The pinch effect revisited

The late Winston H. Bostick's 1977 groundbreaking examination of this aspect of controlled thermonuclear fusion. Part 1 of a series.

We present here an historic scientific essay by Prof. Winston H. Bostick on the development of the plasma pinch from its inception in early fusion energy research experiments through to 1977, which was first published in the Fusion Energy Foundation's International Journal of Fusion Energy, *Vol. 1, No. 1, March 1977. Given his own role in the development of this approach to magnetic fusion, the essay is necessarily semi-autobiographical.*

The following information will help the reader to put the essay in the context of developments since 1977.

In 1977, the United States had the world's largest and most advanced fusion energy research program. But during the Carter administration, the program was essentially put on hold. Then, during the Reagan administration, fusion energy research as well as nuclear power development in general, were permitted to die on the vine, so to speak. Now, under the Bush administration, the fusion program is being completely destroyed by budget cuts.

Therefore, at the time Professor Bostick's paper was published, the U.S. fusion program was relatively healthy and his critique of it was focused on the wrong-headed approach of centering the program on one single method, the tokamak. In the final outcome, both the tokamak and more general research were both cut back. For example, the last major step toward a tokamak fusion reactor was the Princeton Tokamak Fusion Test Reactor, which is currently in operation. Planning for this large experiment was initiated in 1973 and initial design completed in 1976. No other major project of similar size has been initiated since the Princeton Tokamak Fusion Test Reactor.

In fact, experiments to date throughout the world have demonstrated that the tokamak would work as a power reactor. There simply has been no follow-through to actually do that, despite the passage of the 1980 Magnetic Fusion Engineering Act mandating just that.

But this does not mean that Professor Bostick's critique was off the mark. In fact, the same experiments which demonstrated the capabilities of the tokamak as a potential power reactor, have also shown that Bostick was correct in terms of the fact that the nonlinear dynamics demonstrated in the plasma pinch have been found to be essential in understanding the tokamak itself. Furthermore, this deeper scientific comprehension has opened up prospects for realizing even more advanced types of fusion reactors. But neither the tokamak nor these more advanced possibilities are being pursued today, given the budget cuts now being implemented.

The pinch effect is the self-constriction of a column of deformable conductor which is carrying an electric current. The constricting effect on the column is produced by the magnetic field pressure resulting from this current, or equivalently, by the Lorentz force produced by the current flowing in its own magnetic field. Thus, in a controlled thermonuclear fusion research (CTR) magnetic-containment device of the pinch-effect type, the containing magnetic field is generated chiefly by the currents flowing in the plasma itself.

In the sixteenth century the effect of a Lorentz force on a movable, deformable plasma conductor was observed by William Gilbert, the court physician to Queen Elizabeth I of England: He noted that a candle flame was deflected away from a magnet when the magnet approached the flame. J.A. Pollock and S.H. Barraclough at the University of Sydney reported in 1905 an analysis on a piece of lightning conductor (a 1.8 cm-diameter, 0.1-cm-wall-thickness copper tube) which had passed a lightning bolt about the year 1895. The copper tube had been crushed by the "electrodynamic action of the current," and if the tube was assumed to be rigid (not softened to plasticity by the heat) at the time of the passage of the current, it could be calculated that the magnetic pressure had been about 400 pounds per square inch, and the current had been about 100,000 amperes. Photographs of the cross-section of the crushed cylindrical shell are shown in **Figure 1.** Indeed a lightning stroke in the atmosphere is a column of plasma whose diameter is influenced in some measure by the pinching electromagnetic forces.

In 1933, (when the neturon was being discovered and Hitler was on the rise to power), Willard Bennett wrote his famous paper on the steady-state pinch effect (published in 1934). This article treated in a relativistically correct way the effect of the mutual attraction of electrons moving in one direction and the positive ions moving in the opposite direction. The correct relationships showing how the electric charge density depends upon the frame of reference (relationships developed independently again by Budker in his doctoral thesis in 1956) were set forth by Bennett. Bennett calculated the equilibrium radial electron (and ion) density distribution to be

$$n_e = \frac{n_0}{[1 + (r/r_0)^2]^2}$$

where

$$\mu_0 e^2 r_0^2 n_0 v_z^2 = 16kT$$

and

$$\mu_0 I_0^2/8\pi = NkT \text{ (mks units)},$$
$$B_z = 0,\ p = n_e kT_e + n_i kT_i,$$
$$T = (T_e + T_i)/2,$$

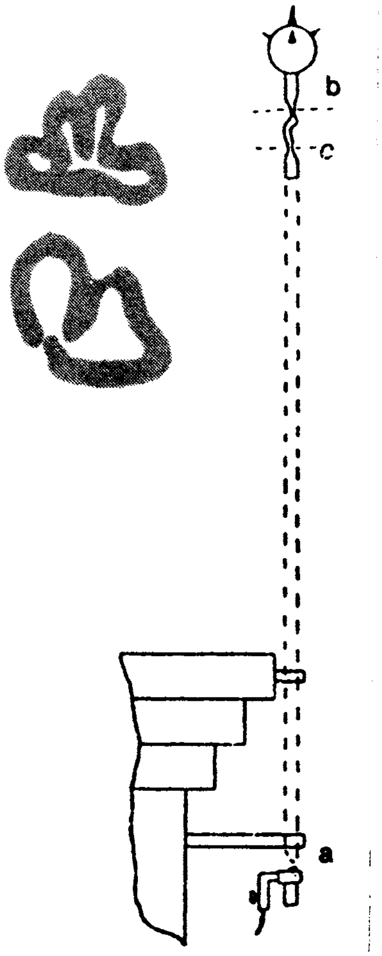
I_0 is the total current,

$$N = N_e + N_i \cong 2N_e =$$

the number of electrons and ions per unit length of column, v_z is axial electron drift and is constant everywhere, k is Boltzmann's constant, e is the electronic charge. It is rather incredible that such a sophisticated and perceptive paper on this phase of plasma physics should appear all by itself at this early date.

About ten years later experimental work on the pinch effect in plasmas commenced with some work by Steenbeck, who worked on induced, pulsed, high currents in a ring-shaped glass tube. Cousins and Ware at Imperial College in England performed experiments of this type from 1947 to 1951 and "were the first to demonstrate" that the current channel ($10^4 - 2 \times 10^4$ amps) did constrict. In 1951, due to security classification, this work was transferred to AEIRL at Aldermaston where extensive development was carried on in the problem of arcing between the segments of the metallic liners used in their discharge tubes. The employment of the applied magnetic field (in 1953) in the direction of the pulsed current led to the SCEPTRE program. Bill Baker at the Lawrence Berkeley Lab (formerly the University of California Radiation Lab) in 1951 produced a pulsed, pinched high current (10^5 amps) discharge between two electrodes in H_2 gas and photographed the constricted (~3 mm diameter) channel. Security classification prevented Baker's work from being published at that time. About 1950 at Los Alamos, planning of experiments (the Perhapsatron) on the pinch effect got under way under the direction of James Tuck. Apparently the Soviets also started work on the pinch effect about the same time: The work on the H-bomb in the U.S.A., U.S.S.R., and United Kingdom had by this time rekindled enough interest in controlled thermonuclear research to get some experimental CTR programs under way at the security-classified weapons laboratories in those countries.

FIGURE 1

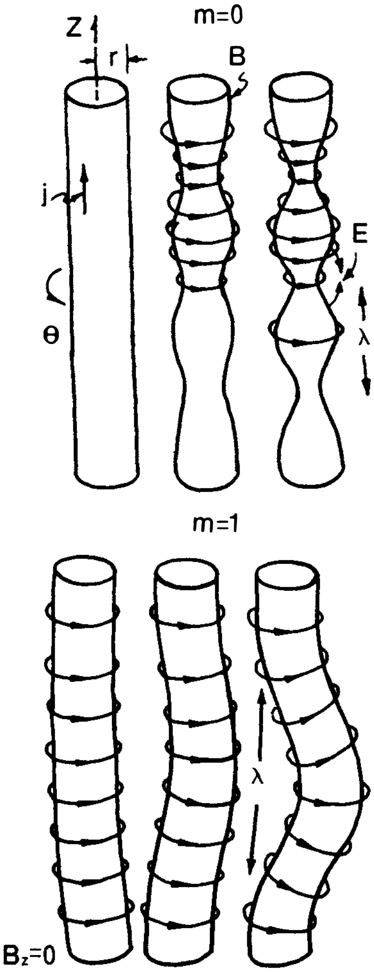


Drawings of the cross-sections of the copper lightning rod that was crushed by the passage of a lightning bolt.

Levine, Combes, and Bostick at Tufts University showed in 1952 and 1953 that an 8,000-ampere pulsed current in low pressure nitrogen gas produced a pinch which concentrated the spectral line emission from singly ionized nitrogen, and concentrated even more the lines from doubly ionized nitrogen.

In June 1952 at a meeting of the American Physical Society in Denver a special session on CTR was held under security classification for those interested physicists who held the appropriate security clearance. The "Matterhorn" project from Princeton University under Lyman Spitzer described their concept of the stellarator with its figure "8" configuration to obviate the "grad B drift," and presented, in brief, the theoretical work of Kruskal and Schwarzchild in which they predicted the sausage (m=0) and kink (m=1) MHD [magnetohydrodynamics] instabilities that the pinch effect would be expected to be subject to (see **Figure 2**). These instabilities were similar to the Rayleigh-Taylor instabilities of fluid mechanics and could be classified as MHD instabilities because

FIGURE 2



Diagrams of the m=0 (sausage) instability and (m=1) kink instability to which the pinched column of plasma carrying a current density j is subject. These are MHD instabilities The axial magnetic field is $B_z=0$.

the pinched fluid was largely regarded as an MHD fluid in the treatment. The e-folding time for such instabilities was calculated to be a characteristic dimension divided by the sound speed in the medium, where the characteristic dimension was the geometric mean of the pinch diameter and the wavelength of the instability. At this meeting the Livermore CTR group discussed the concepts of its mirror machines and also the possibility of radio-frequency confinement. James Tuck and W.H. Bostick made a few remarks about the pinch effect and Herbert York showed a few of the pinch-effect photographs taken by Bill Baker at Berkeley. Victor Weiskopf asked the question: "Just what is this pinch effect?" whereupon George Gamow (always in a jocular mood) approached Weiskopf from behind and pinched him. Van Allen, who was at the time involved in the leadership of Project Matterhorn, expressed great skepticism about the pinch effect and stated that none of the evidence thus far presented had convinced him of the existence of the pinch effect. Thus ended that session in 1952.

1954-63: practical schemes

To locate the pinch effect among the various animals in the CTR zoo we must recognize that the bulk of CTR thinking has traditionally reasoned that the pinch-effect magnetic field will impart energy to the plasma by adiabatic compression (in the dynamic pinch), by shock heating, by Joule heating, and by various instability mechanisms, and that in these processes the plasma can be expected to acquire an energy density approximately equal to that of the magnetic field.

In the experimental investigation of the translation of this magnetic field energy into the plasma energy it has appeared that the plasma becomes more difficult to confine as it absorbs the energy; that is, the instabilities grow more rapidly in the energetic plasma, and the instabilities will very quickly and prematurely result in a loss of the plasma and its energy to the wall of the vacuum chamber.

On the other hand, a successful CTR magnetic containment device must have an energy containment time τ and an ion density n sufficiently large so that an appreciable fraction of the fusionable fuel will be burned; that is the Lawson criterion must be satisfied ($n\tau > 10^{14}$ for a deuterium-tritium (D-T) reactor). In the ordinary dynamic pinch, that is, one with no axial (longitudinal) magnetic field, B_z, it was concluded that the magnetic energy goes very rapidly into the development of instabilities which dump the plasma and its energy from the containing column to the walls before the fuel has an opportunity to burn. Thus, at a fairly early date (about 1954-55 in the U.S.A., perhaps earlier in the U.S.S.R. and United Kingdom) there were growing suspicions that the ordinary dynamic pinch was unsuitable for a practical thermonuclear fusion reactor.

Accordingly, from about 1954 through 1963 a vigorous effort was mounted in the international CTR community to devise a practical scheme employing axial magnetic fields, conducting walls, radio-frequency fields to stabilize the pinched plasma column long enough to permit an appreciable fraction of the fuel to react.

The quantitative concept of the transient pinch as being a process of heating the plasma by an adiabatic compression was generated in the U.S.A. by Levine, Bostick, Combes and transmitted in a letter to Lyman Spitzer in 1953. The stabilizing effect of a conducting copper coating outside the glass-walled pinch vessel was also recognized in the U.S.A. by Levine and Bostick quantitatively in a letter to the Matterhorn group in 1953. These same ideas undoubtedly occurred independently at about the same time or earlier to other workers in the U.S.A., United Kingdom, U.S.S.R., and elsewhere. Because of security classification there was no systematic reporting in the journals.

In 1954 Bostick went to work at Lawrence Livermore Laboratory, but Levine, remaining at Tufts, demonstrated experimentally that an enclosed axial magnetic field (B_z) would stabilize the m=0 (sausage) and short wavelength m=1 (kink) instabilities of the pinch effect. Levine gave a paper on this work at a classified CTR meeting in Princeton in 1955 at the same meeting when Rosenbluth gave his theoretical paper on the stabilizing effect of a trapped axial magnetic field in the pinch. Rosenbluth showed theoretically that the pinched radius must be kept larger than one-fifth of the radius of the return conductor shell and the plasma pressure must be low compared to $(B_z)^2/(2\mu_0)$. The region containing the hot plasma and the B_z field must be sharply bounded from that containing the B_θ pinch field. These are the conditions necessary for stability against the m=1 mode.

Figure 2 shows the sausage (m=0) and kink (m=1) instabilities which develop in the pinch effect when there is no B_z, or axial magnetic field, either inside or outside the pinched column. The MHD instability analysis investigates the stability of the pinch against perturbations of the form

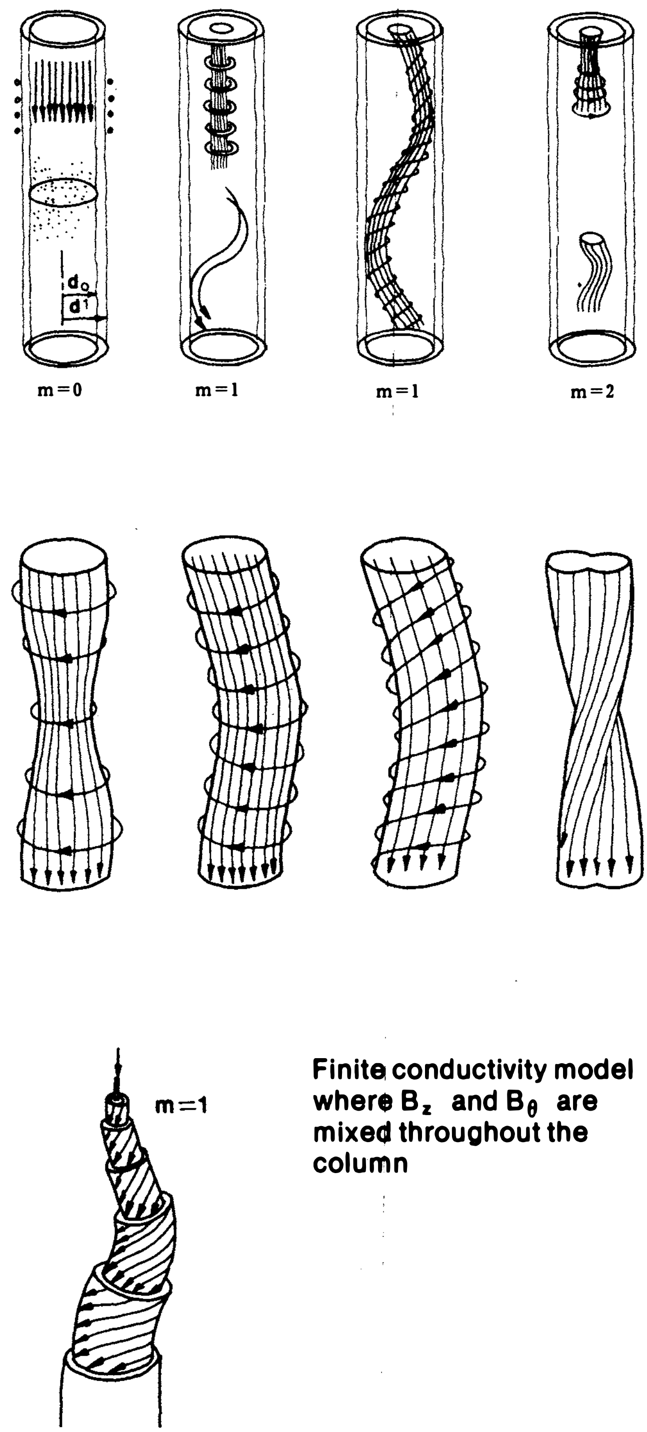
$$\mathrm{Re}^{i(\pm m\theta + kz)} = \cos(kz \pm m\theta).$$

k is the wave number of the perturbation in the z (axial) direction and m is the wave number of the perturbation in the θ direction. **Figure 3** shows the form of these perturbations when $B_z \neq 0$. **Figure 4** shows typical experimental arrangements for the pinch (linear and toroidal). **Figure 5** is a kind of collage of these various early pinch schemes. Figures 2-5 were sketches made about 1956 by the author who was then contemplating writing a book on controlled thermonuclear research.

In 1954 Rosenbluth and Garwin in a classified Los Alamos report came out with their famous report on their "M" theory (M stands for motor) in which they used Maxwell's and Newton's laws to compute the time that it should take for the pinch effect to collapse. They also produced the theory of the Rosenbluth sheath and in doing so they reinvented the Ferraro sheath which was developed by Ferraro in the study of the Earth's magnetosphere.

In the Rosenbluth M theory the calculated velocity dr/dt for the radial collapse, as determined by Newton's second law and the Lorentz force, is $r \sim (E^2/\rho_m)^{1/4}$ where E is the applied electric field and ρ_m is the mass density of the ionized gas which is swept up in "snowplow" fashion by the current sheath. The thickness of the current sheath is calculated to be c/ω_p where ω_p is the plasma frequency and c is the speed of light. In actuality the observed current sheath thicknesses are usually 10 to 100 times this value. Furthermore, as will be shown later (1966), the current sheath is *not* purely planar or purely cylindrical but it corrugates in the two directions which are parallel and perpendicular to the applied magnetic field. Plasma vortex filaments are observed to lie in the grooves of these corrugations and the current sheath is really a tissue made up of these vortex filaments. Thus, the M theory which can be used to compute effectively the gross dynamics of the time for collapse for the linear pinch and the gross shape of the plasma-focus current sheath (Potter's code, for example) is a kind of a myth in a plasma focus as far as the fine structure of the current sheath itself is concerned. And indeed the famous 1934 Bennett theoretical,

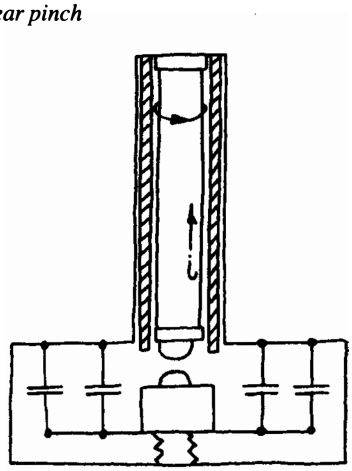
FIGURE 3



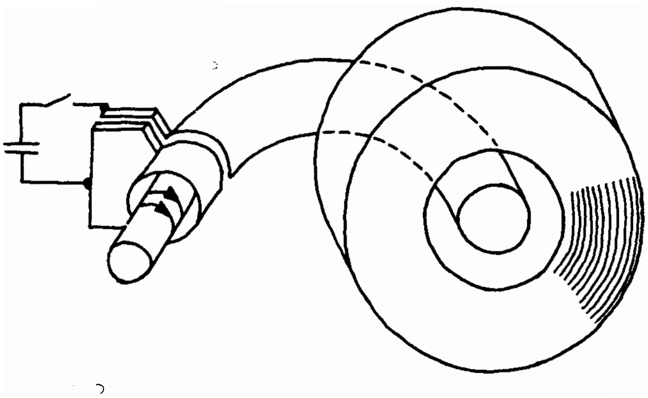
Diagrams of the m=0, m=1, and m=2 perturbations when $B_z \neq 0$ and there is a conducting metallic coaxial return conductor. The applied B_z can be trapped inside the column or it can be both inside and outside the column.

FIGURE 4

a) linear pinch



b) toroidal pinch.



Typical geometrics for pinch-effect apparatus.

steady-state pinch is, in actuality, also a myth: It is never achieved because of the instabilities which destroy it or the vorticity which modifies it.

Stirling Colgate joined the CTR movement in 1954 at Lawrence Livermore Laboratory and was fascinated with Rosenbluth's work. Colgate set up an MHD experiment with liquid sodium where he demonstrated quantitatively that the sausage and kink instabilities did develop, that is, that the MHD, Rayleigh-Taylor instabilities were there.

By this time the Perhapsatron at Los Alamos and the toroidal pinch in the United Kingdom were showing the sausage and kink instabilities and the project Columbus I was under way. Columbus I was an attempt to produce a pinch effect in a high current discharge between two electrodes in deuterium at about 100 microns pressure, in an apparatus like Figure 4. The famous E.O. Lawrence of Berkeley happened to be visiting Los Alamos and saw their experimental setup for Columbus I and heard their tale of woes about cracking glass tubes and leaking seals. He recalled that his highly talented group under Bill Baker at Berkeley had already worked at the pinch effect, and when he returned to Berkeley he put Baker back to work on the pinch effect apparatus similar to that used for the results reported by Herbert York at Denver in 1952. In about two months of work Bill Baker's group was observing X-rays and the 2.45 Mev neutrons, $D+D=n+He^3$, from the pinched discharges in deuterium gas at about 100 microns pressure.

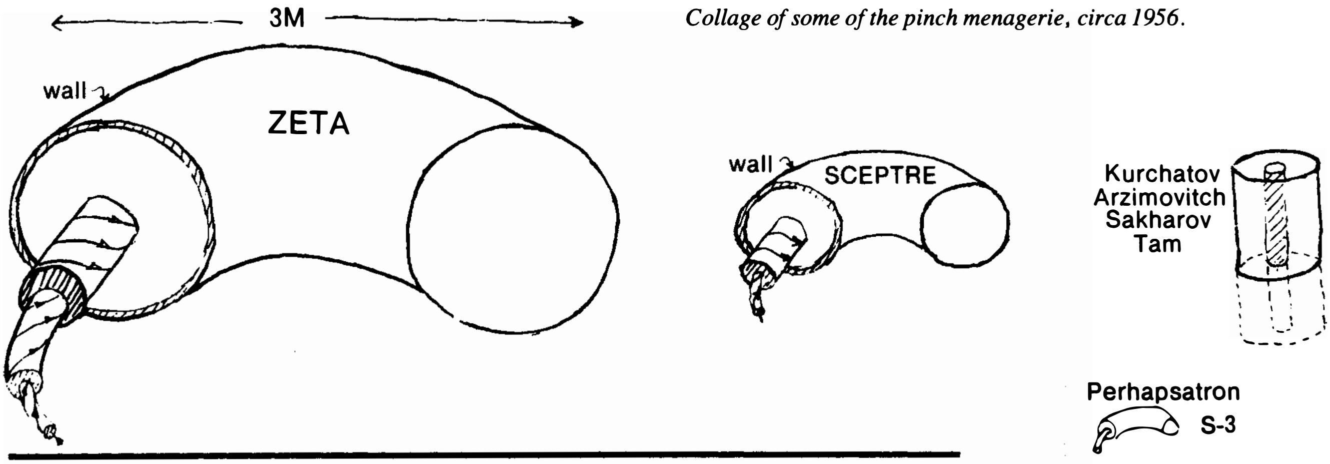
At that classified CTR meeting in Princeton in 1955, at which Levine presented his results on the H-centered (B_z-stabilized) pinch, Baker gave his results on the neutrons and X-rays from the linear (z) pinch.

After Baker's presentation the author recalls hearing one representative from Los Alamos remark in a private discussion that he felt it was "highly unethical" for Berkeley to have started work, under Lawrence's stimulation, on the pinch effect at that time: Los Alamos had no such spectacular results on the pinch effect to report at that meeting, and at least one of their investigators obviously was piqued at being upstaged so suddenly by the Berkeley lab in so important a CTR role as pinch effect research. The experimenters at Los Alamos, emboldened by Baker's results, went back to their lab after that Princeton meeting and soon they were producing neutrons with Columbus I and II. Furthermore, so heady was the wine of their first success that they were wont to assert that these neutrons were very likely true thermonuclear neutrons, and not those produced by a process which electrically accelerated deuterons into deuterons. Colgate at Livermore undertook, with the help of Berkeley's nuclear emulsion scanners, a detailed comparative analysis of the knock-on proton tracks obtained from the neutrons proceeding from the anode-to-cathode and cathode-to-anode directions of the Columbus I pinched discharge.

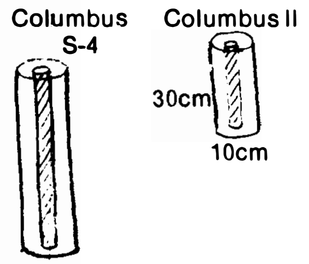
Colgate's results showed clearly that the neutrons proceeding in the anode-cathode direction were, on the average, definitely of higher energy than the neutrons proceeding in the cathode during the pinch, and, therefore, that deuterons were average, the center of mass of the pairs of reacting deuterons in the reaction $D+D=n+He^3$ was moving from the anode to the cathode during the pinch, and, that therefore, deuterons were being accelerated in the anode-cathode direction and reacting with other deuterons which had not been so accelerated and were thus acting as targets for this accelerated beam of deuterons. It was hypothesized that a rapidly pinching sausage instability in the channel produced a high back electromotive force ($\cong -IdL/dt$) and that the resulting choking of the current built up a high positive potential toward the anode and a high negative potential toward the cathode end of the pinched channel. (Such high voltage spikes from the back EMF could be seen on the oscilloscopes which recorded the voltage signals from capacitance dividers.) These high potentials were thought to be able to accelerate a few of the deuterons into other deuterons to produce the

FIGURE 5

Collage of some of the pinch menagerie, circa 1956.



	Energy storage	Half-cycle time	Maximum current	B	Neutrons per pulse	T from neutron yield	T from Doppler
Zeta	5×10^5 J	4ms	84–187 KA	160–400g	$0.4–134\times10^4$	4.6×10^{6}°K	3×10^{6}°K
Sceptre	7×10^4	400μs	20–200 KA	100–1000g	$10^3–10^5$	$2–3.5\times10^6$	$2.5–3.8\times10^6$
Columbus II	10^5	4μs	$1–2.5\times10^6$A	$0–10^4$g	2×10^7B 0, 3×10^6B 23,	2×10^4	$B_z=200$
Columbus s4	1.5×10^4	12μs	2.5×10^5A	0–1750g	$10^3–10^5$		
Beybatchenko Golovin USSR	1.4×10^5	30μs	7×10^5A	0–12000g			
Perhapsatron s3	4.4×10^4	12μs	2.3×10^5A	0–4000g	$2\times10^5–10^6$		
Kurchatov	3×10^5	6–60μs	2×10^6A				
Sweden	10^5	10μs	3×10^5	0			



neutrons. X-rays (approximately 5 kev to 200 kev) were also generated simultaneously with the neutrons. At any rate the results showed that energetic deuterium ions (and electrons) did not represent a thermal ensemble, and therefore the fusion reactions were judged to be nonthermonuclear and hence theologically "impure" as far as the CTR program was concerned. These results were a chastening blow to the ardor of those people working on the pinch effect at Los Alamos.

During the highly limited unfolding of this security-classified story in the U.S.A. there occurred a dramatic international announcement, exceeded in its spellbinding effect only by the explosion of the bombs at Hiroshima and Nagasaki (with the subsequent Smythe report) and the announcement of the successful H-bomb detonations. In 1956 Khrushchov and Kurchatov (after whom is named the Kurchatov Institute of Atomic Energy in Moscow) appeared for a visit at the Atomic Energy Research Establishment at Harwell in the United Kingdom. The press throughout the world carried front-page pictures of Khrushchov and Kurchatov in white laboratory coats inspecting the various sites at Harwell because Kurchatov, in a prepared speech before the United Kingdom scientists assembled at Harwell, proceeded to describe in considerable detail the results of the pinch effect research in the U.S.S.R. One must recognize that the pinch effect research at this moment was not a side show to a CTR circus involving the stellarator, Ogra, mirror machine acts; the pinch effect was *the* featured show in the *main ring*. The Soviet results told of neutrons and X-rays and voltage spikes from their pinch effect apparatus which was similar to that in use in the U.S.A. The Soviets had found that the neutrons came from a nonthermal process, their work was accurate, highly detailed, well planned, well instrumented. Lewis Strauss, then the head of the U.S. Atomic Energy Commission (AEC), made the response to the press that: "The Russian results do not tell us anything we have not known for some time." Strauss's adverbial phrase, "for some time" covered up the fact that the U.S. pinch effect research had arrived at the same conclusion as the Soviets by a margin of only a few months. It could be estimated that the Soviets had been producing such results since about 1953, and the U.S. effort compared to the Soviet was rather thin. One might surmise what Lewis Strauss would have been able to say if E.O. Lawrence had not ordered Baker to get back on the pinch effect research in 1954 and if Stirling Colgate had not insisted on analyzing the neutron energy.

To be continued.