of importance is the requirement for uniform emission from the cathode for a uniform temperature. The calutron cathode is activated by uranium. The light ion used must not carry away the uranium layer rapidly enough to make it non-uniform. This is particularly true if the uniformity changes rapidly with time.

Heavy ions, as seen above, must require high charge consumption rates if a fairly large ion source aperture is used for maximum total ion flux. Use of a geometry originally designed for lighter ions will result in a very hashy or rapidly changing ion beam current; normal beam separation will not be possible. In addition, the high flux of neutral ions required will produce excessive pressure in the acceleration region and so permit excessive sparking. The optimum geometry for a certain gas feed for maximum performance must be experimentally determined.

PLASMA PROCESSES

Structure of the Plasma Volume Defined by the Collimated Arc

The collimated arc structure is not uniform over any cross section. The area normal to the magnetic flux, in particular, has large variations over short distances due to the difficulty of electron motion across the magnetic field. One side of the plasma seems to produce a large fraction of the useful beam. The other side of the plasma causes most of the cathode wear. Since cathode wear is the result of positive ion bombardment, the ion production of the plasma is concentrated on what seems to be the wrong side. Consideration of the details of ionic and electronic movement in the arc serves to explain what seems to be anomalous behavior.

The drift of both electrons and ions in the plasma is clockwise, as viewed in the direction of the magnetic field, moving up the back side of the arc and down the meniscus. Since electrons and ions escape less readily from the plasma through the back side, a skewed temperature distribution results, with the greatest intensity toward the top side of the arc. Here the ionization efficiency for the more difficulty ionized chlorine is greatest; hence the relative output of chlorine ions is also skewed towards the top side while the uranium ion output is relatively greater towards the lower side of the arc. Thus, the cathode wears more rapidly at the upper side where the useful ion output is actually the least.

This system of effects is amplified by the motion of the positive ions in the arc. These positive ions tend to be retained by the electric field inside the arc body, which is most negative in the center. Between collisions the ions drift along equipotential surfaces and cannot escape. Collisions with other ions and with neutrals move them on the average out of the arc in the direction of lower pressure. The total motion is therefore a combination of drift around the arc and motion out of the arc, the two motions, from experimental studies, being almost equally important.

The net motion of the ions both around the arc on constant equipotential surfaces and out of the arc by normal diffusion results in what can be visualized as a "centrifugal twist". The parts of the arc having no direct outlet to the acceleration region are therefore actually large producers of ions.

<u>The Floating Anode</u>

It has been observed experimentally that a reflecting electrode at the anode end of the plasma will produce very beneficial effects on plasma production of U^+ ions and on ionization efficiency. However, certain precautions must be taken.

Consideration of the average 'case history' of the electrons emitted from the cathode with no reflecting anode at the other end of the arc shows that with high energy electrons fed into one end and just as rapidly withdrawn from the other there is a rapid fall of average electron energy (which can be expressed as arc temperature) along the length of the arc. The use of a reflector reduces the required primary electron current by a very large factor because electrons are lost much more slowly, and also produces a much smaller temperature change along the arc length. Secondary effects discussed here and in the next section make the direct insertion of a reflector at the anode end of the arc impractical.

There is a large, positive ion drift toward the cathode and to the floating anode, if present, due to normal diffusion, all of which is accepted because of the high negative potential of the cathode and anode. An excessive drain of positive ions results in plasma hash when the drain is normal to the magnetic field, and in motion of the plasma boundary when parallel to the magnetic field. With no reflecting electrode there is only eight volts, approximately, drawing positive ions from the anode end of the plasma. With a reflecting anode the accelerating potential is, however, increased by a large factor. The results is a double drain on this end of the plasma, one from the meniscus and the other from the plasma boundary facing the electrode. The arc cannot supply ions for this excessive drain, so, since electrons are retained, the result is a very hashy, non-uniform arc. The consistency of this explanation is connected with sheath fields which penetrate somewhat into a plasma.

The anode meniscus has been made stable by reflecting all but those electrons immediately behind the meniscus facing the acceleration slits. As a result this area has only one mode of positive ion drain and excellent electron drain and is consequently stable. The required thickness of this layer is determined by the rate of positive ion formation in it. The experimental value is about one-fourth of the total thickness of the collimated arc. An obvious extension of this line of reasoning is that a large anode slot can be used if the ion drain from the meniscus is reduced by a shield. Experiments have shown this to be true.

Drain of Electrons from the Plasma

Plasma potential with respect to the containing box must be positive to retain electrons for plasma neutralization. Electrons with energies higher than this potential easily and quickly escape across the potential barrier at the ends of the arc if they are in this vicinity. Electrons elsewhere in the arc are trapped on equipotential lines until they are dumped by normal arc processes.

Heretofore, it has been thought that plasma oscillations or "hash" had the function of dumping low energy electrons. An alternative mechanism, which must not include hash because of the bad effect of hash on beam plasma stability, can readily be found by following the electron in its motion.

It is seen that each equipotential surface in the plasma is closed, having, roughly, collimating slot shape with the meniscus facing the accelerating slits on one long side. The electrons move easily along the magnetic flux lines and relatively slowly normal to them. The path normal to the magnetic field is a cycloid following an equipotential line in the normal plane. This is modified by collisions to give a slow net drift out of the arc proportional to the electric gradient and to the electron collision rate, with possibly, an addative element due to electric fields in the arc of the correct periodicity to add kinetic energy to the electrons. The electric gradient and thus the electron normal diffusion is greatest at the ends of the "banana-shaped" equipotential lines exposed when a cross-section is taken normal to the magnetic field, where the equipotential lines are crowded together. An addative element to electron energy gain is found at the meniscus, where the loss of positive ions gives a continuously fluctuating electric field. There are several important dumping areas for electrons. With a floating anode, these are: (a) the floating anode; (b) the area immediately surrounding the floating anode; (c) the ends of the arc box, and, from the addative element mentioned above; (d) the ends of the meniscus from which positive ions are accelerated.

The above description extended to particular cases explains why efforts to improve performance by fields in the arc, behind the arc, etc., have produced "anomalous" results. The motion of the arc constituents are self-modifying and the internal forces are relatively large.

Magnetic Field Intensity Effects on Calutron Performance

The general variation of maximum ion beam intensity with magnetic field and accelerating voltage can be divided into two independent parts: source values and collected values. Collected ion beams depend, for space charge neutralization, on the plasma produced by ionization of gases in the separation region, at the expense of the ion beam. This fact imposes a practical lower limit to the net accelerating voltage at the source, since ionization efficiency is low for heavy ions in the range of accelerating voltage values used and decreases rapidly with voltage. Lower voltages (at least to 3 kv)can be used if an auxiliary electron source is provided

Source values of maximum ion beam intensity depend, in ny simple way, on magnetic field and accelerating voltage because of the various requirements that must be met in order to precisely focus the ion beam on the collector. A steady, non-fluctuating beam is one of these fundamental requirements.

The instability of the ion beam observed when extreme conditions are impressed ~~on~~ the arc may be caused by too high a gradient at the meniscus, a too-low flux of secondary electrons from the arc, or by a non-uniformly activated cathode, usually caused by low gas pressure. Within these elastic limits large changes in ion beam intensity and process efficiency (atoms collected per atom used) can be effected.

An increase in magnetic field (H) increases the collimation of electrons and ions in the arc and begins to reduce diffusion of ions out of the arc. A qualitative description of this process and a theoretical interpretation has been published.[1] This shows that diffusion of ions out of the arc is inversely proportional to the magnetic field strength and to the collision period, squared (t^2), according to

$$\bar{W} = \left(Z - \frac{1}{n}\frac{dp}{dz}\right) t / \left(1 + \left(\frac{e}{m} Ht\right)^2\right) \quad \text{where}$$

Z is the acceleration due to a potential gradient normal to the arc axis,
n is the arc density (gm/cc),
$\frac{dp}{dz}$ is the pressure, gradient along the direction of motion,
$\bar{W}$ is the average velocity of ions out of the arc, and
t is the collision period

1 Chapman, S. and Cowling, T. G., Mathematical Theory of Non-Uniform Gases, Cambridge University Press, 1939, p. 322-329

The net result of increased H is thus an increase of effective pressure in the arc, increased neutralization, and loss of ions in the direction parallel to the magnetic field. The diffusion rate out of the arc is reduced by the ratio $1 + (\frac{e}{m} H t)^2$ to 1, where t has the value of approximately 10^{-4} sec for the thermal energies (500°C) and pressures (two microns) in the arc. Equilibrium requires that efflux equals influx, resulting in an increased arc pressure since the transverse ion current is conserved. The ratio of transverse to direct diffusion is given by the factor $\frac{eH}{m}t$, where transverse diffusion is that around the arc axis.

In addition to decrease of diffusion of ions out of the arc for larger H values there is a decrease in electron diffusion out of the arc, resulting in a greater tendency towards hash. This can be overcome by reducing arc thickness with a resulting increase in electric gradient in the arc and thus in electron drift velocity. Also, since the ions are retained in the arc for a longer period, there is an increase in ion flux in the direction of H with resulting increased losses and wear of the arc chamber and cathode.

One advantage of higher magnetic fields, difficult to estimate, is the increase of stability of the arc with respect to the accelerating potentials applied. The ion current from the arc meniscus follows Child's law up to currents approaching the emission limit of the meniscus, which is set by the rate of ion formation and normal diffusion in the arc. The practical closeness of approach to the strictly emission limited condition depends on the response of plasma electrons to applied potentials.

There is a very real "resistance" to the accelerating potential shown by the fact that the maximum gradient that can be impressed on a meniscus is some function of the magnetic field (probably a simple ratio, from present data). Other things being equal, a larger gradient at the meniscus, presumably producing a larger ion flux, can be supported by a higher magnetic field. As seen above, however, other things are not equal and a further analysis is necessary. Another advantage hard to evaluate for complex ion mixtures in the arc is the differential diffusion resulting from different ion masses. A higher magnetic field raises the arc pressure and therefore the collision rate. The diffusion rate out of the arc is increased, so there is a higher current of ions out, particularly of the heavy ion components. It is clear that acceleration potential variation changes arc sheath position to conform with Child's law. A too high potential tends to push the sheath into the collimated electron stream. Hash results.

The ion current limit is set by the arc meniscus emission limit. This is a function of ion diffusion rate, arc ion density variation due to a high temperature gradient, and rate of ion formation. The last item is independent of magnetic field, except for the fact that the secondary process of low energy electron drain is set by plasma gradients and magnetic field, proportional to $v = c\frac{E}{H}$. This factor is a critical one, since high production of positive ions requires high electron drain and thus a thin arc (which reduces primary ionization probability). There is thus some fixed, stable rate of useful ion production for any given magnetic field. This is one function that must be empirically determined, since it is the net result of opposing gains losses.

CONCLUSION

The above considerations are consistent with both experiment and theory as far as analyses have been completed. A more quantitative theoretical study will correct the guesses that have been made. The above study has been primarily intended to sort experimental observations into a preliminary scheme for evaluation.

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