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## Thesis

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE OF Master of Science

TITLE A Thermodynamic Comparison between the Magneto-Mechanically and Magneto-Calorically Induced Superconductive Phase Transitions in a Type I Superconductor Culminating in a Proposal for a New Type of Superconductive Motor

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# A Thermodynamic Comparison between the Magneto-Mechanically and Magneto-Calorically Induced Superconductive Phase Transitions in a Type I Superconductor Culminating in a Proposal for a New Type of Superconductive Motor

A Thesis

Presented in Partial Fulfillment of the Requirements
for the Degree *Master of Science* in the
Graduate School of the
University of Detroit

By
Peter D. Keefe

University of Detroit
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FOREWORD:

Since the early experiment by Meissner and Ochsenfeld, superconductivity has long been known to possess a once thought anomolous property: the ability of a sample to expel any interiorly present magnetic field simply by lowering the ambient temperature.

This extraordinary capability, found only in the icy realms of the infrequently visited liquid helium temperatures, is a consequence of macroscopic quantum mechanical effects.

A large contingent of investigators have preceded us; spurred by a burning desire to seek phenomenological and microscopic theories to explain the abilities for a metal to suddenly loose all electrical resistance and exclude perfectly any applied magnetic field.

Our investigation of the unique properties of the superconductive phenomenon shall be confined to: (A) an examination of the thermodynamic functions that underlie the observed behavior, and (B) an evaluation of a new work cycle aimed at harnessing the available energies.

To this end, this manuscript is divided into three sections.

The first contains introductive materials designed to give the reader a sufficient familiarity with the subject that the following productive sections may be maximally informative. This is accomplished by presenting (A) an historical outline of the major events which shaped the present science and (B) a brief but inclusive presentation of the over-all physics of the superconductive state.

The second, subdivided into sections devoted to particular aspects of a theoretical experiment designed to evaluate quantitatively the thermodynamic functions, concerns: (A) a description of the experimental procedure, (B) a combination magneto-mechanical and (C) magneto-caloric phase transition, (D) a summary of the results obtained in (B) and (C), and (E) calculations of the ideal field and temperature induced phase transitions. Data on the above is contained in an appendix starting on page 138.

The third, a proposal for a new form of superconductive motor, encompasses the previous thermodynamic treatments. A fully cyclic process is elaborated and four design electives are suggested.

Throughout the text ample figures, curves, notes, and references are included. The reader will customarily find drawings and graphs at the rear of respective sections. Notes and references are indicated by superscripts, alphabetical and numerical respectively, and are also located at the rear of particular sections.

The author wishes to thank Dr. G. A. Blass, who has been his advisor for far longer than the short time involved in the preparation of this work, for his careful review and instructive comments, and Dr. R. W. Kedzie, who has offered much of his time over the past few years to help and encourage him on his quest for development of a superconductive motor.

Finally, the author wishes to thank the entire faculty of the physics department, each member of which was instrumental in enabling him to write this thesis.

P. D. K. April, 1974.

Table of Contents:

Symbols:

| | |
|---|---|
| $H_a$ | Applied Magnetic Field |
| $H_o$ | Critical Field at Absolute Zero |
| $H_c$ | Critical Field as per temperature |
| $H_{c1}$ | Meissner Region Critical Field for Type II |
| $H_{c2}$ | Mixed State Critical Field for Type II |
| $H_{c3}$ | Critical Field for Sheath State |
| $H_s$ | Higher Critical Field for Thin Films |
| $T_a$ | Ambient Temperature |
| $T_c$ | Critical Temperature |
| $G_n$ | Free Energy of Normal State |
| $G_s$ | Free Energy of Superconductive State |
| $S_n$ | Entropy of Normal State |
| $S_s$ | Entropy of Superconductive State |
| $L$ | Latent Heat of Transition |
| $C_n$ | Specific Heat of Normal State |
| $C_s$ | Specific Heat of Superconductive State |
| $Q$ | Heat |
| $H_i$ | Compressed Field between slab and prism wall |
| $B_i$ | Penetration Field in the intermediate state |
| $N$ | Demagnetization Factor |
| $\lambda$ | Magnetic Field Penetration Zone |
| $\xi$ | Range of Coherence between superconductive electrons |
| $\kappa$ | $\lambda/\xi$ |

| | |
|---|---|
| k | Boltzmann's Constant |
| L | Distance Slab is Inserted into the Prism |
| P | Pressure |
| F | Force |
| W | Work |
| T | Transmogrification Point |
| 1 | Stator Magnet |
| 2 | Superconductive Envelopment |
| 3 | Normal Envelopment |
| 4-5 | Sheath |
| 6 | Transmissor |
| 7 | Envelopmental-Transmissor |
| 8 | Cylindrical |
| 9 | Envelopmental-Cylindrical |

A.

HISTORICAL OUTLINE:

H. Kamerlingh Onnes first successfully liquified helium by attaining 4.2°K in 1908. This great feat opened a new domain for scientific investigation: The unthinkably frigid zone just above the absolute zero of temperature. Onnes immediately recognized the vast potential his accomplishment created and decided to perform resistivity experiments at these heretofore unknown temperatures.

It was everyone's guess that electrical resistance would either cease, level off, or increase near absolute zero, either because of heat, impurity, or electronic condensation effects, respectively. See Figure A-1. Onnes decided to measure the resistive properties of mercury, to determine the nature of this electronic phenomenon, at liquid helium temperatures.[1]

Strangely, the resistance of mercury steadily declined with reduced temperature until suddenly at 4.152°K, which was remarkably close to the helium boiling point, the metal lost all resistance to electric currents, within the limits of his accuracy. See Figure A-2.

It was quickly speculated that this perfect or super-conduction of electric current was due to some new condition within the sample yielding a state of infinite conductivity.

Onnes and several other investigators performed tests with spheres of lead and other "superconductive" materials leading to the result that (A) conductivity was indeed perfect and (B) any incident magnetic field was excluded or not from the interior of such a lossless sample depending on its pre-history, that is, whether the field was applied before or after the material became superconducting. See Figure A-3.

It is not with little shock that the scientific community of 1933 was jolted by the news of an experiment by W. Meissner and R. Ochsenfeld which conclusively proved that the magnetic state of a superconductive sample is independent of its pre-history. Incredibly, the applied field which was present in their mono-crystal of tin above the transition temperature was summarily and completely expelled upon reducing the temperature below its critical value, Tc. Therefore, the internal field is *always* zero while the metal is in the superconductive state.[2] See Figure A-4.

How could such a wondrous mechanism, the so-called Meissner Effect, remain undetected for more than twenty years? (A) The previous experimenters had not been properly cautious and careful in taking readings on the fields outside their test samples.[3] (B) Often hollow lead, etc., spheres were used in order to reduce helium refrigerant requirements, resulting in honestly mistaken measurements.[4] (C) The theoreticians had created an entire body of experimentally and mathematically unquestionable phenomenological treatments based on the perfect conductor premise.[5] With the foregoing in mind it is with ease that we are able to understand how the entire scientific world was kept within the bounds of its own preconceived myth (save for a visionary few).[6]

In the intervening years between the discovery of the Meissner Effect and the introduction of the microscopic theory in 1957, investigators groped for two rather elusive points: (A) A theory which would explain the perfect electrical conduction and Meissner Effect coupled with the experimentally found limits underwhich superconductivity may occur: below a certain maximum applied magnetic field and under a particular highest ambient temperature, see Figure A-5, and (B) superconductive materials which would retain their unique properties in very high fields and temperatures.

During this period some confusion[7] resulted because of a lack of universal recongition for many years of two classes of superconductors and the distinction between various phases within each class. Eventually, experimentation proved that: (A) Class I superconductors of the soft metals had a low critical field and temperature and entered an intermediate state (see next section) of alternate domains of superconductive and normal material when the geometry of the sample was other than a thin cylinder in a longtitudinal magnetic field and the applied field reached a locally critical intensity, see Figure A-6, and (B) Class II superconductors of the hard metals and alloys had comparatively high critical fields and temperatures and entered a mixed state (see next section) above a certain less than critical magnetic field independent of sample geometry. The intermediate state and mixed state were often confused and generally research was somewhat minimal since practical use of this phenomenon looked very far away indeed due to temperature (max. around 8°K for $N_b$) and field (Max. around 1800g for $N_b$ [Type II]) limitations.

The greater part of scientific research has actually been done since Yntema in 1955 created the first successful high field superconductive electromagnet by using unannealed niobium wire to attain 7.1 Kgauss. He was soon followed by other experimenters who made use of cold working technology to improve the performance of niobium windings. Finally, since 1961 Kunzler and others successfully developed alloying techniques which produced Type II superconductors capable of withstanding ($N_bS_n$: 200 Kgauss & 18°K) inordinately high fields and almost "warm" temperatures, before losing their superconductive properties. This ushered in a new era of applied research and development, including: computer switching elements, motors, generators, magnets, and lossless bearings, nearly lossless power transmission lines and transformers, etc.

The Bardeen Cooper Schrieffer Theory of 1957 explained the phenomenological theories of F. London on a microscopic basis.[8] Superconductivity was understood to be: (A) a condensation to lower energy by so-called super-electrons due to a quantum mechanical electron pairing process, (B) this pairing process was seen to occur only within a finite distance, the Coherence Length, which, if longer or shorter than the depth to which a field penetrates into the surface of a sample, meant it was either Type I or Type II, (C) the critical fields and temperatures were then just the necessary energy inputs to raise the super-electrons of zero resistance to normal electrons of finite resistance, that is, the electron "fluids" were separated by an energy-gap, and (D) the Meissner Effect was due to a sudden condensation energy outflux at the transition, an energy capable of doing magnetic work.

Today, research is pressing forward at an ever accelerating pace to achieve room temperature superconductors. Some feel that this may be possible by using the long and essentially one dimensional organic molecule, which possesses the necessary symmetry requirements. Some success has been reported, with the present high at 23.2°K.[9] Generators, motors, power lines, and rail transport levitation schemes, using superconductors, have been constructed and successfully tested.[10]

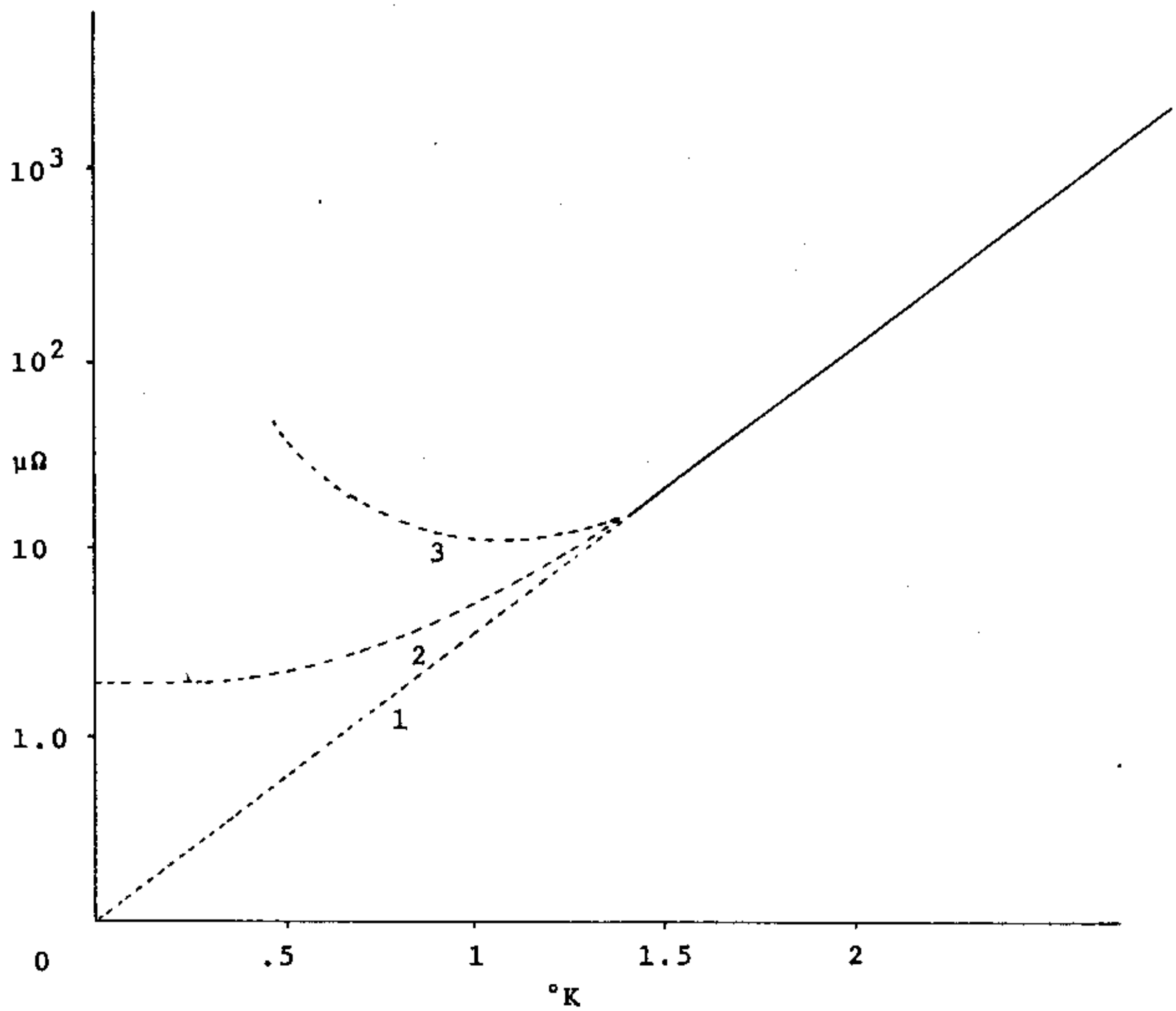



Fig. A-1. As temperature is lowered, the resistance of a metal might: 1. go to zero, 2. level off at a finite value, or, 3. increase, in the neighborhood of absolute zero.

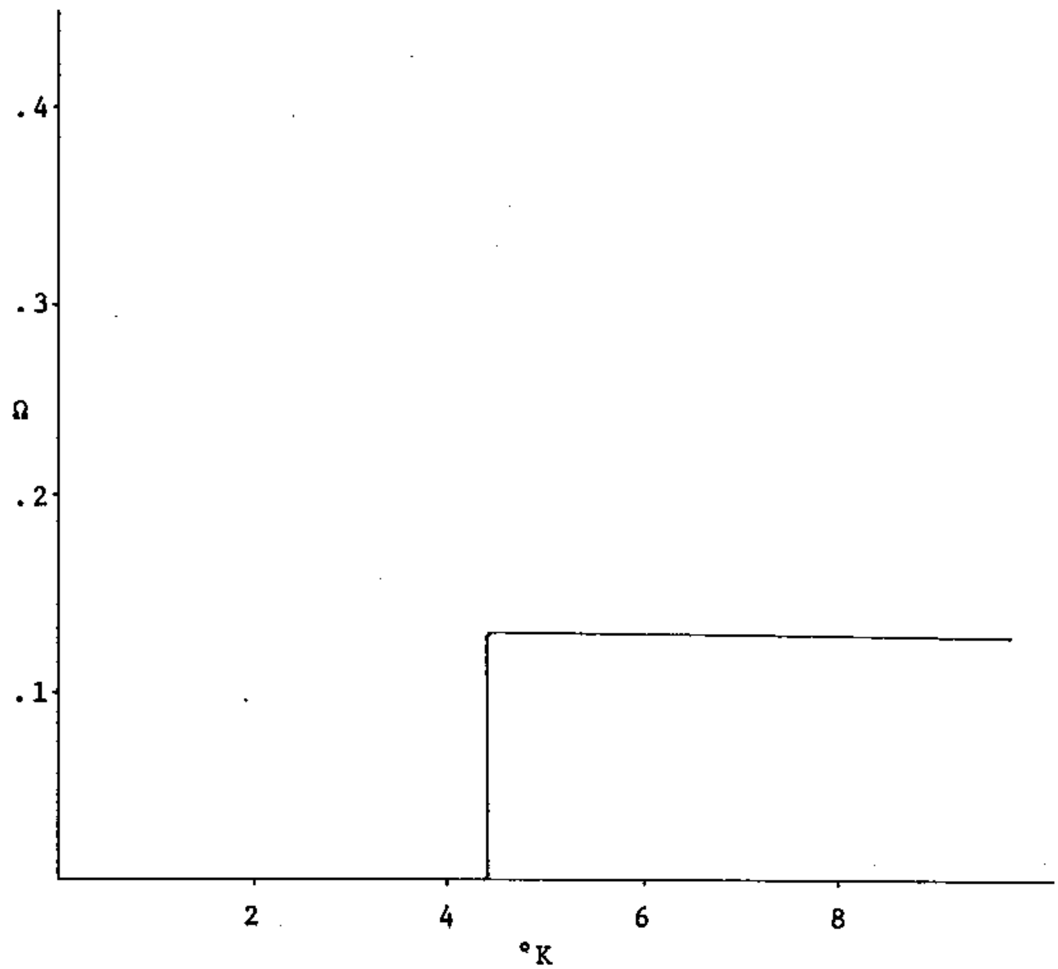



Fig. A-2. At the superconductive transition temperature, Onnes' sample of mercury suddenly lost all measurable resistance to electric current.

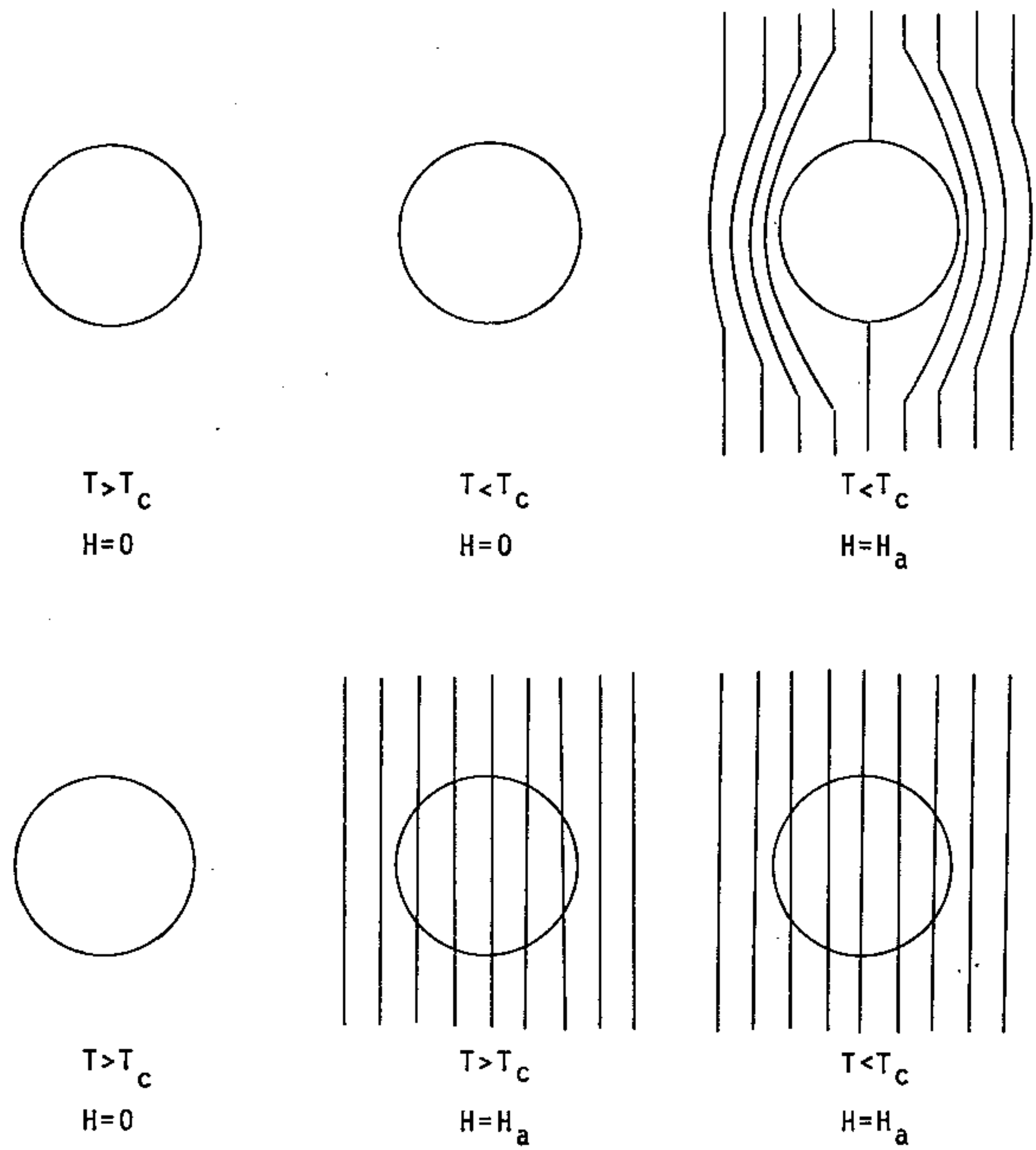



Fig. A-3. A perfect-conductor can exclude an applied field only depending in its pre-history. In order that surface currents be generated, the field must be applied after the material becomes perfect-conducting.

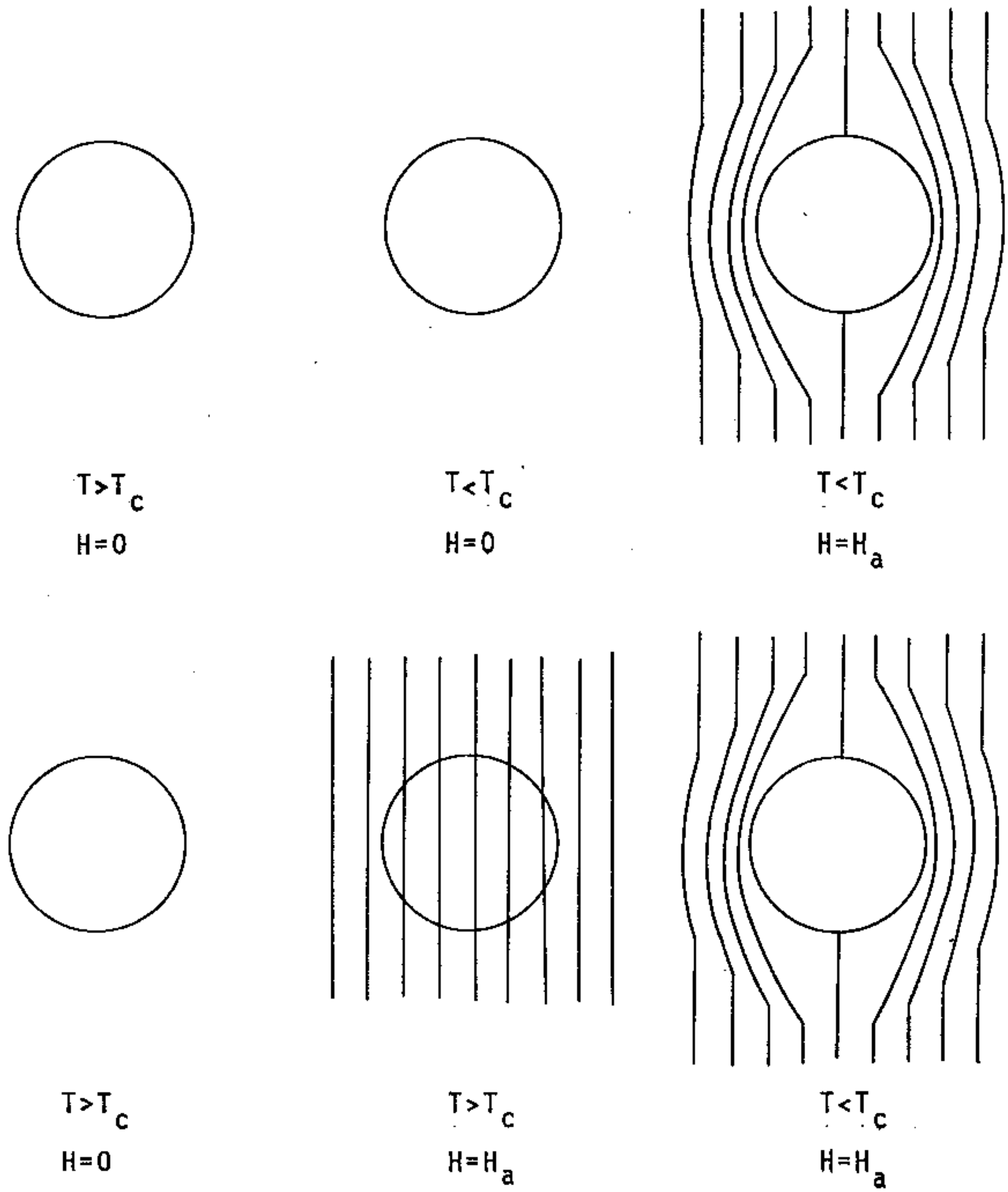



Fig. A-4. A superconductor can exclude an applied field independent of its pre-history. When the temperature is reduced below the critical value, some internal energy of the sample does work to expel the internal field.

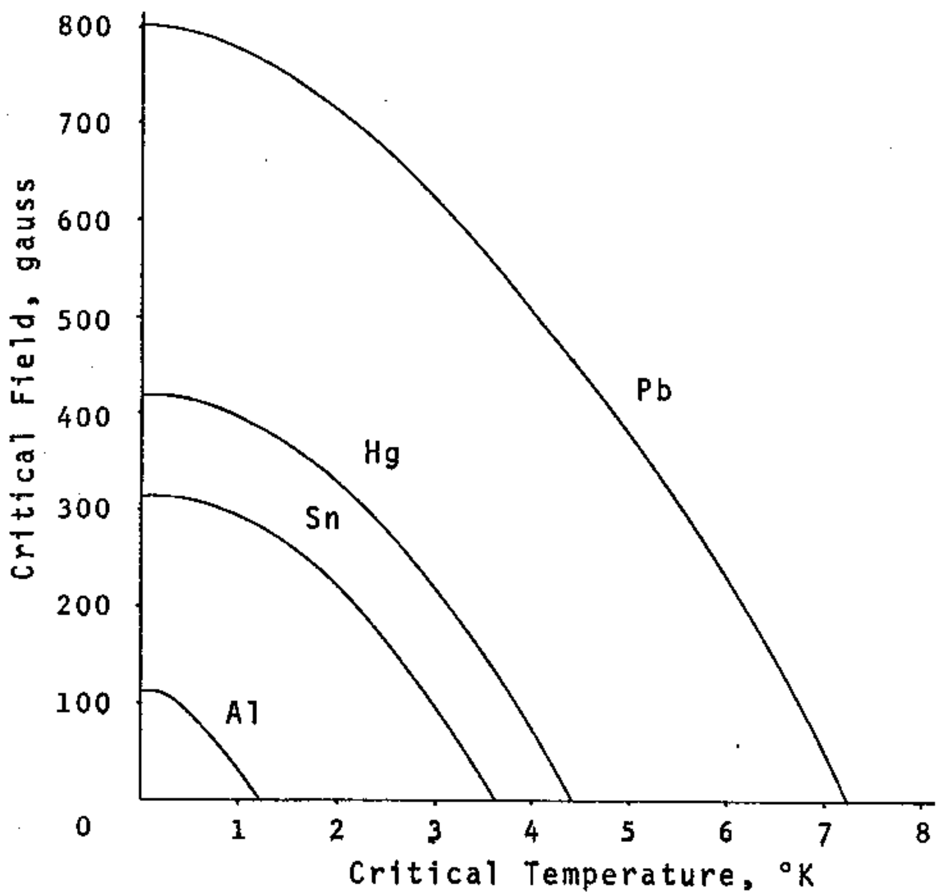
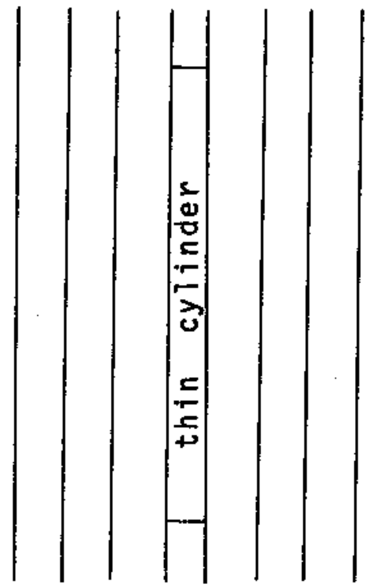



Fig. A-5. Critical field vs. temperature curve. Superconductivity can occur only below these limits; if one should exceed them the material becomes normal. Example: at 600 gauss and 6°K Pb is a normal conductor, at 600 gauss and 3°K Pb is superconductive.




Above: A thin cylinder parallel to the applied field does not distort the flux lines, therefore, $H_c$ is reached at all points at the same time.

Below: A cylinder in a transverse field distorts the field. The intensity at the equator is $2 \cdot H_a$. Therefore, an applied field of $.5H_c$ will cause a critical field on the equator, thus necessitating the onset of the intermediate state.

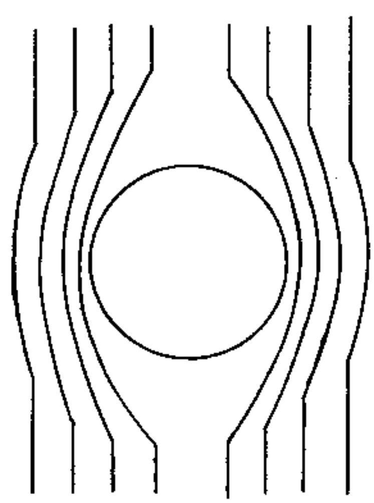


Fig. A-6. The intermediate state occurs when the sample geometry is such that somewhere on the surface $H_c$ is reached before anywhere else.

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B.

PHYSICS OF SUPERCONDUCTORS:

Science has catalogued superconductors into two general types, I and II. I shall address myself to each respectively, and consecutively.

Type I superconductors are familiarly known as the elemental or soft kind. Basically, they show no resistance to electric currents and reject incident magnetic fields below a critical temperature, $T_c$ and critical field, $H_c$. These critical conditions are parabolically given according to: (See Figure A-1)

$H_c = H_o(1-(T_a/T_c)^2)$. $H_o \equiv$ the critical field @0°K.

The exclusion properties are further fully reversible, in that irrespective of the mode of field application (above or below $T_c$) the material will exclude such applied field, within such critical conditions.

This latter effect, the Meissner-Ochsenfeld (Meissner) Effect, is in many ways the basic phenomenon of this activity of nature, and is specifically the basis of the herein described work. We may assume that the expulsion of magnetic field requires some internal energy utilization, as this produces a net external potential energy. This energy is given by the difference in the free energies of the normal and superconductive states as per some applied $T_a$. Since a field of application equivalent to $H_c$ is required for normalization, the above difference must be of the order of:

$$G_n - G_s = H_c^2/8\pi \cdot V,$$

as

$$\int_0^{H_c} M(H)\,dH = -H_c^2/8\pi \cdot V.$$

This is available energy to do work.

It is the propensity of any system in nature to obtain a condition of lowest free energy. When a superconductor is immersed in an ambient magnetic field, a fine mixed state of flux penetration should ensue to lower attendant magnetostatic energy, while maintaining maximum superconductive volume. This does not occur when the conditions involve the existence of a surface energy, whereby the penetrating field will cause internal phase boundaries and an associated energy increment. This condition can be expected when the finite field penetration zone, $\lambda$, into the superconductor is less than the range of coherence of the superconductive mechanism, $\xi$. Type I superconductivity will occur when the ratio, $\kappa = \lambda/\xi < .71$. Thus, a condition of positive interphase boundary surface energy will yield a Meissner-Ochenfeld exclusion required for the expulsion of the flux within the sample.

Microscopically, the manifestations apparent are due to the pairing of electrons into a state of reduced free energy, through lattice intervention. An energy gap is established which must be overcome to raise the super-electrons to normalcy, on the order of $\varepsilon = 3.5kT_c$ @ 0°K/pair. This lowers the free energy, giving rise to macroscopic characteristics. The range of coherence then, (on the order of $10^{-4}$cm) is the distance over which superelectrons interact. (See Appendix B-2)

As has been described, a field $H_c$ is required to drive the material into a state of normalcy. This field is just sufficient to raise the superelectrons across the energy gap. Current-induced transitions are related to the attendant field production. If the applied field is not uniform over the superconductive sample, a condition will result where, at some point, $H_c$ will be reached earlier than at some other juncture at a field of $H_a<H_c$. As $H_c$ must exist in normal regions and $H_a<H_c$ in superconductive regions, a complex state of alternate domains of normal and superconductive substance within the material ensues, called the intermediate state, at field values above $H_a = H_c(1-N)$. (See Figure A-6)

The demagnetization Factor, N, is a geometrical condition which causes the applied, normally uniform field, to be locally displaced. This factor may be approximated for plates (transverse field) as: (See Figure B-3)

$N = 1-(t/2a)$ (where t = Thickness, a = Radius)

Magnetization curves depend directly upon the N factor resulting from the geometry of a sample: (See Figure B-1)

$M = -H_a/(4\pi(1-N))$.

Thus in considering energies of a superconductor in a magnetic field:

$$\int_0^{H_c} M(H)dH = -H_c^2/8\pi = \text{constant for any material } N.$$

In the intermediate state, the surface energy acts to limit the minimum size of said domains. The magnetization changes linearly with increasing field, as per N factor conditions. The magnetic flux will penetrate a sample in such intermediate state as:

$$B_i = H_c - (H_c - H_a)/N.$$

With an N equal to 1, flux penetration immediately ensues as per application of $H_a$, thereby magnetization is a maximum at low field and decreases linearly with increasing $H_a$. An N equal to 0 will yield no flux penetration until $H_a$ equals $H_c$, so that magnetization is zero at initial application of $H_a$, rising linearly to a maximum at $H_c$ equal to $H_a$. Areas of resulting curves are always: (See Figure B-2)

$$H_c^2/8\pi \cdot V.$$

The thermodynamics of superconductivity are related to the condensation of the electrons, so that contributions to any unique heats are related to the electrons, not the lattice. A difference in entropy exists between the two phases: (See Appendix B-1)

$$S_n - S_s = -\mu H_c dH_c/dT \cdot V.$$

Thus we may examine the specific and latent heats:

$$C_s - C_n = (T\mu H_c d^2H_c/dT^2 + T\mu(dH_c/dT)^2) \cdot V.$$

and,

$$L = -T\mu H_c dH_c/dT \cdot V.$$

In the absence of an applied field the latent heat is zero, as it is at $T_c$ and $T = 0°K$ with an applied field. These thermodynamic properties will be treated in Appendix B-1.

All Type I materials discovered to present generally have rather low critical fields and temperatures. (Pb, for instance, normalizes at 803 gauss at 0°K and 7.2°K at 0 gauss). It is hoped future discovery will yield higher critical limit superconductors.

Class II superconductors are different from Type I in that this alloy or hard type has a negative interphase boundary surface energy. The range of coherence is shorter than the appreciable penetration depth of the applied field; in other words: $\kappa > .7071$.

Specifically, due to atomic structure arrangement, the electronic mean free path is low in these materials with an attendant reduction in the coherence length. (Impurities may cause the same condition in type I). The material will enter a mixed state of an extremely small and uniform arrangement of superconductive-normal regions, as was intimated previously concerning the surface energy. Said fine structure consists of fluxon penetrations on the order of $2 \times 10^{-7}$ gauss, ie., a Cooper pair. Since the penetration depth is more dependent on the applied field than in type I, a certain field of application is required to cause said penetration to exceed the range of coherence, called $H_{c1}$. The mixed state will continue to some higher ($N_b$-$S_n$: 200,00 gauss) $H_{c2}$. The areas of magnetization curves are equivalent to the thermodynamic critical field, $H_c$: $H_c^2/8\pi \cdot V$. (See Figure B-1)

Superconductivity can exist in higher fields than that permitted by $H_{c2}$, ie., to some critical field $H_{c3}$, on the surface regions only, denoted as "surface superconductivity". Such may occur in type I or II materials where the coefficient $\kappa > .41$. Said $H_{c3}$ is largely determined by angle of field incidence, with maximum parallel to the surface:

$$H_{c3} = 2.4 \kappa H_c,$$

and minimum for perpendicularity of incidence:

$$H_{c3} = 1.414 \kappa H_c.$$

This condition only transpires when the surface boundary involves an insulatory medium; therefore, the elimination of the above is effected via metallic contact thereat, ie., elimination of the insulator.

Thin films of superconductive material, in which the thickness 2a is less than the penetration depth, will necessitate flux penetration. This condition will yield a reduction in the magnetization. To obtain an area of $H_c^2/8\pi \cdot V$ for the magnetization curve, a higher critical field is required:

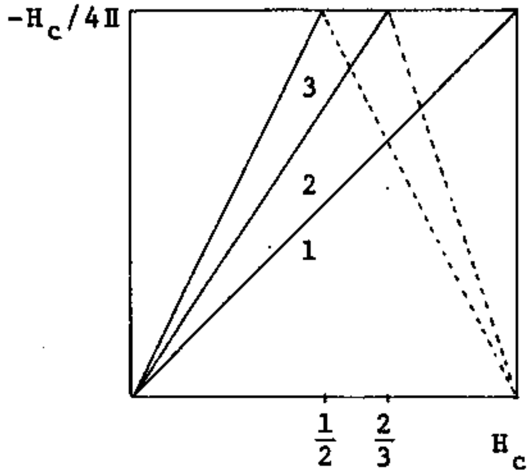
$$H_s/H_c = \sqrt{3}(\lambda^2 \xi / a^3)^{1/2} \qquad \lambda \text{ and } \xi \text{ are bulk values.}$$

This state is analogous to the mixed state of type II materials.

Very highly annealed macroscopic specimens may experience a hysteresis effect, supercooling-superheating, in which the flux entrance or expulsion occurs above or below $H_c$, respectively. This activity is related to the surface energy and the requirement for the formation of nucleation sites, similar to super-cooling-heating vapor-liquid conditions at familiar temperatures. The indicated transition sites are always $10^{-3}$ to $10^{-4}$ cm below the surface, whereat the boundary propagates along the surface and then interior regions. The net effect is to alter the general shape of the magnetization curve, necessitating a larger mechanical magnetic work function in one direction, smaller in the other.

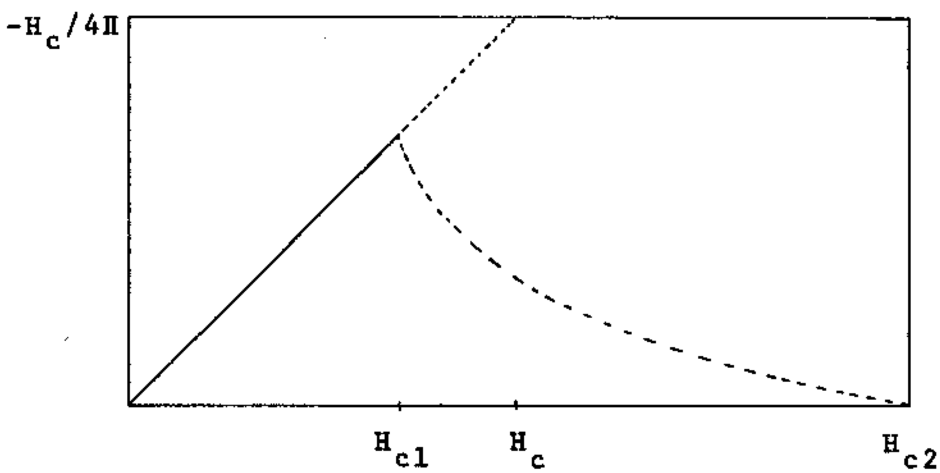
Hence, a heat influx is necessary to establish energetic equality.

Type I:




1. N=0 The material does not enter the intermediate state.
2. N=$\frac{1}{3}$ The material enters the intermediate state above $H_a=2/3H_c$.
3. N=$\frac{1}{2}$ The material enters the intermediate state above $H_a=1/2H_c$.

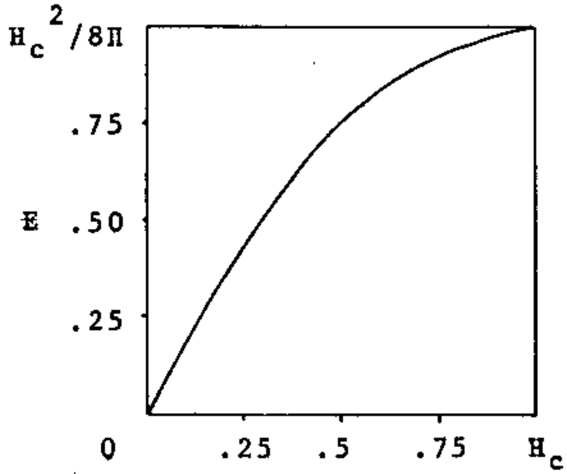
Type II:



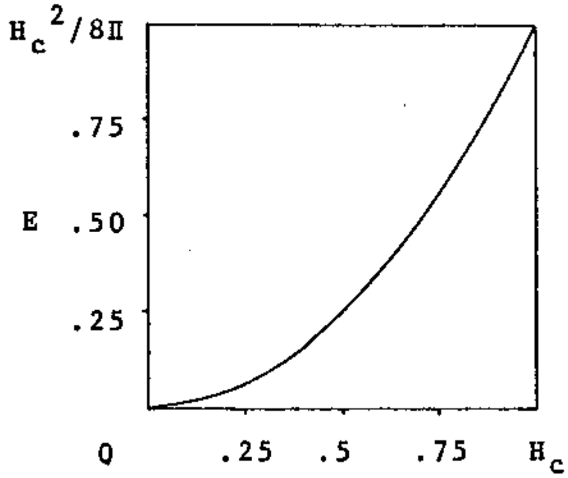

The material behaves as essentially Type I until $H_{c1}$ is reached, whereupon the mixed state ensues, continuing through $H_{c2}$. Above $H_{c2}$ normalcy is complete. The entire area is equivalent to that obtained with the extropolated curve to the thermodynamic critical field, $H_c$.

Fig. B-1. Typical Magnetization Curves.

Magnetostatic energies of an N=1 superconductor in applied field $H_a$




Magnetostatic energies of an N=0 superconductor in applied field $H_a$




Amount material superconductive with N=1 in applied field $H_a$

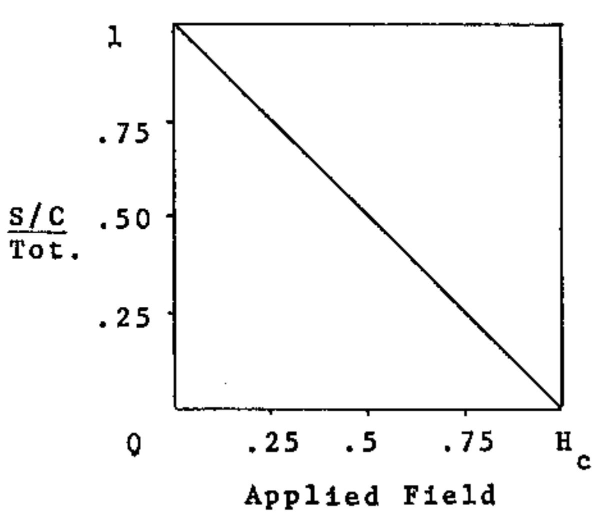
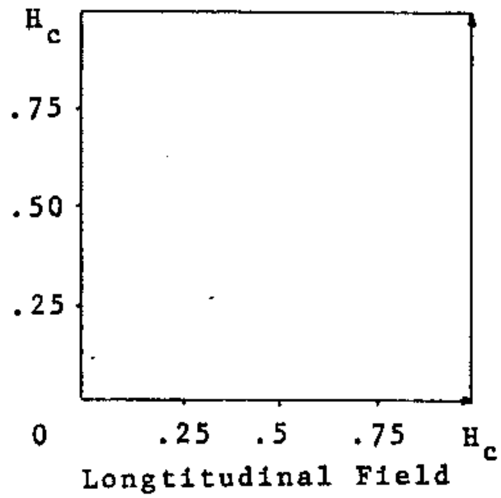



Fig. B-2. Some effects of demagnetization factor.

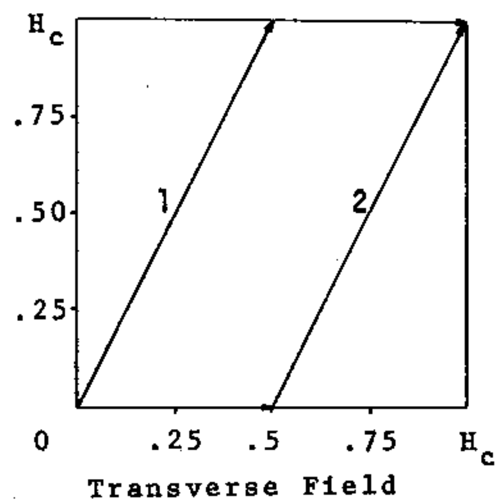
Fig. B-3. Effects of certain geometries in an applied field.

Cylinder:



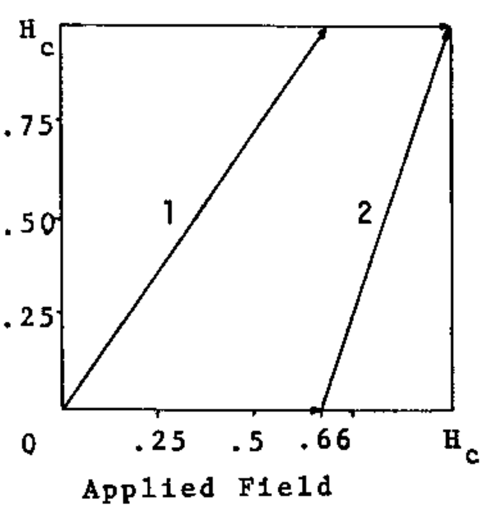

There is no intermediate state onset. The field is homogeneously distributed. Full normalcy transpires when $H_a=H_c$. The surface field is everywhere $H_a$.

Cylinder:




The intermediate state onsets at $.5H_c$. The equatorial field is given by 1. The polar field is given by 2. The equatorial field is a constant $H_c$ in the intermediate state. The polar field remains zero until $H_a=.5H_c$. Field penetration is given by 2.

Sphere:




The intermediate state onsets at $.66H_c$. The equatorial field is given by 1. The polar field is given by 2. The equatorial field is a constant $H_c$ in the intermediate state. The polar field remains zero until $H_a=.66H_c$. Field penetration is given by 2.

APPENDIX B-1:

THEORETICAL SURVEY:

A superconductor may be considered as a diamagnet whose internal peculiarities enable a certain magnetic work at 0°K. This implies an involvement of the internal energy, ie, magnetic work plus the superconductive state free energy at 0°K yield normalcy.

Specifically:

The magnetic Gibbs Potential may be written as:

$$G = U-TS+PV-\mu H_a M$$

We have then:

$$dG = dU-TdS-SdT+PdV+VdP-\mu H_a \cdot dM-\mu M \cdot dH_a$$

For a gas, $dU = TdS - PdV$. so, in our magnetic case:

$$TdS = dU-HdM+PdV$$

Substituting for TdS and cancelling terms in the equation for dG:

$$dG = -SdT-MdH-VdP$$

dP is negligible, Therefore:

$dG = -SdT - MdH$

At constant temperature: $dG = -MdH$

Now, using (0) and (Hc) to denote whether there is an applied field present and n and s to denote the phase:

We have: $Gn(0) = Gn(Hc) = Gs(Hc) = Gs(0) - MdH \cdot dV$

Therefore, $G_n(0)-G_s(0) = -\int_0^{H_c} M(H_c)dH \int_0^V dV.$

Integrating, we have finally:

$Gn(0) - Gs(0) = Hc^2/8\pi \cdot V$

This is the difference in free energies between the superconductive and normal states.

(After Lynton and Zemansky, Heat and Thermodynamics, 1968, 5th ed.)

SPECIFIC HEAT:

$C = VT \cdot dS/dT$

Taking the partial of S with respect to T:

$Cn - Cs = -VT \cdot d/dT \cdot (Hc \cdot dHc/dT)$, or

$Cn - Cs = -VTHc/4\pi \cdot d^2Hc/dT^2 - VT/4\pi \cdot (dHc/dT)^2.$

Integrating:

$$\int_0^{T_c} (C_n - C_s)dT = -\int_H^0 TV/4\pi \cdot (H_c \cdot dH_c/dT), \text{ generally, or,}$$

$$\int_0^{T_c} (C_n - C_s)dT = \int_{H_c}^0 VH_c/4\pi \cdot dH_c/dT \cdot dT - VTH_c/4\pi \cdot dH_c/dT \Big|_0^{T_c}.$$

The former term relates the magneto-mechanical heat energy and the latter concerns the latent heat contribution.

We have finally: $\int_0^{T_c} (C_n - C_s)dT = -H_c^2/8\pi \cdot V$,

the magentostatic available energies. (After Zemansky)

During some process, if the temperature varies, via design, leakage, joule heating, or latent evolutions, the above specific heat will exhibit itself.

In any transition 3 thermodynamic functions must be considered: the heat capacity of the normal regions and the superconductive regions plus the latent heat.

THE LATENT HEAT OF TRANSITION:

Recall: $dG = -SdT - MdH$

An incremental change in temperature, while H is constant gives:

$dG = -SdT$

ie, $S = -dG/dT$

Since $G_n(0) - G_s(0) = H_c^2/8\pi \cdot V$

Differentiation yields:

$S_n - S_s = -VH_c/4\pi \cdot dH_c/dT.$

This is just the entropy change between phases at temperature Ta. The heat absorbed or evolved at the transition is:

$dQ = VTdS.$

$Q = VT(S_n - S_s)$

$Q = -VTH_c/4\pi \cdot dH_c/dT.$

This is the latent heat of transition above 0°K and below Tc. It is evolved when phase change is present above absolute zero while in a magnetic field.

(After Lynton)

THE MAGNETODYNAMICS:

The minimum volume such that expulsion of flux transpires:

The energy density of a magnetic field of H gauss is:

$E = H^2/8\pi$.

It is well known that: $dW = Pdx$.

Consider the case of a superconductor in such field, an infinitesimal exterior contraction would yield a work of:

$dW = \mu H^2/8\pi \cdot dx$.

Therefore, $P = \mu H^2/8\pi$ dynes/cm$^2$. (After Newhouse)

It is necessary for a superconductor to expel a magnetic field below critical conditions (considering N=0 for simplicity). This can only transpire with sufficient free energy such that the Meissner-Ochsenfeld pressure can overcome the Maxwell stress. Since a condensation of electrons, resulting in free energy difference, occurs, per unit volume, to accomplish the above, we have:

$dW = M(H)dH$

$$W = 1/4\pi \cdot \int_0^{H_c} M(H)dH$$

$W = 1/8\pi \cdot H^2 = Gn(0)-Gs(0)$, the energy per cubic centimeter.

These results may immediately be applied to two interesting cases: (A) a superconductor completely surrounded by an applied magnetic field and (B) a superconductive plane upon one side of which a magnetic field is applied while on the other side there is no applied field, ie, this superconductor is acting as a magnetic field confinement shield.

(A) On the basis of the results, reversible exclusion of flux can only occur under conditions when the sample wholly occupies the volume of displacement. A hollow sample, for instance, could not possibly expel completely a magnetic field from its interior with a simple reduction of temperature below Tc. A Meissner Effect will only be noted in solid materials.

(B) Since we have found how surface pressure and free energies per unit volume are related, a shield wall, which might find practical application in magnetic circuit design, can only reversibly expel an interior field via the Meissner Effect if for every $cm^2$ of surface experiencing a pressure of $H_c 2/8\pi$ there is a superconductive volume of 1 $cm^3$ present.

In either of the cases above the superconductor will exclude any incremented magnetic field until its intensity reaches Hc, independent of thicknesses, etc. Upon reduction of the field below Hc, however, frozen-in flux will surely nearly equal Hc (depending on the degree of variance from (A) & (B) ).

APPENDIX B-2:

A FEW NOTES ON THE MICROSCOPIC THEORY:

This presentation is intended as a background for the phenomenological discussions that follow.

Frolich and Bardeen (1950) presented an hypothesis that the electrons moving in a crystal lattice set up a swarm of virtual phonons, due to lattice distortions as a result of the coulomb interactions.

Bardeen, Cooper and Schrieffer (1957) showed that this phonon cloud could be responsible for the superconductive state if it were able to mask the coulomb repulsion between electrons and in fact result in a net attraction.

The BCS Theory, as it has become known, succeeded in demonstrating that the basic interactions resulting in superconductivity were due to electron pairs.

If, for example, an electron interacted with the lattice, a phonon would be emitted that would eventually be absorbed by a neighboring electron. If the electronic energy change (which results from scattering) is less than the quantized phonon energy, $h/2\Pi \cdot \omega_q$, then the interaction between these two electrons is in fact attractive.

Cooper (1956) showed that if a net attraction between electrons just above the Fermi surface occurs, then a bound state can result. This, being a result of phonon interaction, can happen only to electrons lying within a shell of width $h/2\Pi \cdot \omega_q$.

This bound state is lower in energy than that for a normal metal of "non-condensed" electrons by an amount $Hc^2/8\Pi \cdot V$ at 0°K. An energy gap is therefore present separating super-electron pairs from the normal electron sea (3.52kTc per pair at 0°K).

The results of mixed state investigations in type II materials have revealed that flux penetrates in discrete quanta, called fluxons. A fluxon is that field which would be produced by an electron pair ($2 \times 10^{-7}$ gauss, ie, hc/2e).

The specific heat and the other macroscopic mainfestations may be derived directly from the theory.

See Lynton pp. 109-131.

# I.

## A THERMODYNAMIC COMPARISON BETWEEN THE MAGNETO-MECHANICALLY AND MAGNETO-CALORICALLY INDUCED SUPERCONDUCTIVE PHASE TRANSITIONS IN A TYPE I SUPERCONDUCTOR

### Prefatory Remarks:

In this section we shall investigate the nature of the work functions required to initiate the superconductive phase change.

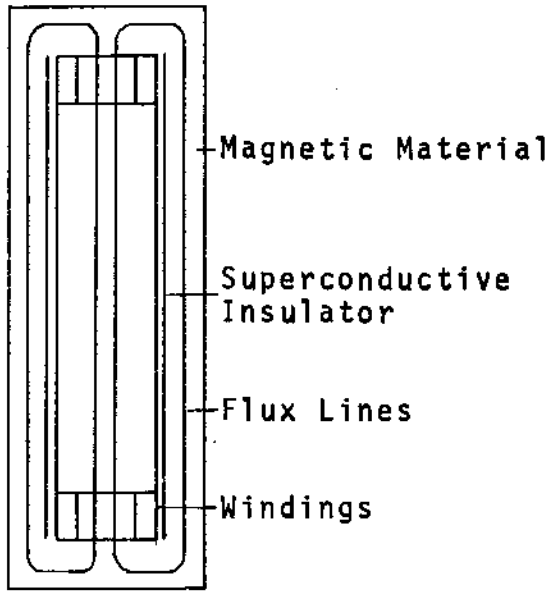
There are two functions which determine the state of a sample: Field and Temperature. Hence, there are two ways in which to cause the transition from the superconductive to the normal state: do magnetic work or thermal work. In any event, for the thermodynamics to have any consistent validity the final work must always be the same: $Hc^2/8\pi \cdot V$.

To investigate the nature of this transitional duality, we will cause a superconductive sample at 0°K to be physically forced into a magentic field of .5Hc gauss, thereby performing only a mechanical work, whose net effect will be to bring the material closer to the normal state. Immediately thereafter, we will finalize normalization by leaving the sample situated entirely within this field and raising the temperature to .707Tc, thereby investing only thermal energy.

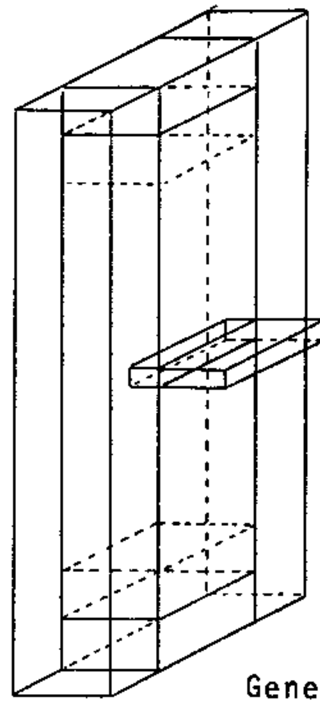
In the former case the work performed will be based solely upon the external forces, whereas the latter will be based solely upon the internal energies.

Data from these two processes will be obtained and analyzed for consistency.

Finally, the macroscopic manifestations of demagnetization factor, intermediate state, and penetration field will be incorporated into the former case as a purely mechanical consequence of a critical field, the latter as a microscopic consequence.




Configuration for establishment
of the required magnetic circuit.
(After Cioffi)



General
View

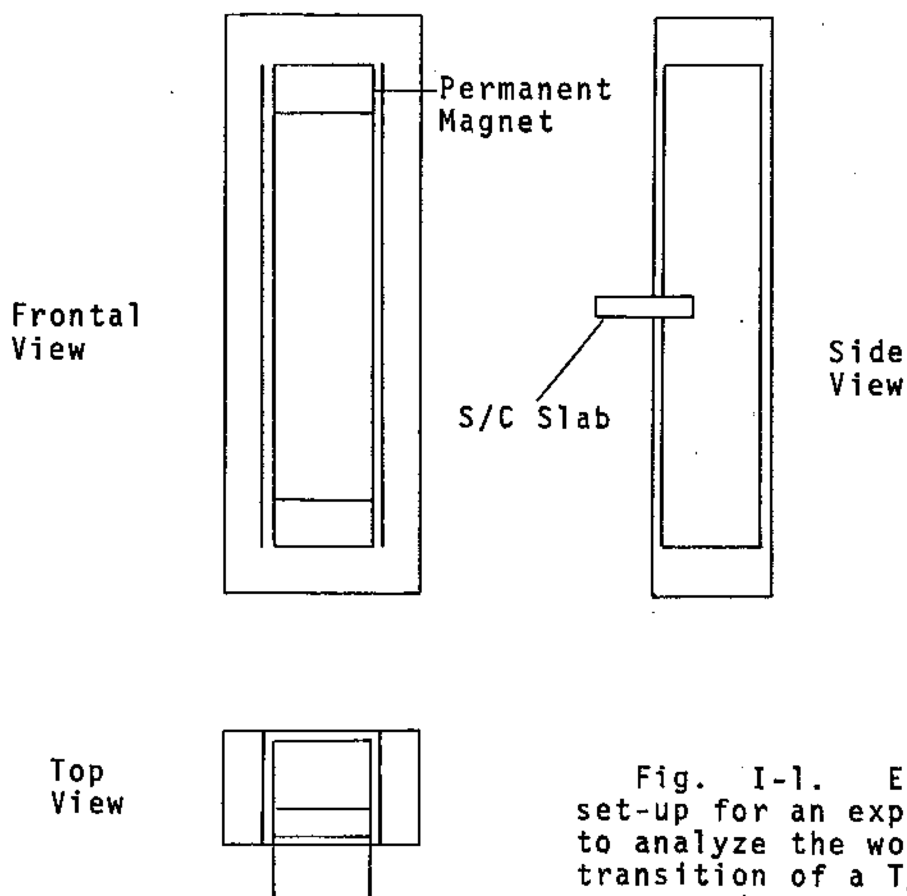
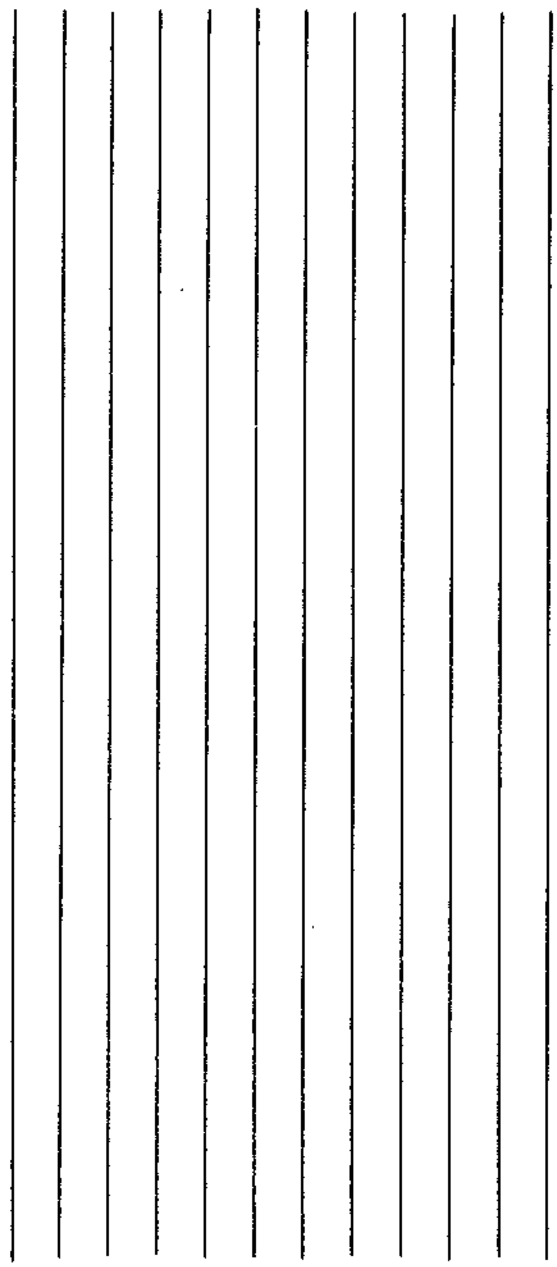



Fig. I-1. Equipmental set-up for an experiment to analyze the work of transition of a Type I superconductor.



$L/L_0 = 0$

$H_a = .5H_c$

$H_i = .5H_c$

$B_i = 0$

$T = 0°K$

Fig. I-2a. Schematic field distribution. The field is undisturbed and completely homogenious previous to the introduction of the slab.

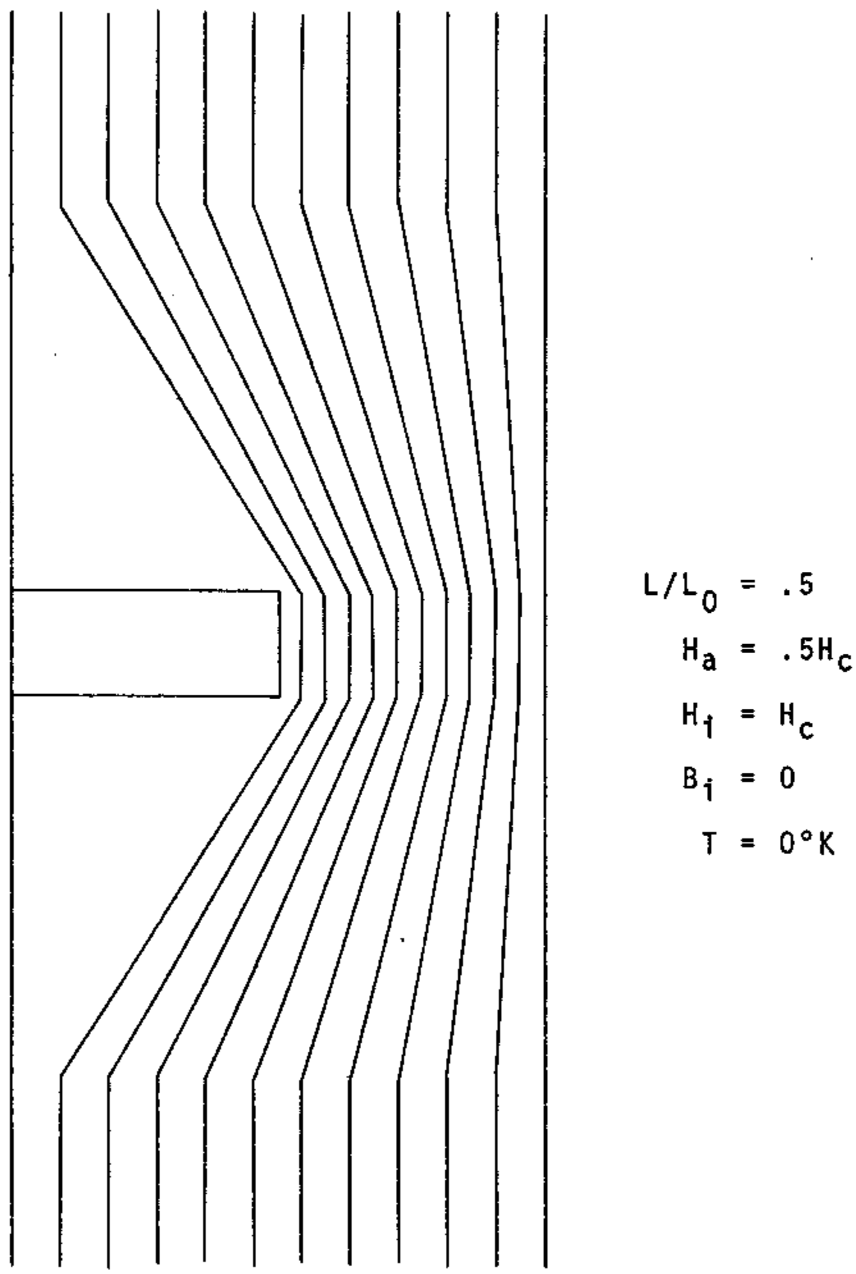



Fig. I-2b. Schematic field distribution. The slab is inserted half way in, it is still fully superconductive but about to enter the intermediate state.

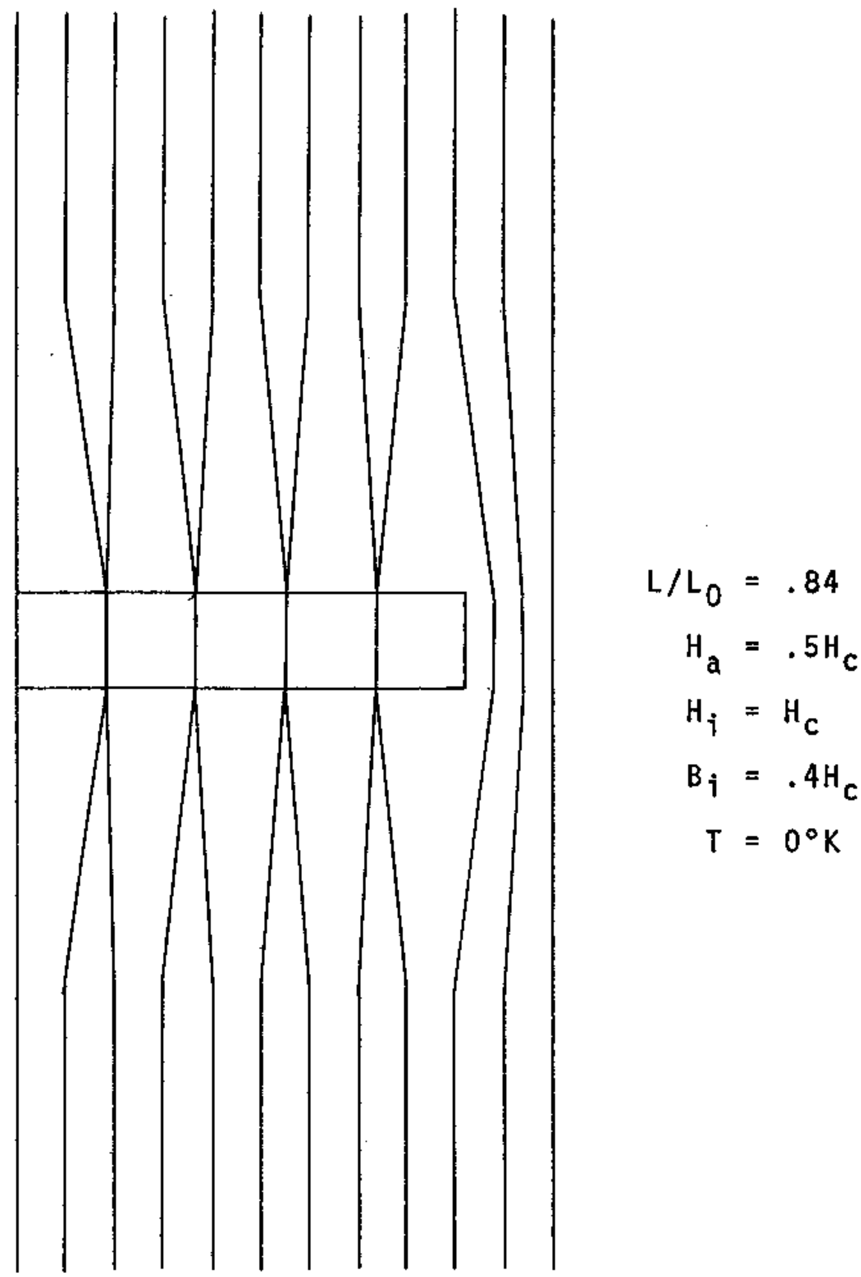



Fig. I-2c. Schematic field distribution. The slab is inserted far enough into the prism such that it is now in the intermediate state.

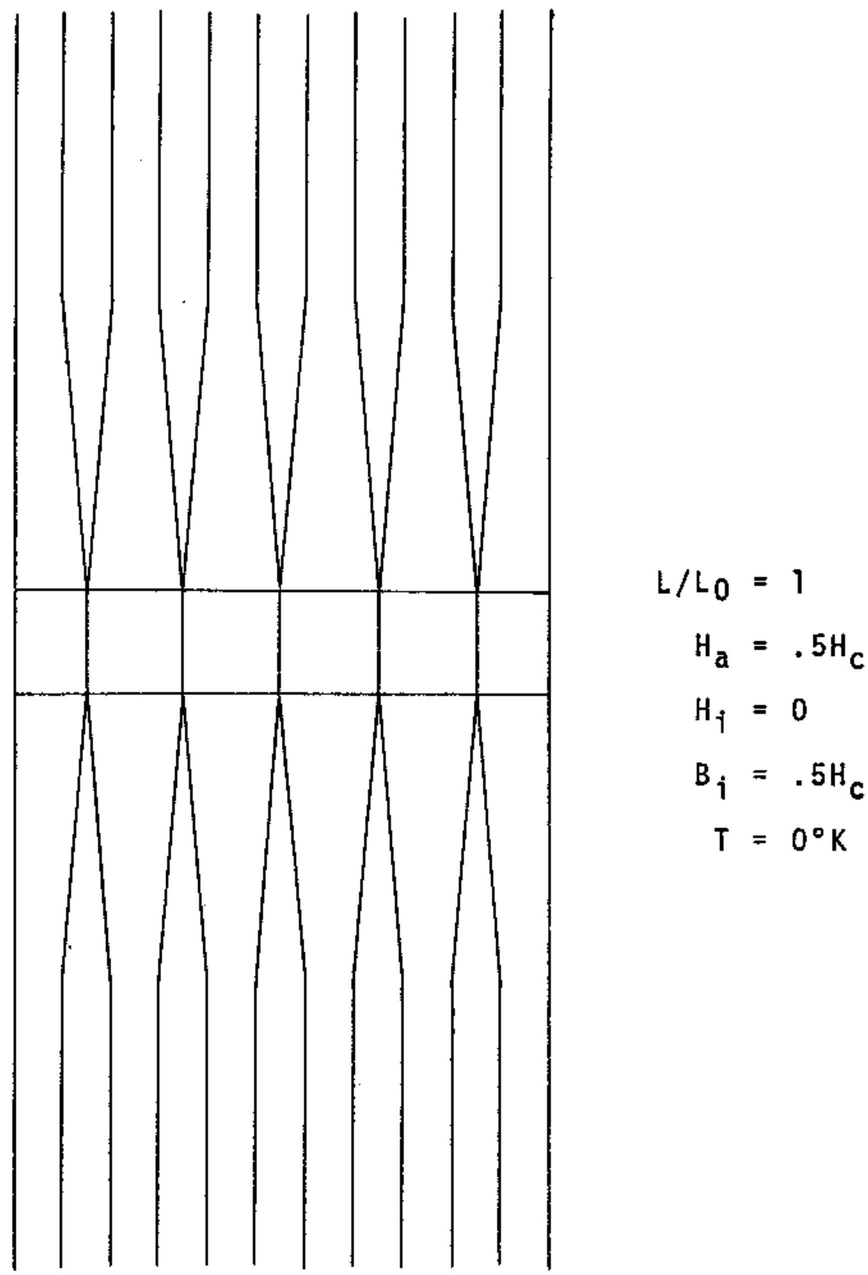
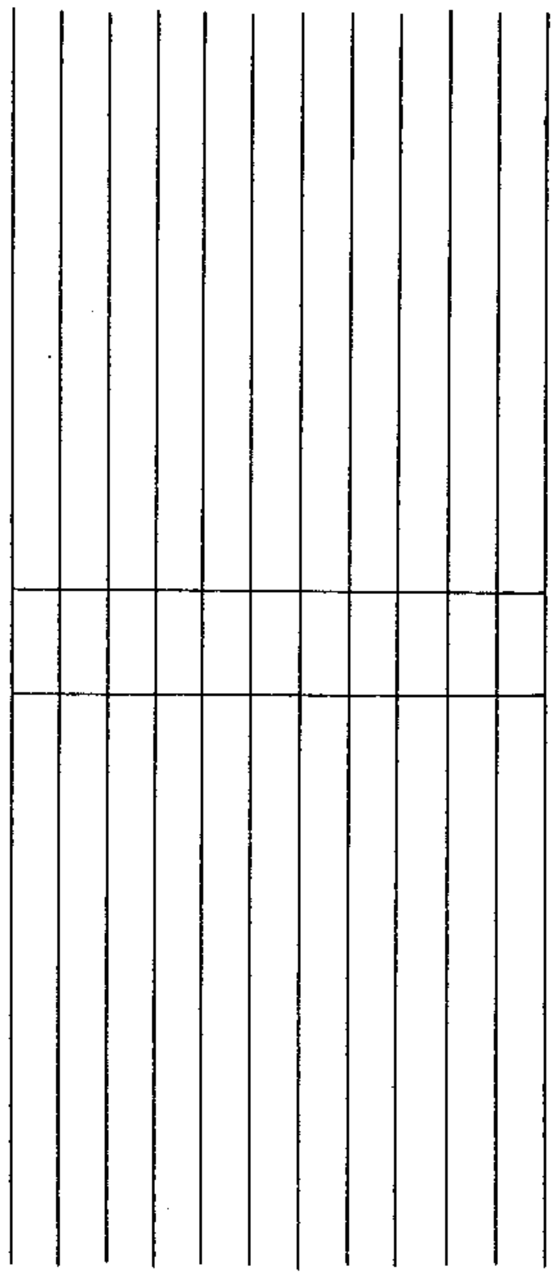



Fig. I-2d. Schematic field distribution. The slab is fully inserted into the prism. The intermediate state allows all the field to pass through the slab in normal laminae.



$L/L_0 = 1$

$H_a = .5H_c$

$H_i = 0$

$B_i = .5H_c$

$T = .7071T_c$

Fig. I-2e. Schematic field distribution. The slab is fully inserted into the prism and has been driven completely normal by a rise in the ambient temperature.

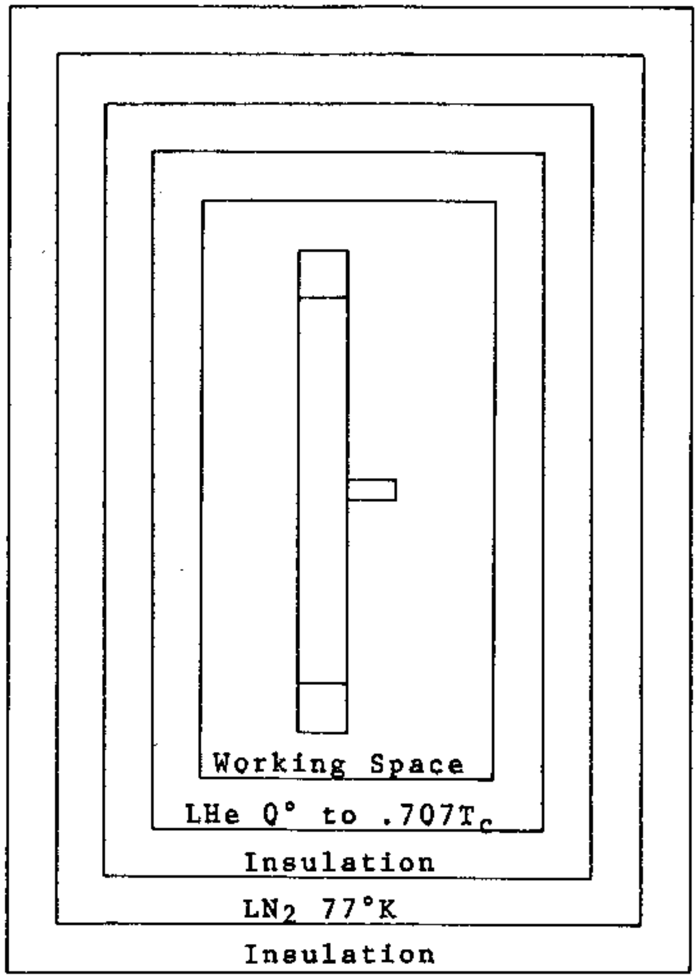



Fig. I-3. Schematic of the cryogenic cryostat system. Refrigeration apparatus not shown. Within the working space is located the experimental apparatus of Fig. 1.

# I.

## A THERMODYNAMIC COMPARISON BETWEEN THE MAGNETO-MECHANICALLY AND MAGNETO-CALORICALLY INDUCED SUPERCONDUCTIVE PHASE TRANSITIONS IN A TYPE I SUPERCONDUCTOR

### I. Statement of the Theoretical Experiment:

We wish to obtain data on the mechanical and caloric energies required to fully normalize a superconductive sample in the region between 0°K and Tc and 0 gauss and Hc. To this end, we utilize a specially configurated magnetic circuital apparatus into which our subject sample will be inserted.

### A. Environmental Considerations:

The type I superconductive state is exhibited below a critical temperature Tc, which is no more than a few degrees above the absolute zero. Our experiment must, therefore, be performed within the confines of a suitably prepared liquid helium cryostat. The unit may utilize conventional insulating technique via liquid nitrogen radiation shielding and vacuum-superinsulation multilayered walls. We employ radiation cooling within the experimental working space. The working space ambient temperature can be varied via cooling of the surrounding helium bath from Tc to approximately 0°K, by use of external vapor pumping, adiabatic demagnetization, and nuclear demagnetization refrigerational apparatus. See Figure I-3.

B. Determinations Specific to the Creation and Maintenance of a Totally Confined Magnetic Circuit via the Utilization of Superconductors:

Conventional technique to control leakage and fringing flux in a magnetic circuit has long been to employ ferromagnetic materials which, due to the high permeability they possess as compared to that of air, act as a confinement medium for the magnetic field. Inherent in this system, however, is the loss of flux from the confined circuit because it relies not on an imposed boundary limitation but rather the extremely high but imperfect flux conductivity of these materials to achieve localization of the flux.

This situation leads to increased requirements on core flux generation where the magneto-motive force originates. Further, overall working space must be enlarged to account for cross-sectional nonuniformity of the magnetic field at the outer regions.

Since a superconductor excludes all incident magnetic fields from its interior, we may assume that if such a material were designed in the form of a long hollow cylinder, then a field generated in its interior would be entirely constrained within the precise limits of that cylindrical volume. Hence, a magnetic circuital configuration can be managed by use of a superconductive field confinement cylinder placed around an air-gap working space with conventional ferromagnetics used only for the return path.[1,2]

See Figure I-1.

a. Advantages:

The field will be entirely constrained within the region of the cylinder.[3] This will enable us to use smaller magnets in order to generate the required flux densities in the air-gap. Further, the field will extend only into the regions of space that the experiment exactingly requires.

The field homogeneity will be nearly complete. There are no edge effects.[1] Therefore, the entire space-field within the air-gap is suitable for an experiment requiring constant flux density over all space.

This technique[a] has been experimentally tested and verified to indeed be a means to closely approach the ideal magnetic circuit.[1,2]

b. Design:

We wish to experiment within the region of a square quadrilateral prismatic air space[6], the limits of which are delineated by the presence of a similarly shaped superconductive material. This superconductor is made in the form of a thin rolled insulated sheet, designed so as to eliminate a shortened turn.[c,4,1] See Figure I-1. The confinement material may be fabricated out of the so-called high field filimentary type II materials employed below $Hc_1$, or suitable type I. In any event, the thickness of the wall must be sufficient to fully exclude the applied longtitudinal field, ie, thicker than the penetration depth.[d,2]

At the extrema of this quadrilateral region are located the seats of magneto-motive force, which are situate entirely within the superconductive wall. These magnets may be of permanent, superconductive, or conventional electromagnetic type, the latter being undesirable due to joule heating effects. We require a static field in our experiment, as such, we may employ a superconductive permanent magnet[5] constructed from a multiply connected or filimentary superconductor, as our magnetic field agency.

Directly connected to the magnets and extending beyond the confinement prism is a symmetrically arranged[1] ferromagnetic return path for the magnetic flux from the upper magnet to the lower one.

C. Experimental Specifics:

We wish to cycle a superconductive sample from (1) 0°K and 0 gauss to 0°K and .5Hc, and (2) from this latter state to .707Tc and .5Hc. In the former we do purely mechanical work, in the latter purely thermal work. We will compare data on the works to achieve these respective states and determine the completeness of the superconductive thermodynamics.

To achieve this goal, we construct a sample of very pure annealed type I superconductor in the shape of a thin slab.[e] The dimensions are 5.2 cm long by 5 cm wide with a cross-sectional area of 1 $cm^2$(5 cm x .2 cm). The critical field and temperature are $H_c$ and $T_c$ and in the former case we have an ambient field of $.5H_c$ and temperature of 0°K, in the latter case the field remains $.5H_c$ but T varies from 0°K to $.707T_c$, at which point the material is fully normal, that is, normally conductive.

The sample is introduced into a magnetic field of $.5H_c$ via the configuration above. This slab size imposes the following dimensional requirements: The square hollow quadrilateral geometric prism must be 5 cm on a side. The length is somewhat arbitrary, however, we will set it at 50 cm. The magnets must produce a field of precisely $.5H_c$ in the working space. The confinement prism must have a critical field greater than $H_c$. Finally, a rectangular opening at the mid-length point must be cut in one free side of the prism, so that the slab may be introduced into the interior. Initially, the slab enters the prism as far as the wall inner surface, ie, it does not protrude inward and indeed acts as the local prism wall relative to the internally confined field. This slit is cut such that the 5 cm dimension of the slab coincides with the wall width.

The circuital configuration is resident in the aforementioned cryogenic system.

NOTES AND REFERENCES:

a. Cioffi finds that magnets used to produce a field of 4000 oer. in an air-gap of 15.51 $in^3$ at a uniformity of $\pm$2 Oer. for maser application can be reduced from 750 lbs. of Alnico V (leakage and fringing accounting for 95 percent of the volume and weight) to just 10 lbs. of magnetic material via superconductive techniques.

b. This is because we want to be able to consider a rectangular slab leading edge, which thereby requires a square shaped flux confinement set-up.

c. A shortened turn would mean that any flux change we might initiate via our magnets would be permanently resisted by the prism material (it would maintain the field that was present when it became superconductive).

d. If it were not thicker, then some flux would penetrate.

e. This will allow for only one critical field and no losses due to flux being frozen in by irreversible effects.

1. Cioffi, P.P., Journal of Applied Physics, V. 33 N.3 March, 1962. pp. 875-879.

2. Newhouse. pp. 161-162.

3. Swartz, P. and Rosner, C., Journal of Applied Physics, V. 33 N.7, July, 1962. pp. 2292-2300.

4. Hempstead, Kim, and Strnad, Journal of Applied Physics, V.33 N.11, November, 1963. pp. 3226-3236.

5. Bean, P. and Doyle, M., Journal of Applied Physics, V.33 N.11, November, 1962, pp. 3334-3337.

6. Holt, Charles A., *Electromagnetic Fields and Waves*. New York, 1967. pp. 361-366.

## II. The Experiment: Part I: The Magneto-Mechanics:

### A. Procedure:

The cryostat is first cooled via liquid nitrogen through filling the $LN_2$ cavity and allowing time for the inner members to arrive at thermal equilibrium at 77°K. The liquid helium is introduced at atmospheric pressure at 4.2°K. After allowing additional time for the cryostat to achieve final thermal heat transfer rates between the inner chamber, the LHe cavity, and the external environment, we energize the vacuum pumps to cool the helium to 1.2°K by rapidly reducing the vapor pressure. Next, we activate the ionic demagnetization of paramagnetic salts apparatus to achieve .001°K. Finally, our helium is cooled to essentially 0°K via nuclear demagnetization of our paramagnetic salts. This process is repeated periodically to maintain and adjust our inner chamber ambient temperature as we require. Our experiment is ready to begin with the superconductive permanent magnets operating and producing .5Hc gauss as the temperature falls below the requisite critical value of the materials employed.

We have the applied field and temperature values at .5Hc gauss and 0°K within the inner chamber working space. We effect to initiate the insertionary process of the slab into the confined magnetic field volume at the rather slow rate of .1 cm per second, using a mechanical apparatus.[a] This will allow for unhurried measurement taking and ensure continued lossless qualities in the slab.[b]

As the slab enters the field region the magnetic flux is excluded from the interior of the material necessitating the compression of the field between the leading edge of the slab and the opposite prism wall. This condition deviates from the thin longtitudinal cylinder concept, and the intermediate state is assuredly going to occur when the compressed field attains the value of Hc, or two times the applied field strength.

B. Analysis:

We are interested in obtaining data on the work required to insert the slab; however, other interesting effects are occurring concurrently: (A) the change in demagnetization factor as the field compresses, (B) the penetration field going through the slab while in the intermediate state, (C) the compression of field with length of slab insertion, (D) the amount of volume of material normal in the intermediate state as the slab approaches the opposite flux confinement prism wall, and (E) the force on the leading edge of the slab as the field compresses. We will examine these in the same periodic manner that we will observe the work and work per unit volume inserted.

A) Change in Demagnetization Factor with Slab Insertion Distance:

Discussion:

The demagnetization factor is entirely basic to the proper assessment of the work values.[c] It is dependent on the degree to which the field is distorted about a superconductive sample; thus it is a purely geometrical consequence.

In our case, the distortionary quotient is changing as the slab enters the prismatically confined magnetic field regions, since obviously the flux lines are increasingly more lengthened and pushed away from their "natural positions", ie, the flux density is increasing immediately between the slab edge and the opposite prism wall, and decreasing in the regions immediately below and above the inserted length of slab.

This increment in field density on the leading surface of the slab is directly responsible for the transition from the pure to the intermediate state, since Hc will be reached on this edge earlier than anywhere else on the sample surface.

We expect that the demagnetization factor depends on the incremented or compressed field, Hi, and on the critical field, Hc. When Hi equals Hc the intermediate state must ensue,[d] and since we have an applied field of .5Hc, the demagnetization factor is .5.[e] The change of the demagnetization factor from $.5Hc \leq Hi \leq Hc$ is, then, $N = (Hi-Ha)/Hc$.

There is, however, a significant development after Hi first equals Hc because the intermediate state transpires, necessitating Hi remain constant on the leading edge exactly equal to Hc[f]. Thus, we turn to the only other significant field strength value which during the remaining process does change: the penetration field.[9] For now, assuming this happens, since this field is given as:

$$Bi = Hc-(Hc-Ha)/N,$$

we can solve for N and we obtain:

$$N = (Hc-Ha)/(Hc-Bi).$$

Since Hc=Hi the equations are seen to be identical with Bi equal to 0 in the former case.

Data: See Figure II-1.

The demagnetization factor was seen to vary from 0 to 1 during the insertional process from L=0 to L=5 cm. N equaled .5 when Hi first equaled Hc, as anticipated. The demagnetization factor value plotted against the reduced insertional distance, $L_{in}/L_{tot}$, indicated a perfectly linear relationship there between.

B) Change in Penetration Field with Slab Insertion Distance:

Discussion:

With the onset of the intermediate state the sample must retain Hc as the external field value, since a small amount below would allow for restoration of the pure superconductive state, and above would require entrance into the normal state. For this circumstance to continue in ever increasing fields, some relief must occur so that the surface field does not exceed Hc. This can only happen if the weight of the increased applied surface fields is relieved by an allowance of some of the flux to actually penetrate the sample sufficient to precisely retain the surface field at Hc, independent of the applied field.

In our case, the slab is not subjected to any increased applied field -- Ha equals .5Hc at all times. However, as the sample enters farther into the prism Hi increases to Hc, the demagnetization factor increases, and when Hi equals Hc, relief is found by some flux penetration into the slab.

We would expect this intermediate state consequence not to take place until Hi equaled Hc, whereat the penetration flux Bi would equal 0.[h] Immediately thereafter this field exhibits itself, continuing until the slab is entirely into the prismatic volume, whence, the field will have "no choice" but to penetrate entirely the superconductive slab, whereat Bi equals Ha and N equals 1.

The penetrational field then depends on the critical and applied fields plus the demagnetization factor. At N equals 1, Bi equals Ha. At Ha equal to Hc, Bi equals Hc. Hence:

$$Bi = Hc-(Hc-Ha)/N.$$

In our case, Bi depends directly on how the area between the slab edge and the prism wall and Hi are related to the original area and Ha. Figuring the total flux: Ha x Ao = the original flux, Hi x A = the compressed flux. Finally, by subtraction and division by the cross-sectional difference $(A_o - A)$ we have:

$$B_i = (H_a \times A_o) - (H_i \times A)/(A_o - A).$$

Data: See Figure II-2

The penetrational field was seen to remain zero until $H_i$ equaled $H_c$. The intermediate state onset then transpired and as N increased above .5 the penetration flux increased from zero to a final value of $B_i = H_a = .5H_c$, at the insertion length of 5 cm when N equaled 1. A graph of penetration field versus insertion distance indicated a parabolic relationship between them.

C) Change in Prismatic Field Intensity with Slab Insertion Distance:

Discussion:

The magnetic field flux is a constant in the prismatic volume.[i] The flux density, $H_i$, is determined by the cross-sectional area through which it is constrained to pass.

As the slab is inserted into the prism, the cross-section decreases between the slab leading edge and the prism wall. Assuming that the total flux does not change, and in our experiment it does not, the density of flux must increase directly as the area decreases.

Thus, $H_i$ constantly increases as the distance inserted increases until $H_i$ equals $H_c$, whereupon N equals .5 and the intermediate state onsets, resulting in Hi = constant = Hc thereafter.

The compressed field depends, naturally, on the applied field value and in addition on the ratio of the original area to the present one. Hence:

Hi = Ha x (Ao/A).

Data: See Figure II-3

The compressed field was found to increase from Ha at L = 0 cm to Hc at L = 2.5 cm, thereafter to remain Hc. When L = 5 cm, all flux was of a penetrationary nature. A graph of compression field versus insertion distance indicated a parabolic relationship between these functions from L = 0 to L = 2.5 cm.

D) Change in Amount Normal in the Intermediate State with Slab Insertion Distance:

Discussion:

As the applied field value increases while the sample is in the intermediate state, some field must increasingly penetrate the sample. The only way in which this may happen is if a portion of the material normalizes, thereby creating a region through which the flux may pass. These regions can only be normal if a local penetration field is at least Hc. We know on the basis of the foregoing that Hc is not exceeded on the leading edge. Hence, it is immediate that

Hc is the exact value of the local field penetration and that in any normal regions a field of Hc completely occupies the space.

In our case, the slab enters the intermediate state when L = 2.5 cm.[j] At this point the material is entirely superconductive. As N increases from .5 to 1 and Bi increases from 0 to Ha, we recognize that the normal regions increase from 0 to, logically, 1/2 the volume inserted, since we have an applied field of .5Hc (thereby Hc occurs over 1/2 the volume).[k] We note that the penetration field is integrally related to this, and, in fact, is numerically equal to the ratio: (Volume Normal)/(Volume Superconductive).[l]

Data: See Figure II-4

The volume normal was seen to remain zero until Hi = Hc at L = 2.5 cm and increased to .5 at L = 5 cm. As per the Bi graph, ie, here we graph volume normal versus insertion length, we find a parabolic relationship between the variables.

E) Change in Force with Slab Insertion Distance:

Discussion:

There is a surface pressure exerted by any magnetic field which is in direct contact with a perfectly diamagnetic body dependent on the field squared, ie,

$P = (H^2/8\pi)/A$,

where A is one $cm^2$. This is derived in the previous section on the physics.

In our case, the slab experiences a surface pressure of: $(H_a{}^2/8\pi)/A$. The force is then just the pressure times the total area. The slab edge area is precisely 1 $cm^2$ (5 cm x .2 cm) and we obtain:

$F = H_a{}^2/8\pi$ dynes.

As the slab is inserted $H_i$ goes up and the force becomes: $H_i{}^2/8\pi$, until $H_i = H_c$, whence the force remains $H_c{}^2/8\pi$ for the rest of the insertional process.

Data: See Figure II-5

The force was seen to increase from an initial value of $.25H_c{}^2/8\pi$ at L = 0 cm to $H_c{}^2/8\pi$ dynes at L = 5 cm. At 5 cm the field was entirely of a symmetrical penetrationary nature and no net forces existed. A graph of force versus insertional length revealed a parabolic relationship between the variables. Force was seen to be a constant $H_c{}^2/8\pi$ dynes from L = 2.5 cm to essentially 5 cm.

F) Work as a Function of Insertional Distance:

Discussion:

In any mechanical system the work is always:

$dW = F \cos\theta \cdot dx$

A magnetic system is unique only in that the force is $H_a^2/8\pi \cdot A$. The familiar procedure is to integrate over x to find the total work.

In our case, F is going to vary with x, the insertion length, as per the preceding discussion. Knowing how F varies, we may integrate the above equation to obtain the final total work performed in inserting the slab into the prismatically confined magnetic field, if we wished to perform our experiment in theory.

The work which goes into the system is mechanical energy supplied via an apparatus designed to push the slab into the field. The energy then goes into the potential energy of the compressed magnetic field, which on the basis of the foregoing is from $.5H_c$ to $H_c$. The actual magnetic work performed in such a process is:

$$\int_{.5H_c}^{H_c} HdM \cdot V.$$

This integration is just $(H_c^2/8\pi - .25H_c^2 8\pi) \cdot V$, which is: $.75H_c^2/8\pi \cdot V$. We know that the area under the N = 0 magnetization curve is $H_c^2/8\pi \cdot V$ and subtracting the area under the $.5H_c$ portion from the entire curve, ie, that under $H_c$, yields the same answer: $.75H_c^2/8\pi \cdot V.^m$ The magnetization curves for all demagnetization factors are unique unto themselves, but always equalling a total area of $H_c^2/8\pi \cdot V$.

We will compare the work of insertion: (A) with distance into the prism and (B) relative to the demagnetization factor demagnetization curves at .5Hc applied field for each similar N that insertion brings about. These will be calculated on the basis of the work per unit volume, which is just the total work divided by the total inserted volume in cc (the work then is in ergs/cc).

Data: See (A) Figures II-6 and II-7; and (B) Figures II-8 and II-9.

(A) The work per unit volume is seen to increase from $.25Hc^2/8\pi$ ergs at $L = 0$; the reason being that the work is associated with $N = 0$ initially and the area under the magnetization curve is $.25 \times .25Hc^2/8\pi$, hence any amount of insertion requires $.25Hc^2/8\pi \cdot V$. The work increased from this value with L until a final value of $.75Hc^2/8\pi$ was recorded. This was the value anticipated and the total work was $3.748Hc^2/8\pi$ for the 5 cc inserted into the prism. A graph of work per unit volume versus insertional length indicated that the variables were parabolically related with an inflexion point located at 2.5 cm. This was due to the nature of the force incrementation with dx, ie, parabolic at first and constant after 2.5 cm from the insertion point.

(B) A comparison of the works as computed from the area under the magentization curves for various integer N values @ Ha = .5Hc with the mechanical work measured in our experiment when the N values attained integer status, indicated a perfect agreement between the purely magnetic and magneto-mechanical data. See Figures II-8 and II-9.

NOTES:

a. This can be effected by spring, hydraulic fluid, or magnetic pressure, as required.

b. A sample is lossless while superconductive to about $10^{12}$ Hz., however, in the intermediate state joule heating might occur due to eddy current generation as the slab moves through the field.

c. Since this function is a measure of when the slab will begin to normalize, we could not be sure if the field would not just infinitely compress when the slab is fully inserted; then we would do infinite work.

d. Obviously, if the surface could withstand a field greater than Hc, then Hc would not be the critical field.

e. This is because the ratio of applied field to surface field is then .5/1 = .5.

f. If the surface field ever fell below Hc, the portion normal at that locality could return to superconduction.

g. This is the field which actually goes through the slab. It increases from zero to .5Hc and depends on N.

h. Obviously, below Hi = Hc the material must be completely superconductive.

i. The density may vary, but we have so designed our permanent magnets such that whatever we do with the slab, the total flux within the prism is constant.

j. We have this from knowledge that N = .5 at L = 2.5 cm. At a field of .5Hc, this means Hi = 1. The data on the compressed field confirms this.

k. We need Hc in any normal regions. Our area is A and field is .5Hc, so that Hc (a flux density) can only be achieved by halving the area.

l. This is because Hc is contained in the exact area of all normal regions, ie, knowing Bi one knows the amount normal.

m. This is the applied field versus magnetization curve.

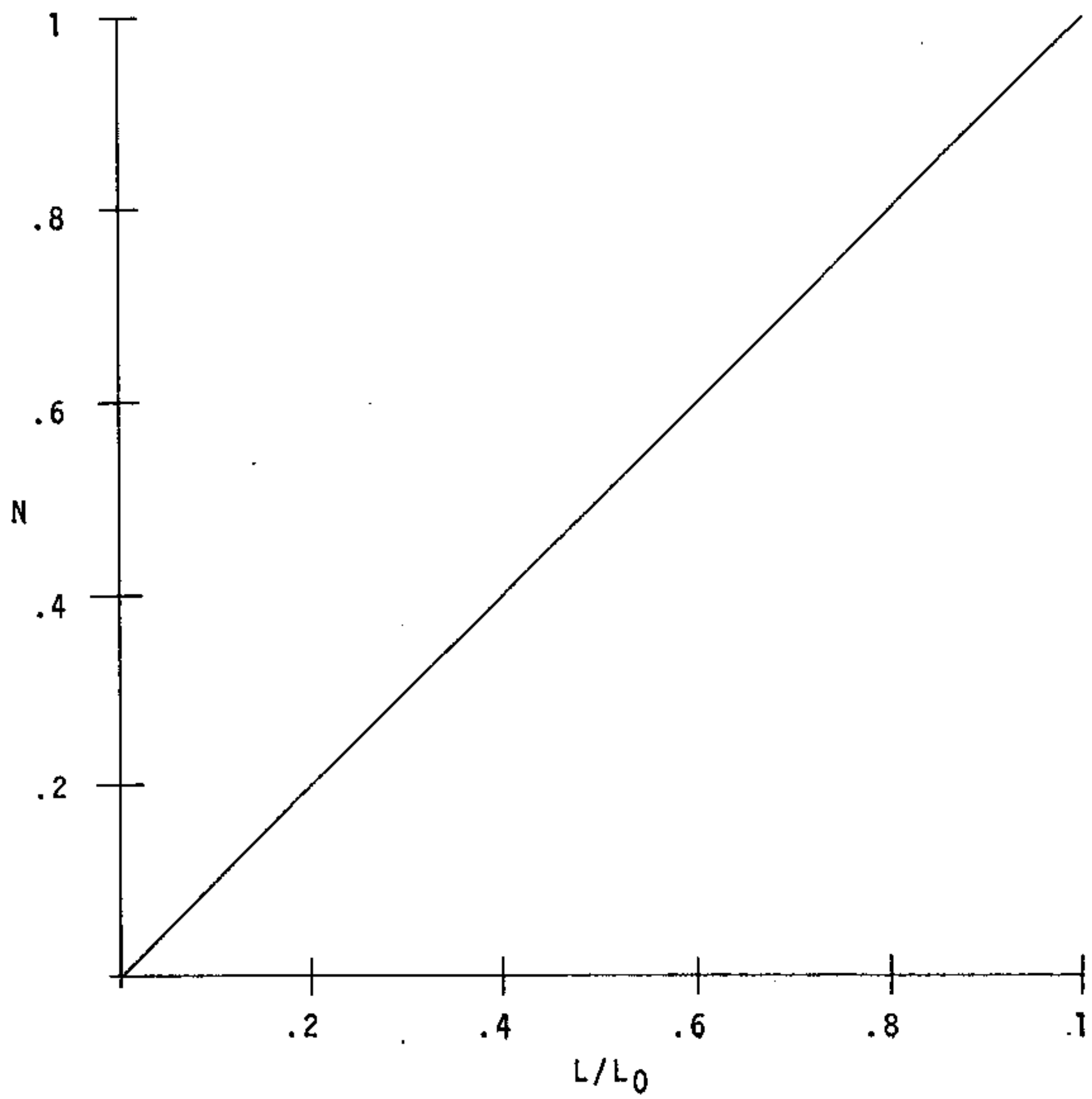



Fig. II-1. Insertion Length vs. Demagnetization Factor.

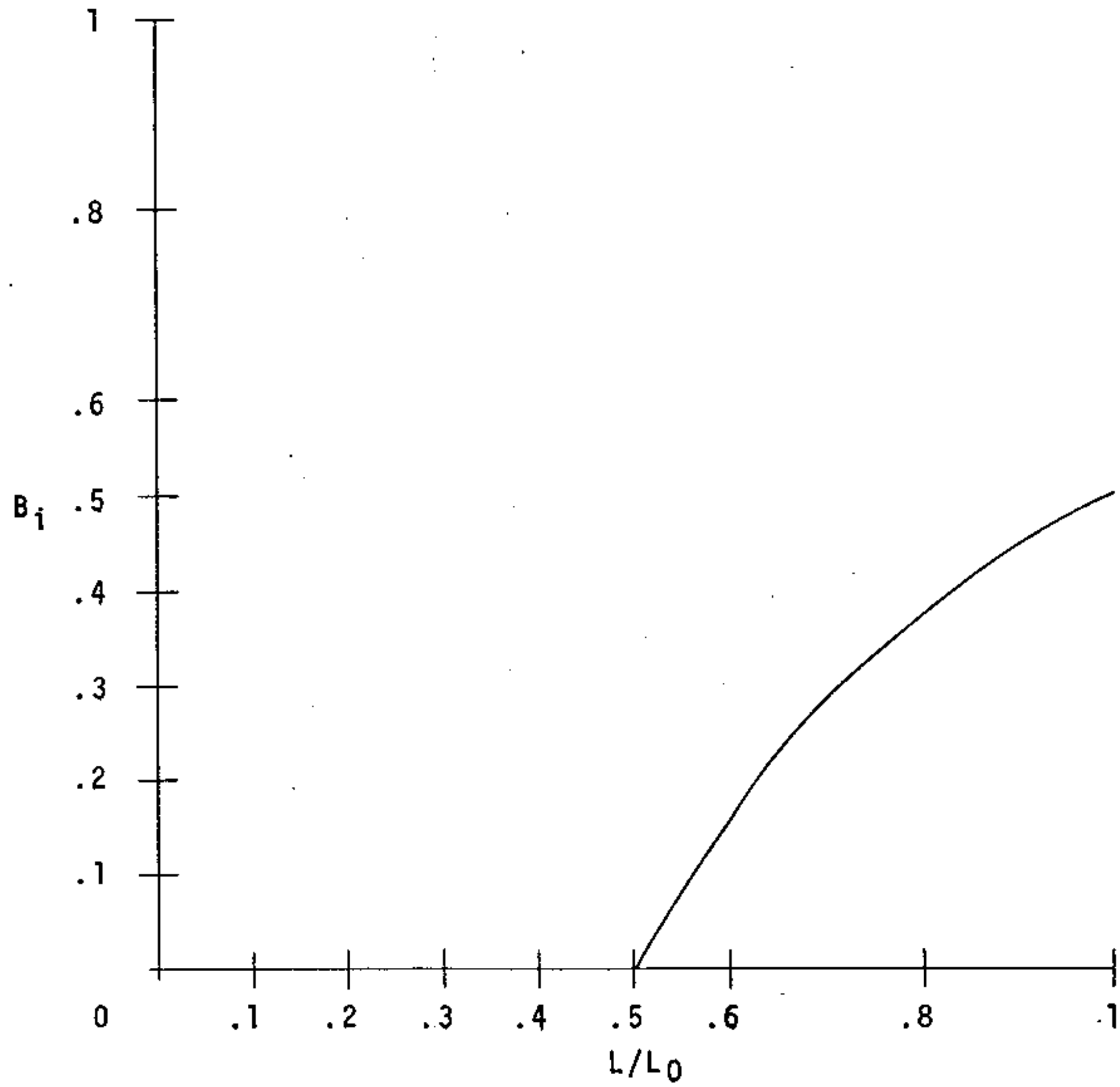



Fig. II-2. Insertion Length vs. Penetration Field [$H_c$] in the intermediate state.

Fig. II-4. Insertion Length vs. Amount Normal. To obtain this from the above, the ordinate is read as (amount normal/ initial amount superconductive), ie, $V_n/V_{tot}$.

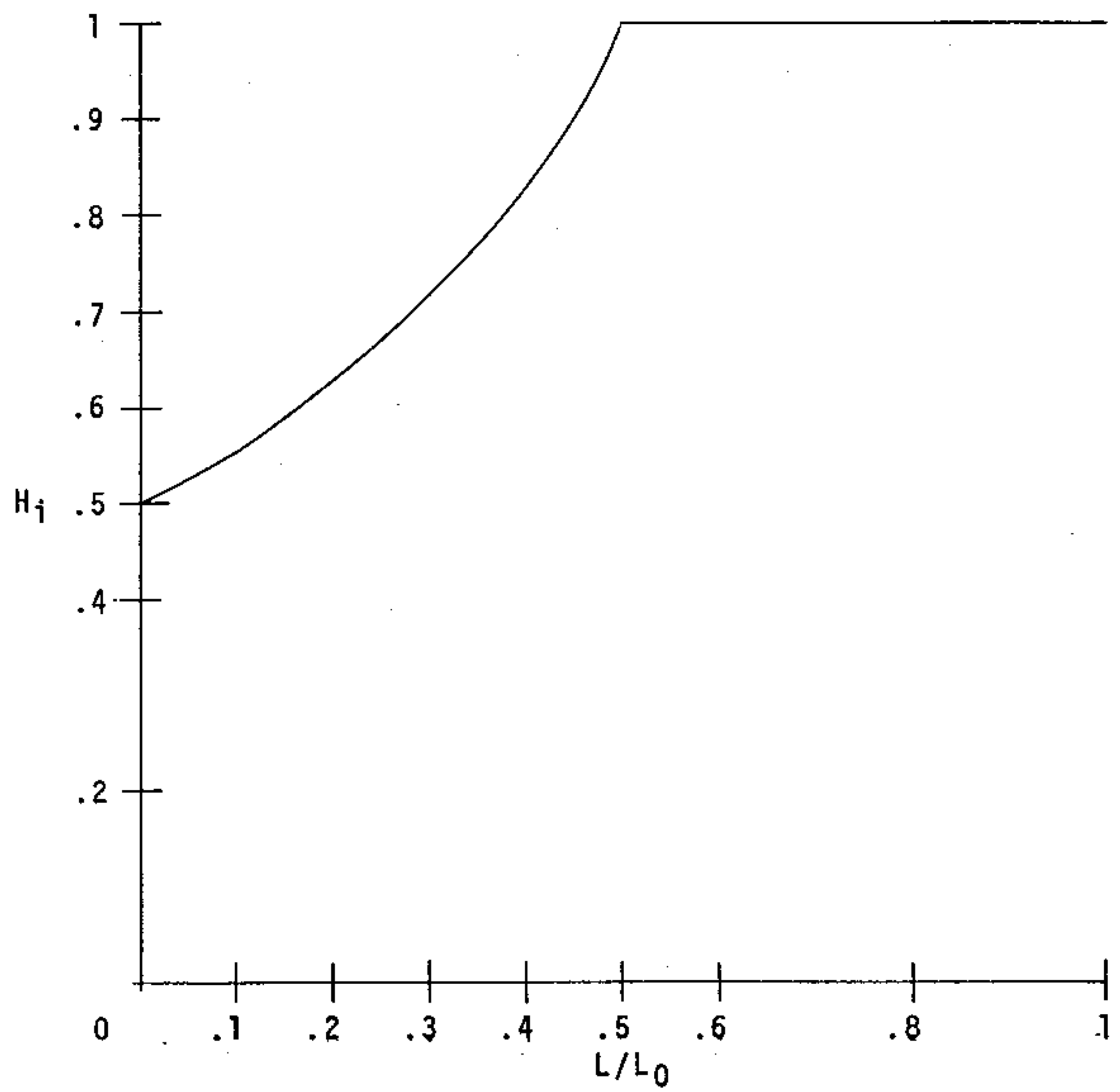



Fig. II-3. Insertion Length vs. Flux Density between the leading edge of the slab and prism wall.

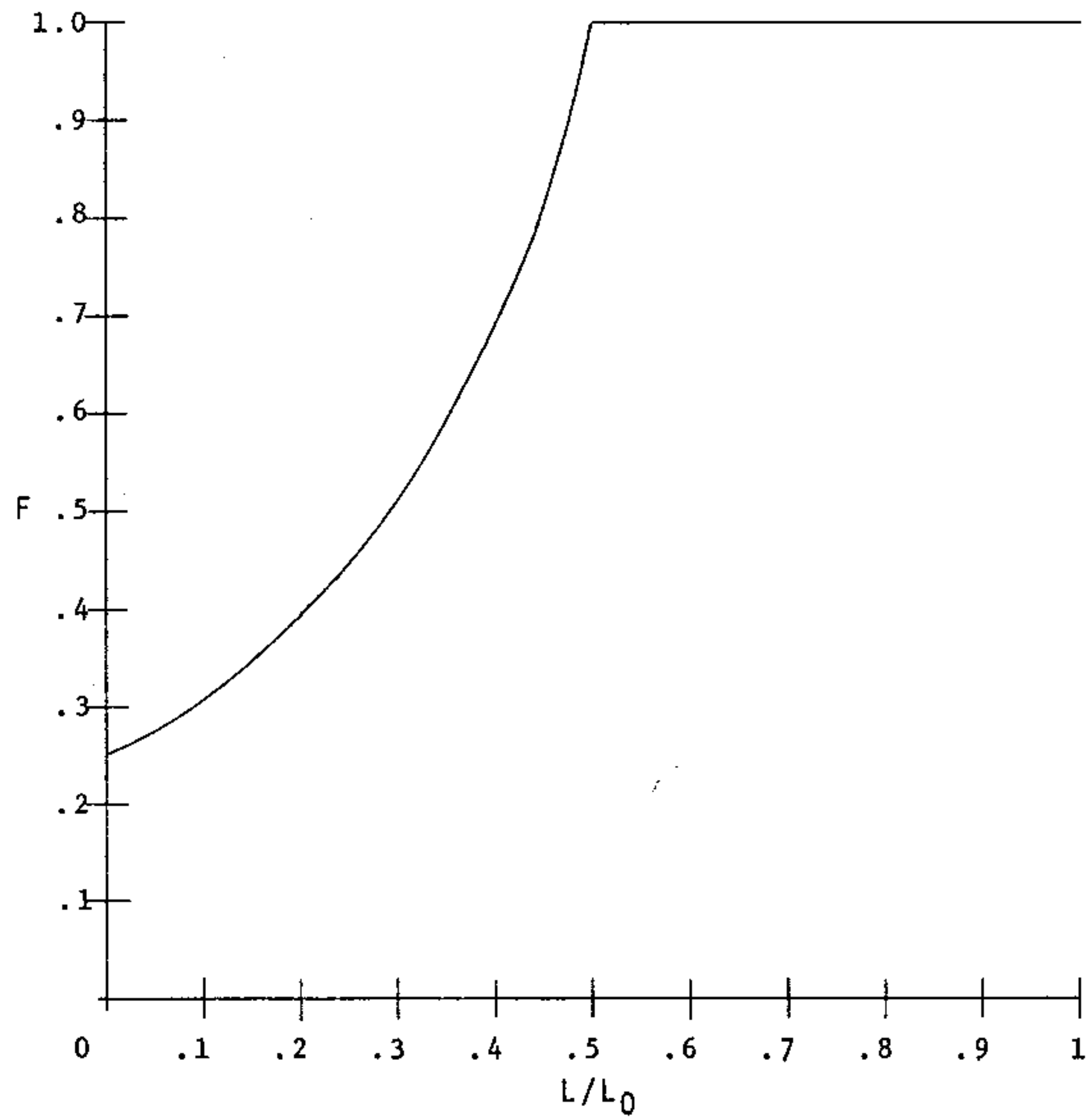



Fig. II-5. Insertion Length vs. Force, [$H_c^2/8\pi$ dynes/cm$^2$].

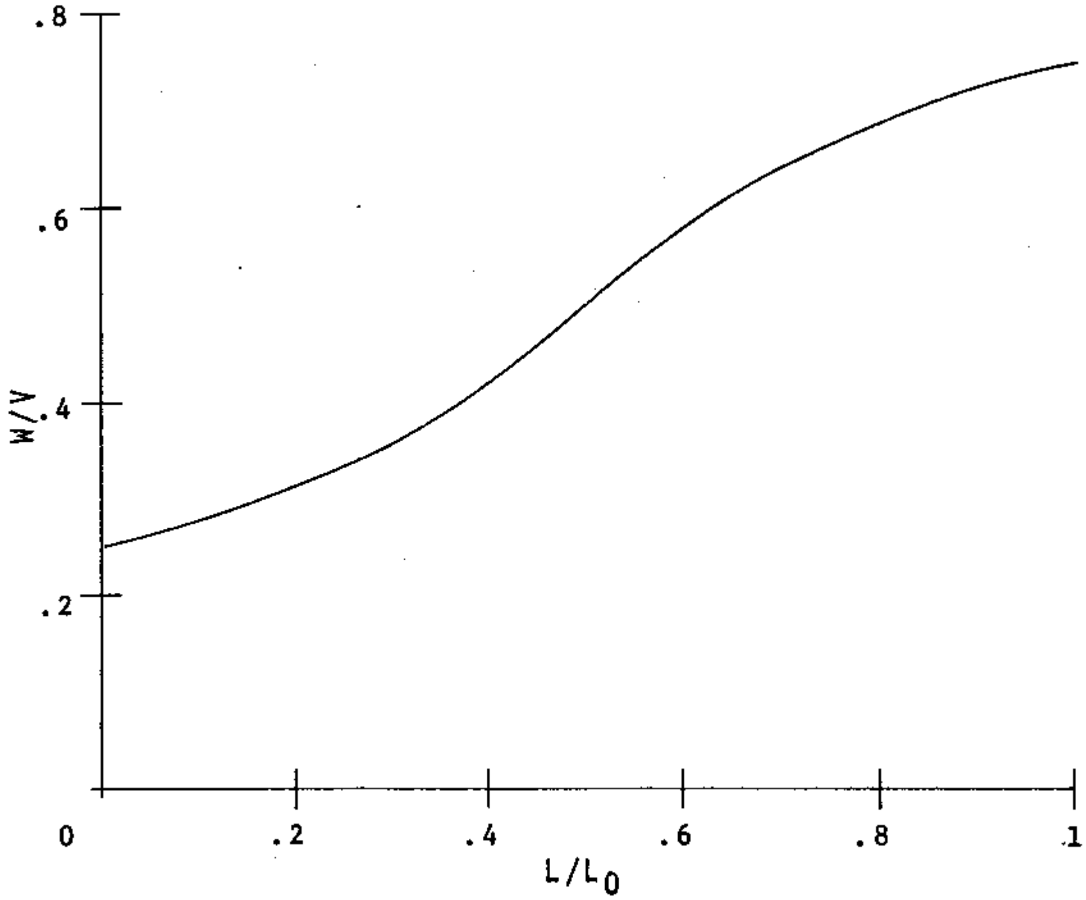



Fig. II-6. Insertion Length vs. Work per Unit Volume, $[H_c^2/8\pi$ ergs/cc].

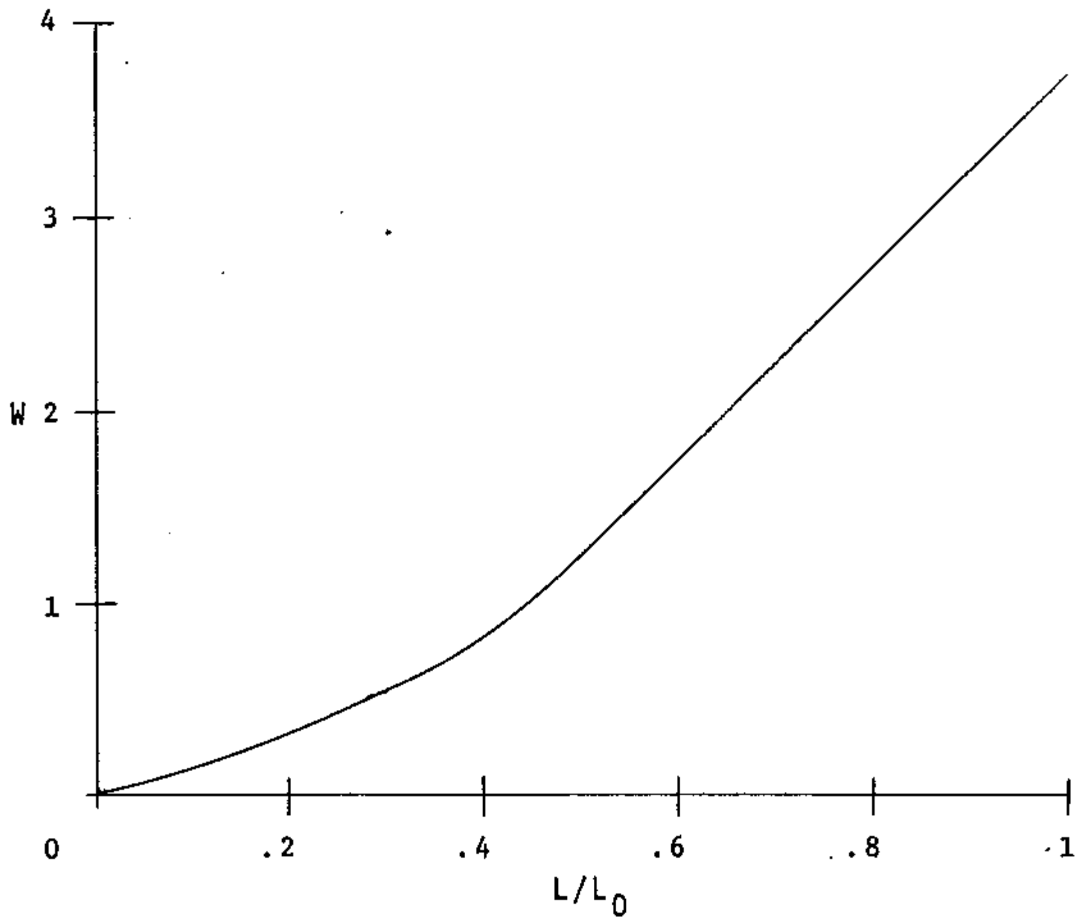
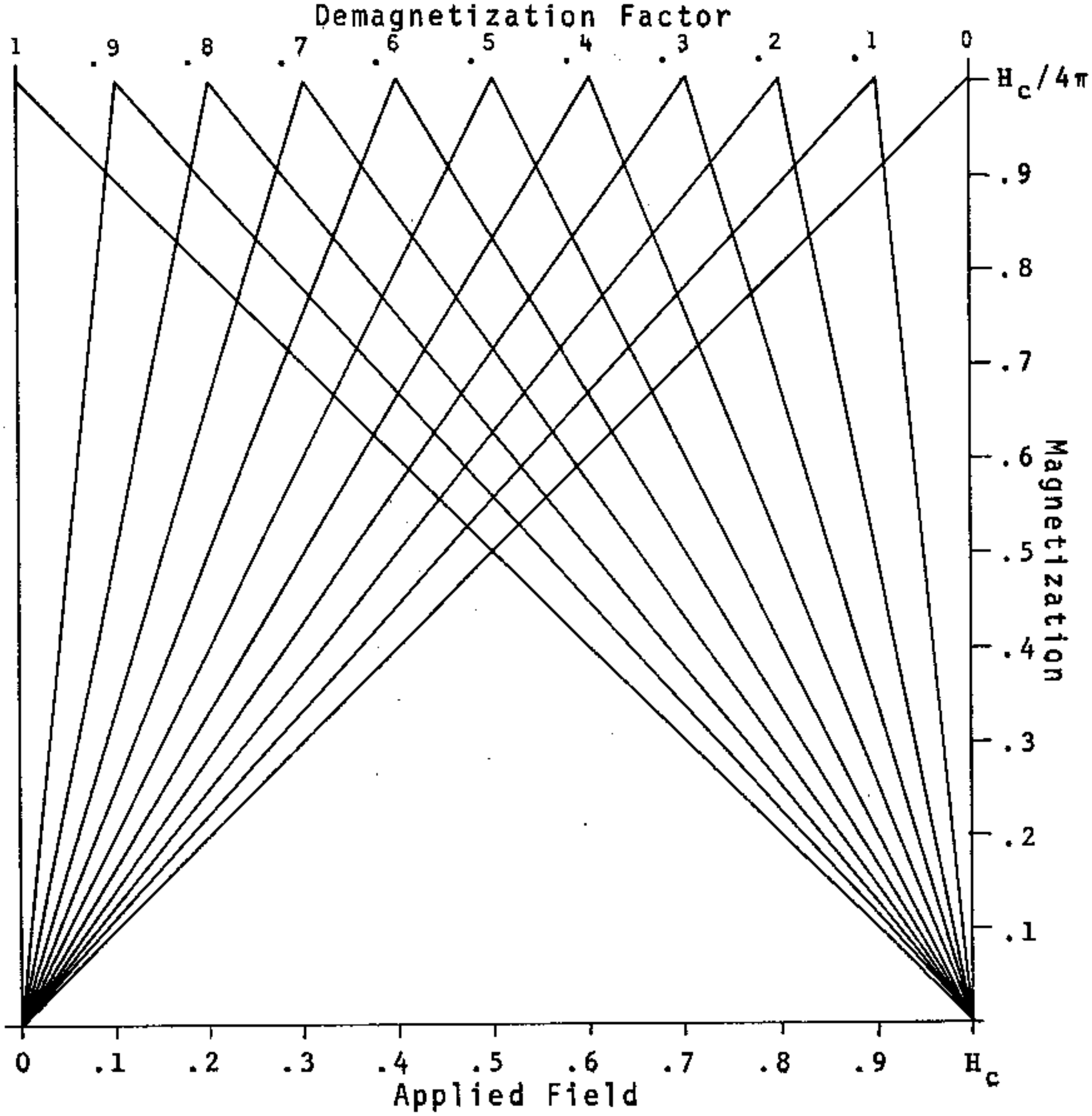



Fig. II-7. Insertion Length vs. Work [$H_c^2/8\pi$ ergs].

Fig. II-8. Magnetization Curves.



A COMPARISON OF MAGNETO-MECHANICAL & THERMODYNAMIC DATA:

$H_a = .5H_c$

| N | Magneto-Mechanical | Thermodynamic |
|---|---|---|
| 0 | .25000000 | .250000 |
| .1 | .27765745 | .277750 |
| .2 | .31235162 | .312500 |
| .3 | .35695416 | .357142 |
| .4 | .41641679 | .416665 |
| .5 | .49965020 | .500000 |
| .6 | .58306938 | .582670 |
| .7 | .64264792 | .642857 |
| .8 | .68732810 | .687500 |
| .9 | .72207714 | .722000 |
| 1.0 | .74987499 | .750000 |

Fig. II-9. A comparison between the experimental results with the area under magnetization curves. Units: $H_c^2/8\pi$ ergs/cm$^3$.

THE IDEAL FIELD INDUCED TRANSITION

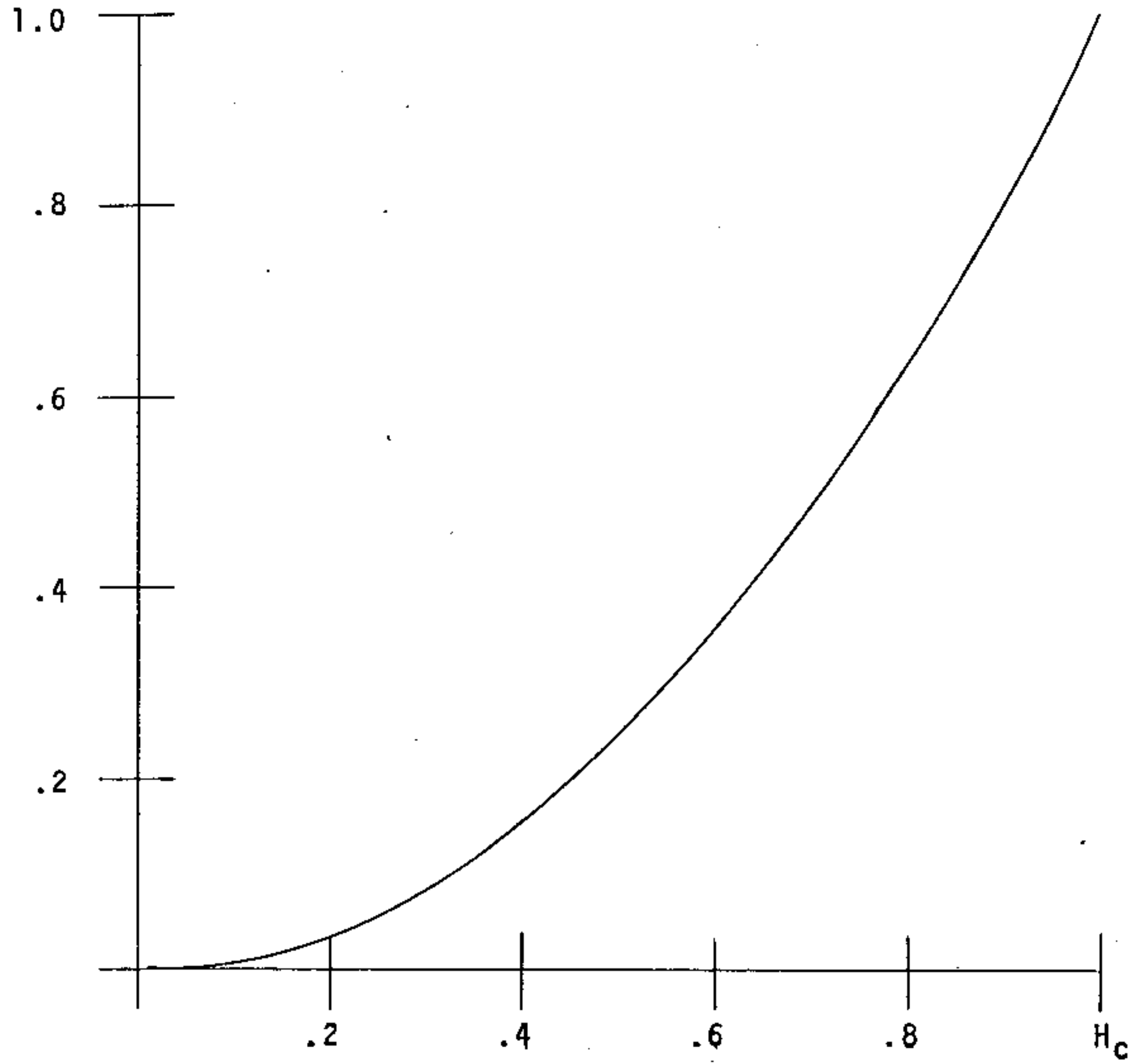



Fig. II-10. Applied Field vs. Work [$H_c^2/8\pi$ ergs/cc].

$$W = 1/4\pi \int_0^{H_c} H_a \, dM \cdot V$$

THE IDEAL FIELD INDUCED TRANSITION

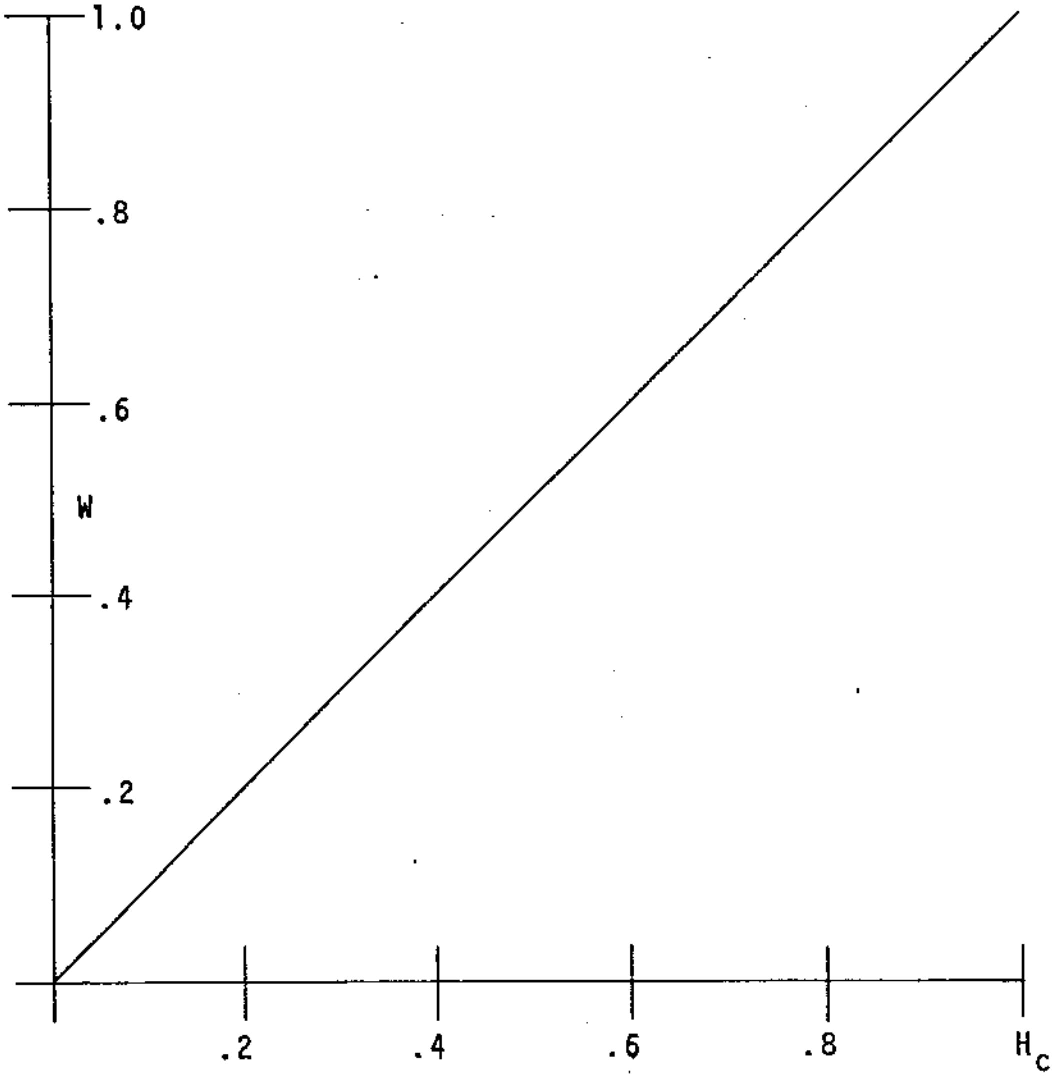



Fig. II-11. Applied Field vs. Work @ $H_a$ [$H_c^2/8\pi$].
(instantaneous values)

## III. The Experiment: Part II: The Magneto-Calorics:

### A. Procedure:

The slab is now entirely inserted in the prismatic volume. Presently, the field of penetration is equal to the applied field, .5Hc, one-half the volume is normal, and the work so far accrued toward normalization is $.75Hc^2/8\pi$ per unit volume.

The ambient temperature in the cryostat has throughout the entire foregoing experiment been kept constant at 0°K. The field intensity has also been constant and will remain at .5Hc. The temperature will now be allowed to rise at the slow rate of .01°K per second. This is easily effected by limiting the cooling capacity of our refrigeration equipment so that heat seepage into the inner cryostat chamber barely exceeds that removed, by a controlled amount.

As the temperature rises we expect that more material will become normal and, assuredly, some form of thermal energy will have to be utilized to accomplish this transition.[a]

### B. Analysis:

We wish to examine the precise work that will be necessary to normalize the superconductive slab while it is in the constant applied field of .5 Hc, while the temperature increases to the critical value.[b] There are various other attendant occurrences, however, which warrant our attention: (A) the specific heat change with temperature, (B) the latent heat change, and (C) the change of superconductive volume within the slab. We will examine each of these with the same rigor that will be applied to the work and work per unit volume functions.

A) The Specific Heat as a Function of Temperature:

Discussion:

The specific heat or heat capacity of a substance is unique to the material and varies depending on the variable held constant, ie, volume, pressure, etc.[c] The heat capacity is a measure of the amount of heat which must be supplied to raise the temperature of a sample a certain number of desired degrees. The heat influx is a form of work or thermal energy which is given to the sample, thereby imparting a "potential" energy[d] called "temperature".

In our case, the variable held constant is the applied field strength. This has value to us because pressure and volume in a superconductor essentially do not change with temperature, however, magnetization does. (A gas would be just the opposite.)

We are only concerned with a difference between the specific heats of the normal and superconductive phases. The heat required to raise the temperature of a superconductor compared to that required to raise the temperature of the same substance while normal, in a strong magnetic field which drives it normal, should equal the difference in free energies between the respective states. This is exactly what we seek to know. We are then really finding: Cn-Cs.

We know from the earlier section that a superconductor can do magnetic work, on the order of $Hc^2/8\pi \cdot V$. So that a difference in entropy must exist between the normal and superconductive states on the order of: (See derivation in section on Physics)

$$Sn-Ss = -(1/8\pi)\cdot(dHc^2/dT).$$

The specific heat is just $T/dT\cdot(Sn-Ss)$ and we obtain:

$$Cn-Cs = -(T/4\pi)\cdot(Hc\cdot(d^2Hc/dT^2)+(dHc/dT)^2)\cdot V.$$

As was indicated in the early remarks contained in the section on Physics, the critical field and temperature are given by a parabola: (The Tuyn Curve).

$$Hc = Ho(1-T^2/Tc^2),$$

where Hc is the critical field at an applied temperature, Ho is the critical field at 0°K, T is the applied temperature, and Tc is the critical temperature at zero gauss. Making use of this relationship, we know the change of Hc with T, ie, dHc/dT, and we obtain:

$$Cn-Cs = (Ho^2/2\pi Tc)\cdot(T/Tc-3(T/Tc)^3)\cdot V.$$

It has been found[1] that particular elements deviate slightly from this relationship. These variations may be described by:

$D(T) = (H_c - H_{cp})/H_o$,

where $H_c$ is the experimentally observed critical value at some applied temperature and $H_{cp}$ is that computed via the parabolic law at the same temperature. Actual deviations have never been observed to be greater than a few percent. We will anticipate that the Tuyn Parabolic Law satisfies adequately our need to know $dH_c/dT$.

We might note that at $T = T_c$, there is a discontinuity in the specific heat since $C_n - C_s = -(T_c/4\pi)\ (dH_c/dT)^2\ V$. (This is the so-called Rutger's formula.) By Tuyn's Law we can see that $dH_c/dT$ is finite at $T_c$, so that there is a finite difference between the respective heats. Microscopically, a large number of superconductive electron pairs are breaking up in this region of temperature and since each requires a small amount of energy to become normal ($3.52kT_c$), the specific heat of the superconductive phase is very large compared to that of the normal state. See Appendix B-2.

Data: See Figures III-1 and III-2

It was found that as the temperature increased from 0°K, the heat capacity of the superconductive phase was less than that of the normal phase. This was because of the difference in the electronic specific heats, which, in the case of the superconductor, depends on the number of Cooper, or super-electron, pairs. Once a pair is formed its entropy is zero and it contributes nothing to the specific heat. A very large number of pairs are created near $T_c$, so that in the vicinity of 0°K there are very few normal electrons in the superconductive phase and the normal phase actually has a higher heat capacity.

At T = .577°K the sign of the specific heat changed, indicating that now the heat capacity of the superconductive state exceeded that of the normal state, as more Cooper pairs switched to normal electrons.

Finally, at $.7071T_c$°K the specific heat went to zero, indicating that the superconductive and normal phases were of the same heat capacity, ie, the superconductive state had transformed into the purely normal state.

Maxima were recorded at T = $.3T_c$°K (.00000785 ergs) and T = $.65T_c$°K (-.00000186 ergs). Minima were recorded at T = 0°K, T = .577°K, and T = $T_c$°K.

Below $.577T_c$°K heat into the sample was less than that of the normal state, above this value heat in exceeded that of the normal state. Net and cumulative heats will be discussed as per the work functions.

B) Latent Heat as a Function of Temperature:

Discussion:

A heat of transition is generally required to effect a phase change. Water for instance requires a heat of fusion on the order of 79.7 cal./gm. in order to change from the solid to the liquid phase at 0°C. Generally, this requirement is brought about due to the nature of the chemical bonding which is quite different between any two phases under consideration and which allows for an entropy difference in the form of "molecular order" between states.

In a superconductor, the latent heat of transition occurs when a difference in the entropies between the normal and superconductive states is present. This transpires when the "electronic order" of the respective states is different and comes about by the introduction of a magnetic field. This causes the Cooper pairs to circulate in macroscopic concert; the net effect being to supply energy to them to exclude the field.[e]

Ordinarily, in the absence of a field the pairs split and become normal as heat is supplied, so that at $T_c$ there are no pairs left and the entropies of the two states are equivalent. However, if a field is applied:

$$S_n - S_s = -(1/8\pi)\cdot dH_c^2/dT.$$

and depending on the field at which transition occurs, a latent heat should be exhibited.

The latent heat is just $Q = T(S_n-S_s)$, so (See Physics)

$Q = -(T/4\pi)\ H_c(dH_c/dT)\ V.$

Again referring to Tuyn's Law:

$S_n-S_s = (H_o^2/2\ T_c)\ (T/T_c-(T/T_c)^3)$, and

$Q = (TH^2{}_c/2\ T_c)\ (T/T_c-(T/T_c)^3)\ V.$

Data: See Figures III-3 and III-4.

The latent heat was seen to increase from zero at 0°K to -.00005625 ergs as the material in the sample changed from the superconductive to the normal state. The heat was negative, that is, this was a heat influx into the sample. The entropy of the normal state being greater than that of the superconductive meant that the sample would cool upon this transition. We maintained the instantaneous temperature constant, however, so that a heat additional to that of the specific heat was necessary to raise the temperature of the slab. The curve of latent heat versus temperature indicated an exponential relationship.

C) Change in Superconductive Volume as a Function of Temperature:

Discussion:

A sample in the pure superconductive state will completely exclude an applied field until somewhere on the surface the field reaches $H_c$; the intermediate state then occurs in higher applied fields, until the entire material is normal at $H_c$.[f] With the onset of the intermediate state, from the section on mechanics, we have that the amount superconductive decreases with increase in the numerical value of the demagnetization factor.[g] The intermediate state contains normal regions through which flux of a density of $H_c$ may pass. Generally, in the intermediate state the amount normal varies linearly with the field according to the penetration flux, which is directly dependent not only on N but also $H_a$, while $H_c$ is constant.

In our case, N is a constant, numerically equal to 1, and so is $H_a$, which is equal to $.5H_c$ gauss. However, as the temperature is increased, according to Tuyn's law the critical field must decrease from its maximum at 0°K. But, the equation for penetration flux is useless at N = 1 for this purpose[i] and we must seek a relationship between $H_c(T)$ and $H_c$ at 0°K.[j]

We have by Tuyn's Law:

$$H_c(T) = H_c(1-(T/T_c)^2),$$

so that at any applied temperature we know the new critical field. Taking the ratio of this value to the applied field yields:

$$H = H_a/H_c(T).$$

The volume superconductive is then just:

$V_{sc} = V(1-H)$,

where V is the total volume in the field.

Data: See Figures III-5 and III-6

It was found that the volume superconductive decreased exponentially with increased temperature, being a maximum at 0°K and minimum at $.7071T_c$°K = $T_c$ at $H_a$.

D) Caloric Work as a Function of Temperature:

Discussion:

In the previous section on the mechanical works, we found that the total accrued work of insertion was $.75H_c^2/8\pi \cdot 5$ cc. In order to normalize fully our sample, we naturally expect that from "somewhere" in the process of heating the slab above the transition temperature, a work of $.25H_c^2/8\pi \cdot 5$ cc will be done so that the total work input might be the thermodynamic value of $H_c^2/8\pi \cdot 5$ cc. To this end, we suspect the specific and latent heats as the agencies by which this requirement can be fulfilled.[k]

The work, then, which is associated with the rise in temperature of the slab while in a magnetic field of $.5H_c$ gauss, is of a thermal nature due to a combination of (A) specific and (B) latent heats. We will consider these separately and collectively.

Data: See Figures III-7 and III-8

(A) The specific heat was seen to be a net positive heat as compared to that of the normal state. As the temperature increased, the superconductive volume, upon which this function is based, decreased. Above .577°K the net accumulated specific heat began to decrease, in accord with the earlier discussion. The final value was found to be: .6815 ergs/5 cc at $.7071T_c$°K.

(B) The latent heat, which depended upon the change of superconductive volume to normal material, increased exponentially. The net accrued heat was at all times negative and finally amounted to: -1.9315 ergs/5 cc at $.7071T_c$°K.

In combination, the specific heat was seen to be a net positive and the latent heat a net negative quantity. The latent heat, which at low temperature was numerically far inferior to the specific heat, increased in relative value at higher temperatures; so that at $.577T_c$°K the net heat input was exactly zero. Above this temperature all heats were negative and finally at $.7071T_c$°K, which was the critical temperature at $.5H_c$, according to Tuyn's Law, the net heat was: -1.2501 ergs/5 cc, or $.25H_c^2/8\Pi$ ergs per cubic centimeter, as required.

NOTES AND REFERENCE:

a. We assume that if we are going to normalize the slab work must be done, and the only thing we are doing is changing the temperature.

b. The critical value in this field is only $.7071T_c$°K.

c. In any case differences in heat capacities depend on whether any mechanical work is done, such as in $C_p$, in the process of heating.

d. This potential energy is usually in the form of kinetic motions of the atomic constituents in the material in question.

e. Notice that in the derivation for the specific heat, a latent heat and magnetic term were present. Assuming that a superconductor remains normal well below $T_c$ due to a field, then some thermal work involved in $C_n$-$C_s$ is lost. This is made up for by the latent heat and magnetic work when the substance undergoes transition, or solely by magnetic work if it does not.

f. This $H_c$ is for the entire volume occupied by the sample.

g. $H_a$ remains constant. This circumstance is peculiarly absent in the literature.

h. This maximum at 0°K is the highest field at which superconduction can take place. $H_c$ = 0 gauss at $T_c$.

i. We had been using N as the bellwether for information on the amount normal, since flux penetration depended on it. Now N is a constant as is $B_i$ so we can no longer proceed this way. Essentially, the experiment is changed.

j. We know that the actual critical field is going to get lower with increased T. This situation must be the underlying basis of the volume change since as the field gets closer to our applied field value, the normal volume must get closer to its maximum value that it will attain at $T = T_c$, ie, 100 percent of the volume in the field.

k. As far as we know, these are the only heats present. Some others, possibly unique to the Meissner Effect, can not at this point be ruled out, however, without experimental verification.

1. D.K. Finnemore, D.E. Mapother, and R.W. Shaw. Physical Review. Volume 118. No. 1, April 1, 1960. Pp. 127-129.

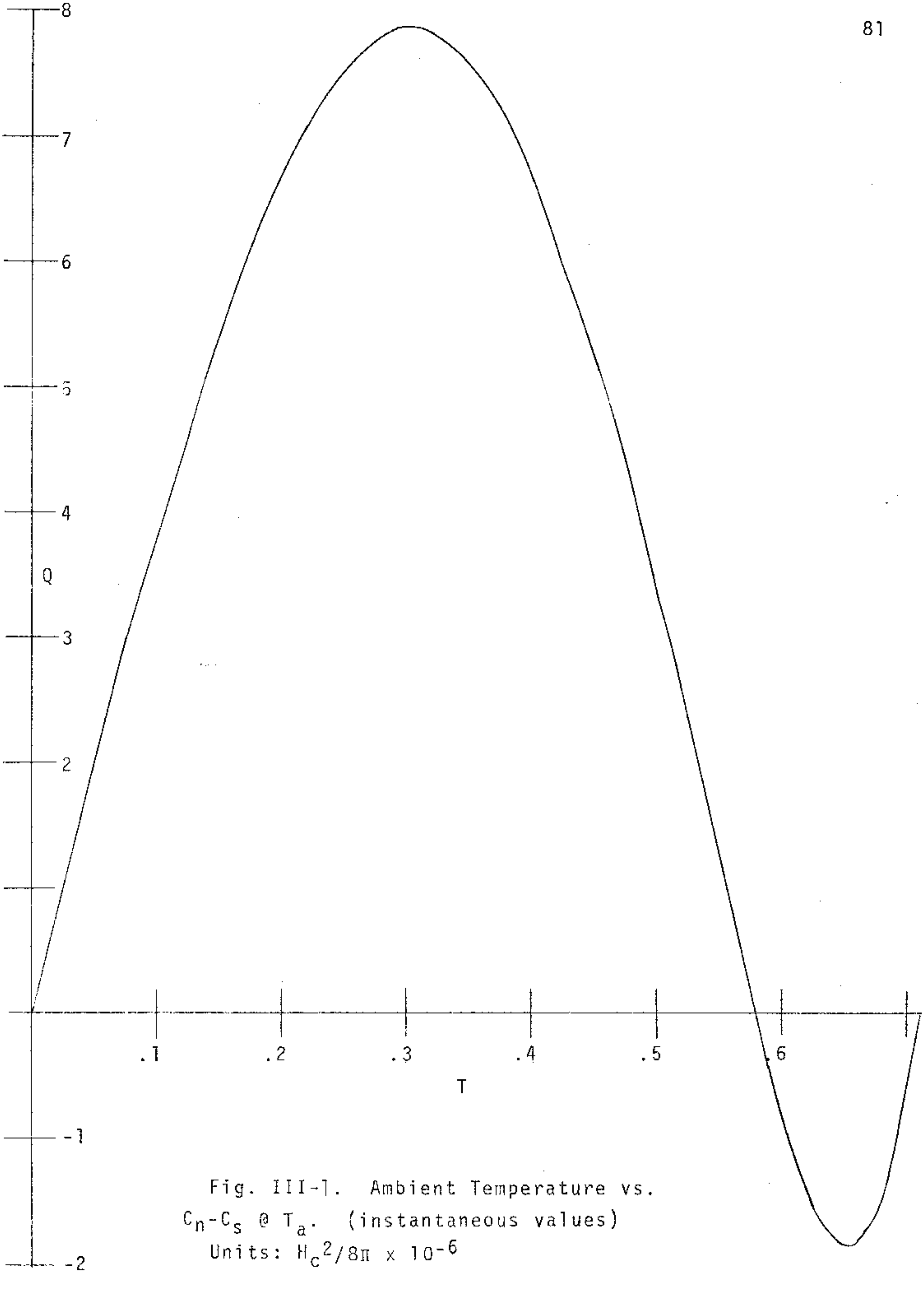



Fig. III-1. Ambient Temperature vs. $C_n - C_s$ @ $T_a$. (instantaneous values) Units: $H_c^2/8\pi \times 10^{-6}$

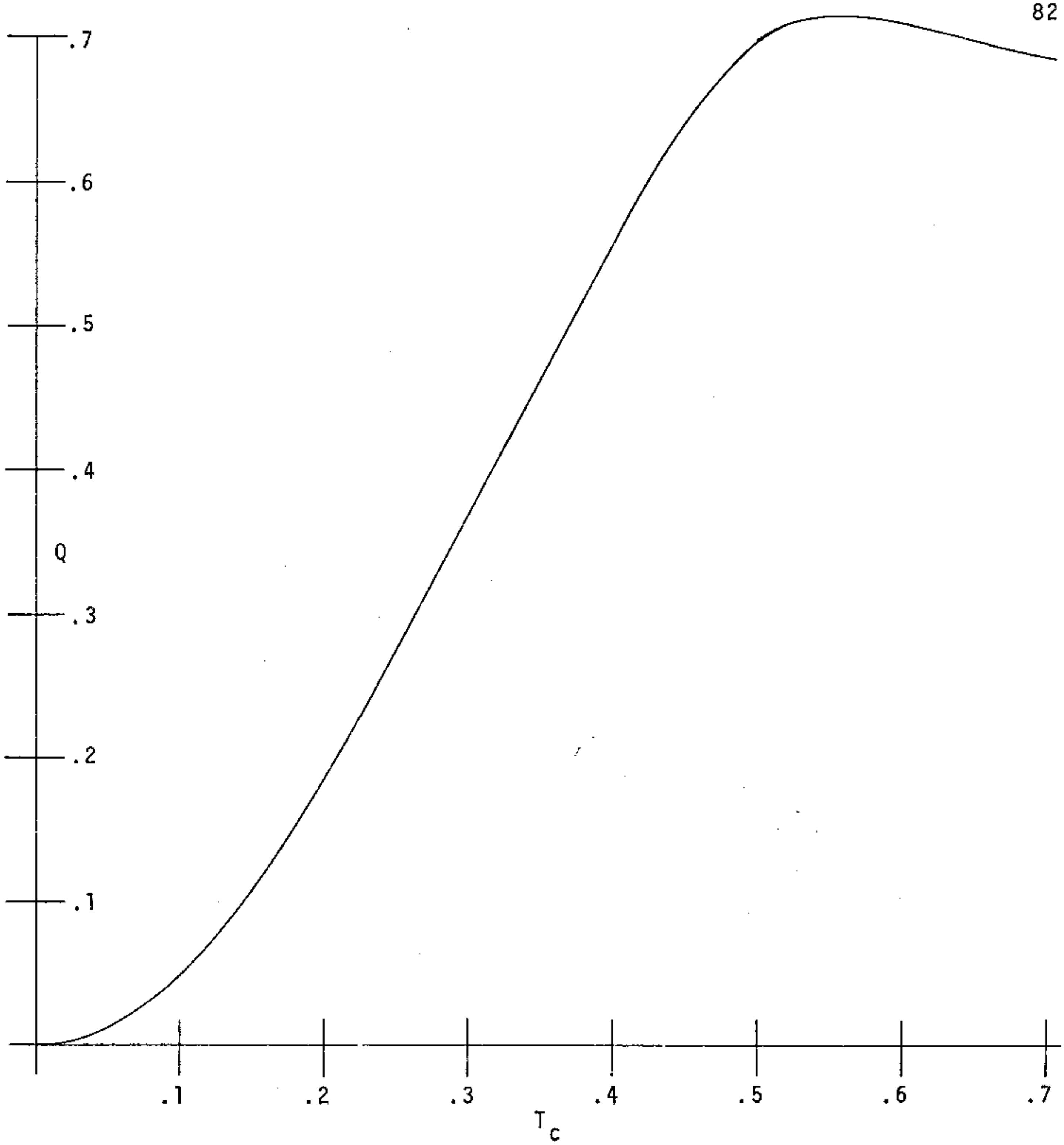



Fig. III-2. Ambient Temperature vs. Specific Heat.

$C_n - C_s = H_o^2/2\pi T_c \cdot [T/T_c - 3(T/T_c)^3] \cdot V$

Sign of $C_n - C_s$ changes @ $T_c/\sqrt{3} \approx .577T_c$

Units: $H_c^2/8\pi$

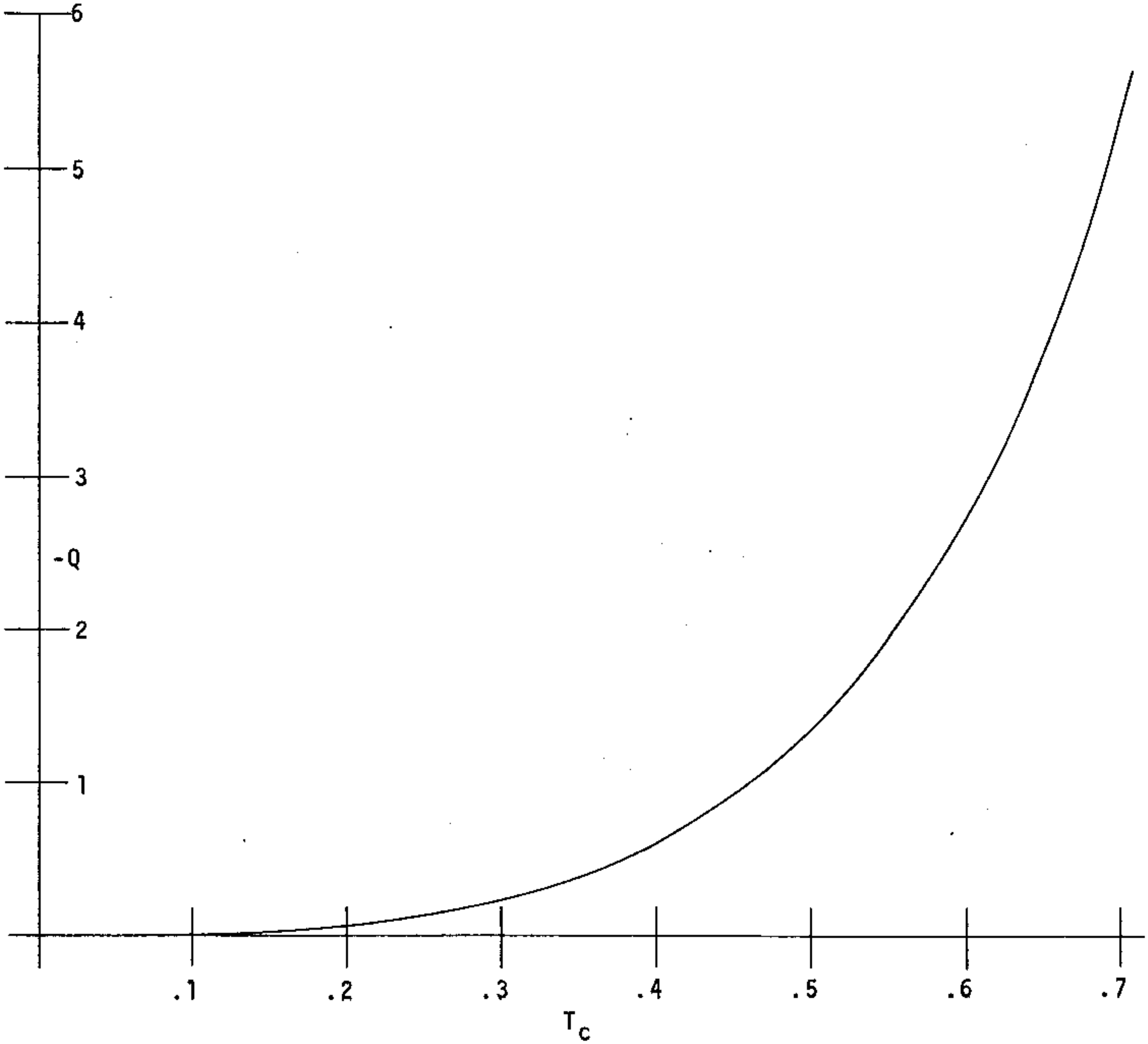



Fig. III-3. Ambient Temperature vs. Latent Heat @ $T_a$.
(instantaneous values) $-[H_c^2/8\pi \times 10^{-5}]$

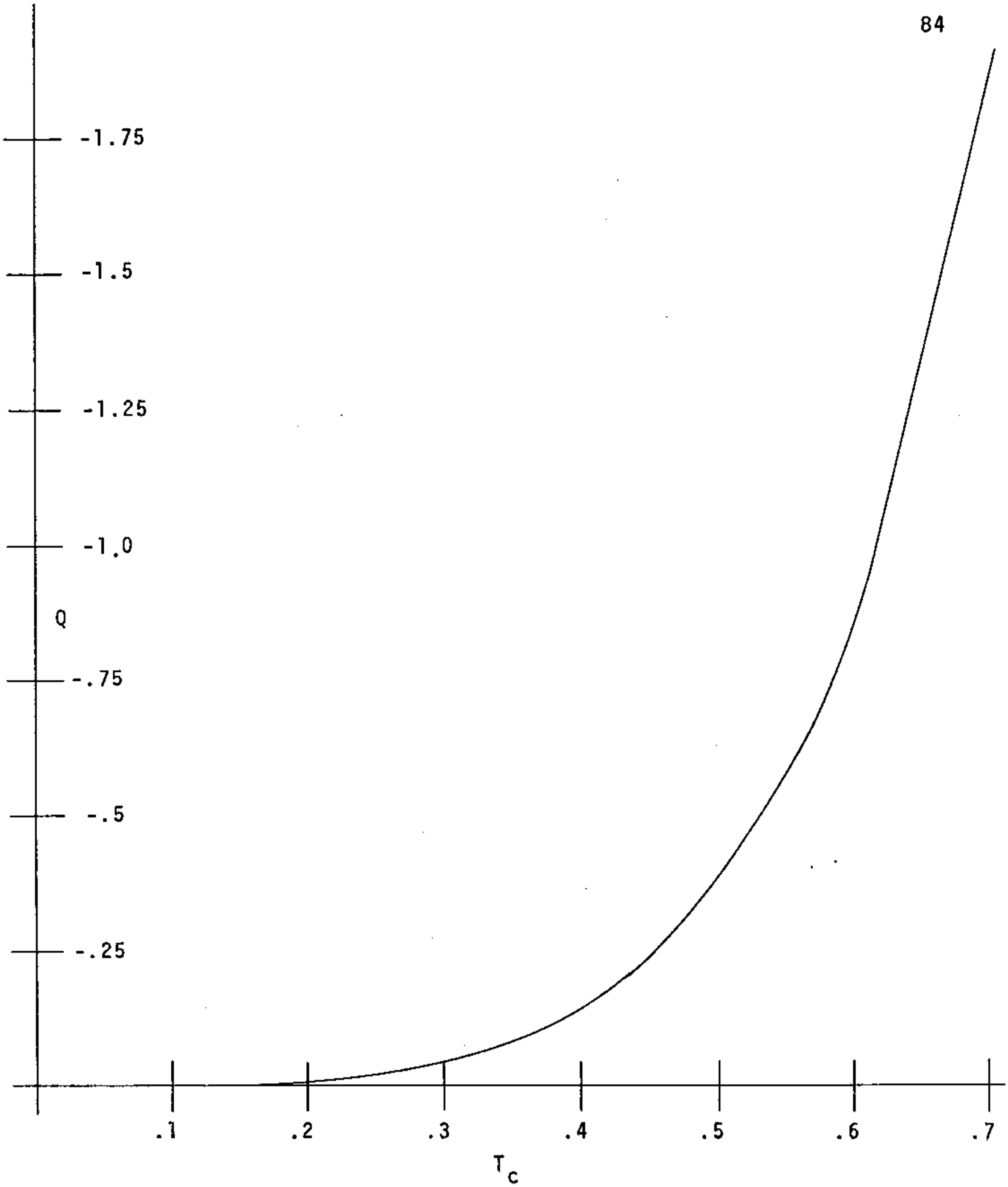



Fig. III-4. Ambient Temperature vs. Latent Heat $[H_c^2/8\pi]$.
$Q = T(S_n - S_s) = T \cdot H_c^2/2\,T_c \cdot [T/T_c - (T/T_c)^3] \cdot \Delta V.$

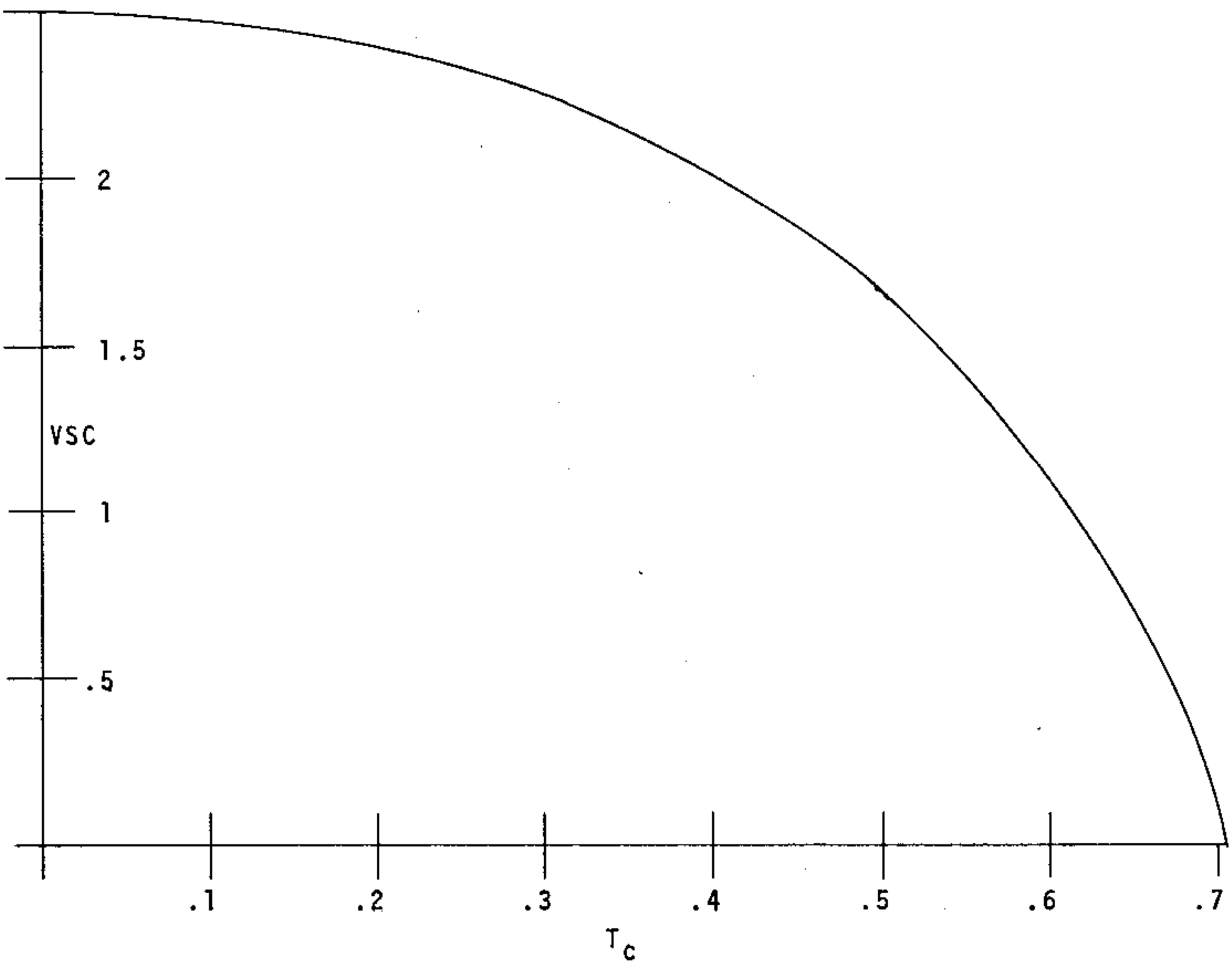



Fig. III-5. Ambient Temperature vs. Volume Superconductive [cc.].

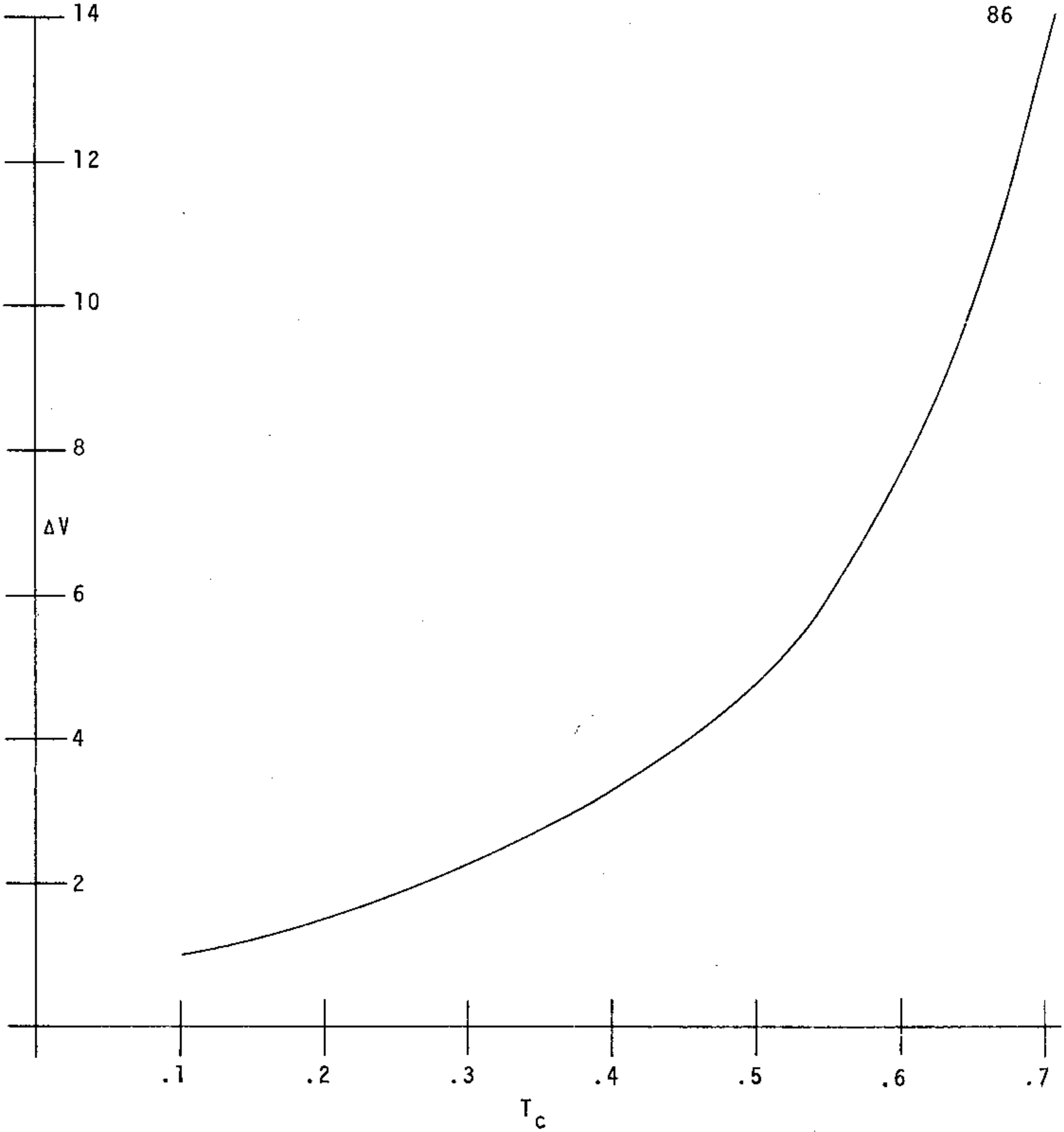



Fig. III-6. Ambient Temperature vs. Change in Superconductive Volume in cc.

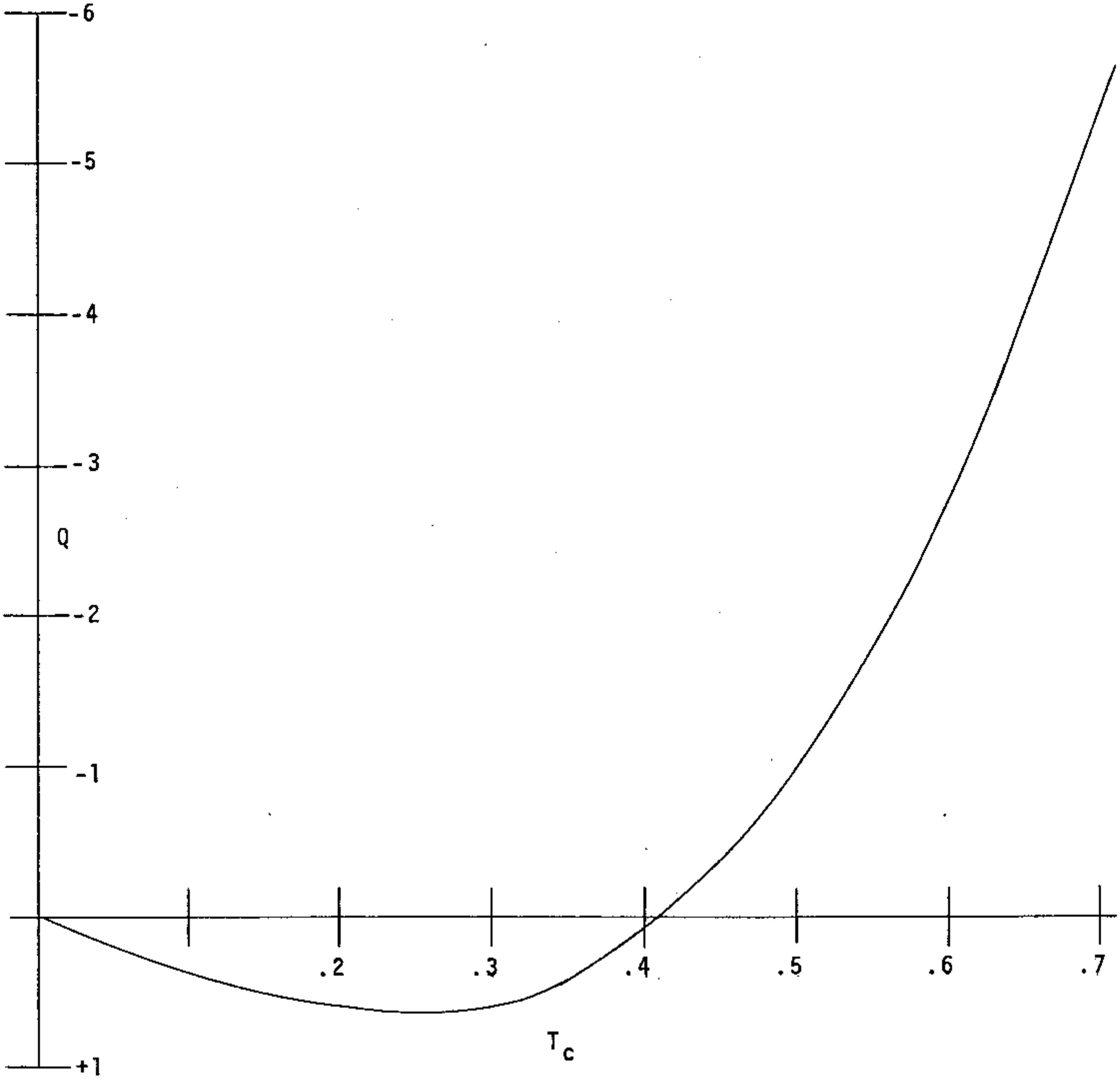



Fig. III-7. Ambient Temperature vs. Net Q : $C_n$-$C_s$ + L.H. @ $T_a$ (instantaneous values)
Units: $H_c^2/8\pi \times 10^{-5}$

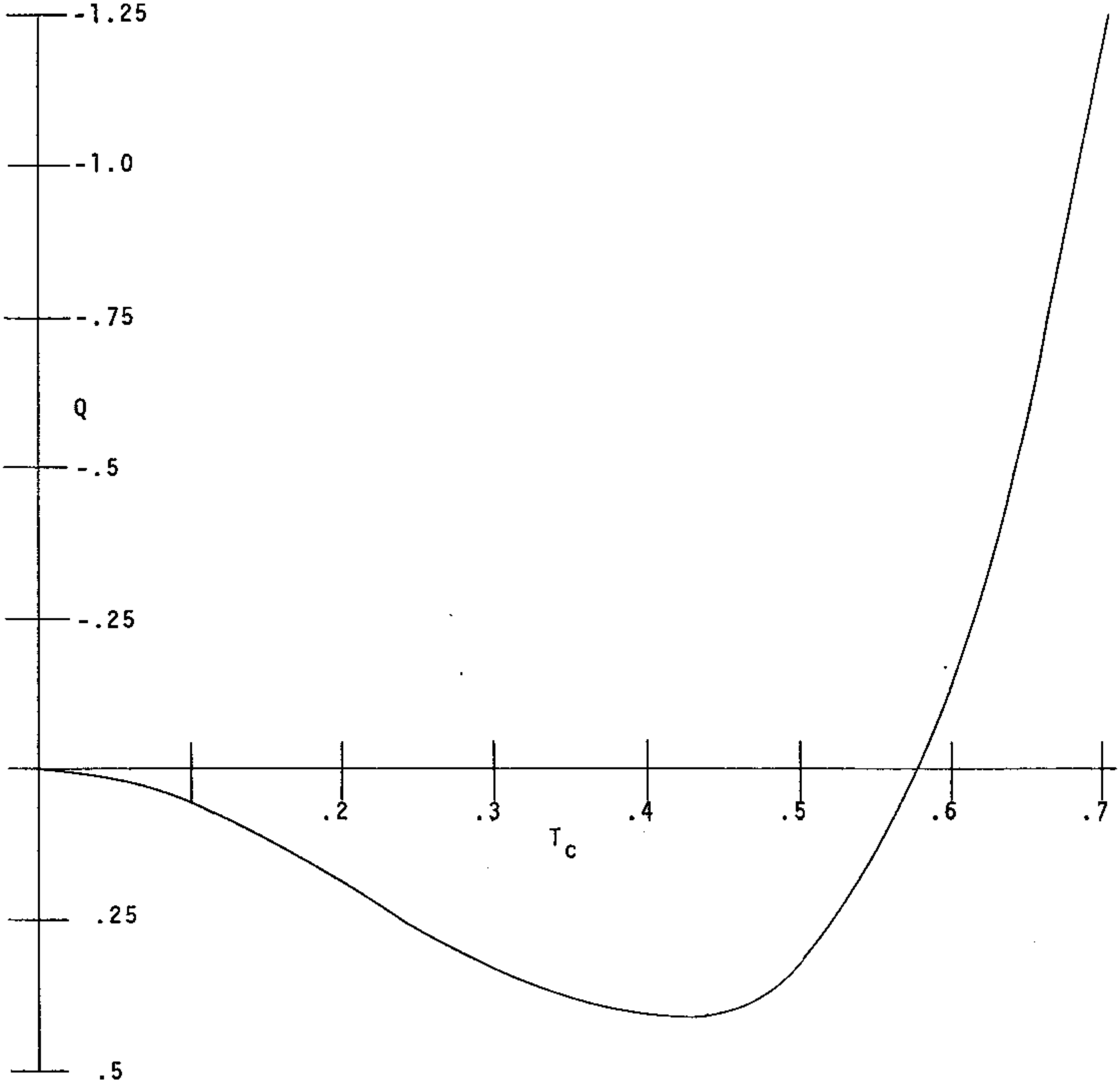
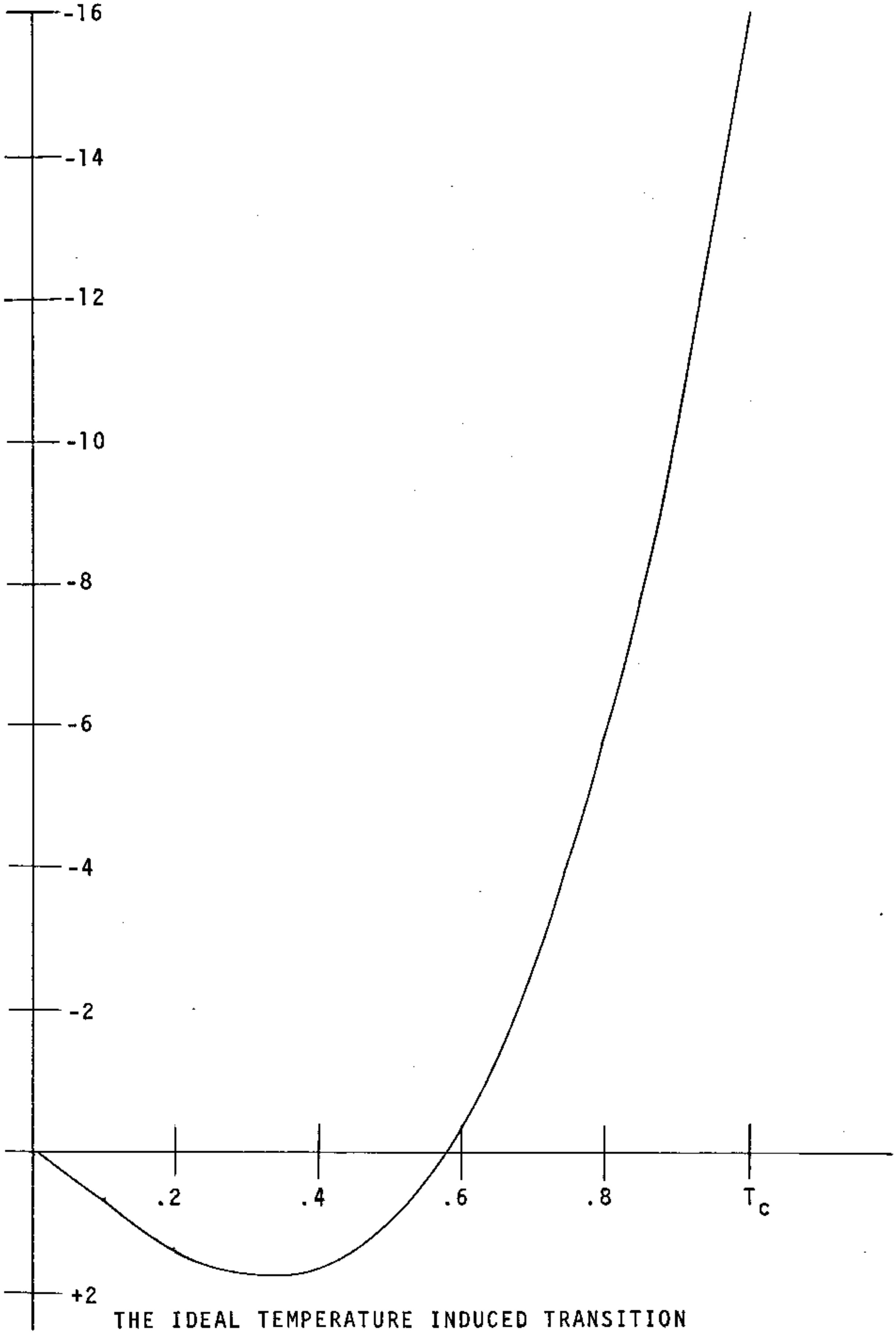



Fig. III-8. Ambient Temperature vs. Total Q: $C_n - C_s$ + L.H. $[H_c^2/8\pi]$




THE IDEAL TEMPERATURE INDUCED TRANSITION

Fig. III-9. Ambient Temperature vs. $Q = T(C_n - C_s)$: $[H_c^2/8\pi \times 10^{-5}]$ (instantaneous values)

THE IDEAL TEMPERATURE INDUCED TRANSITION

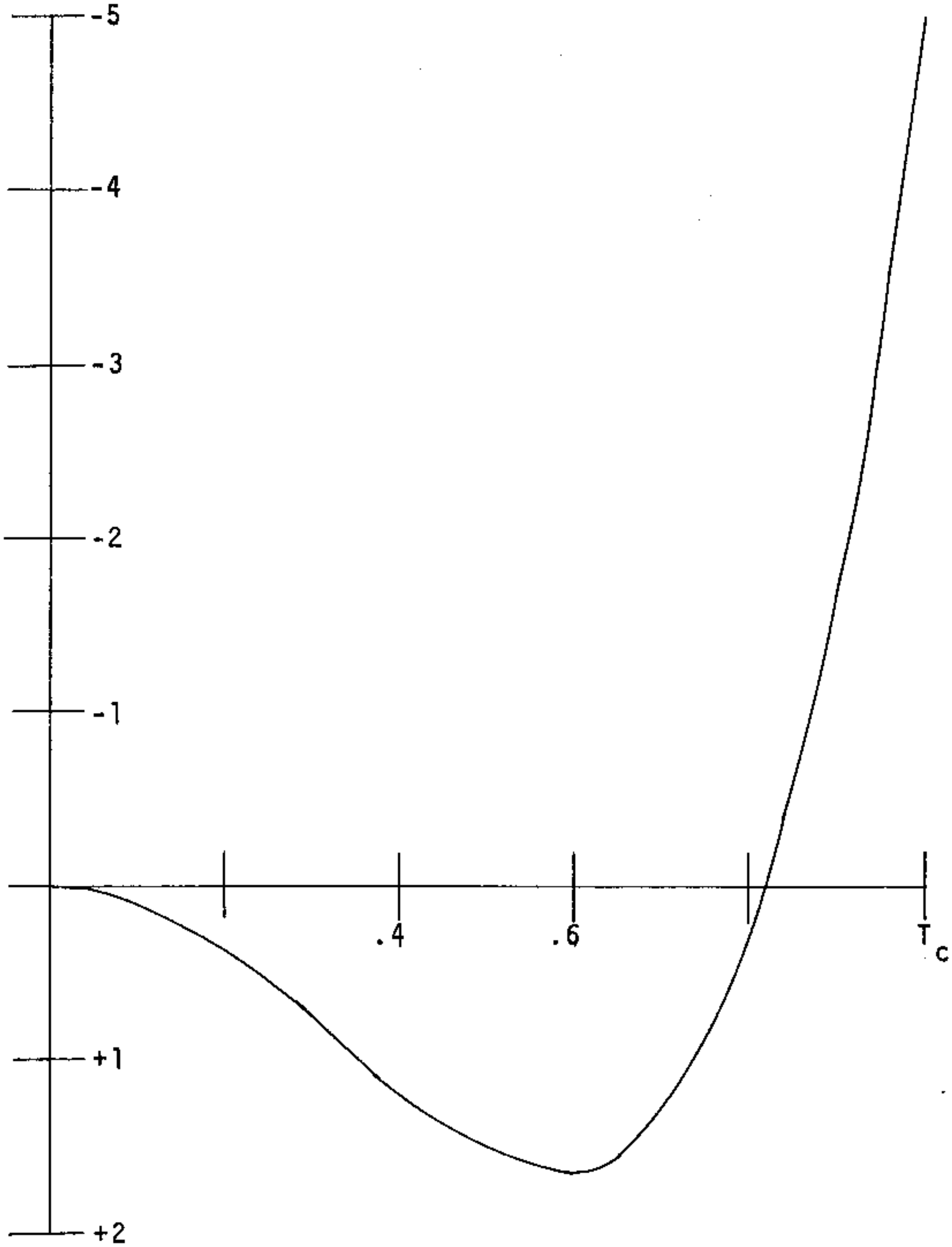



Fig. III-10. Ambient Temperature vs. $Q = T(C_n - C_s)$: $[H_c^2/8\pi]$.

# IV.

We will now summarize the thermodynamical phase transition processes previously discussed.

A table of accepted magnetic and caloric data is included (Figure IV-4.). The differences cited between critical values, as per each element, is due to impurity effects.

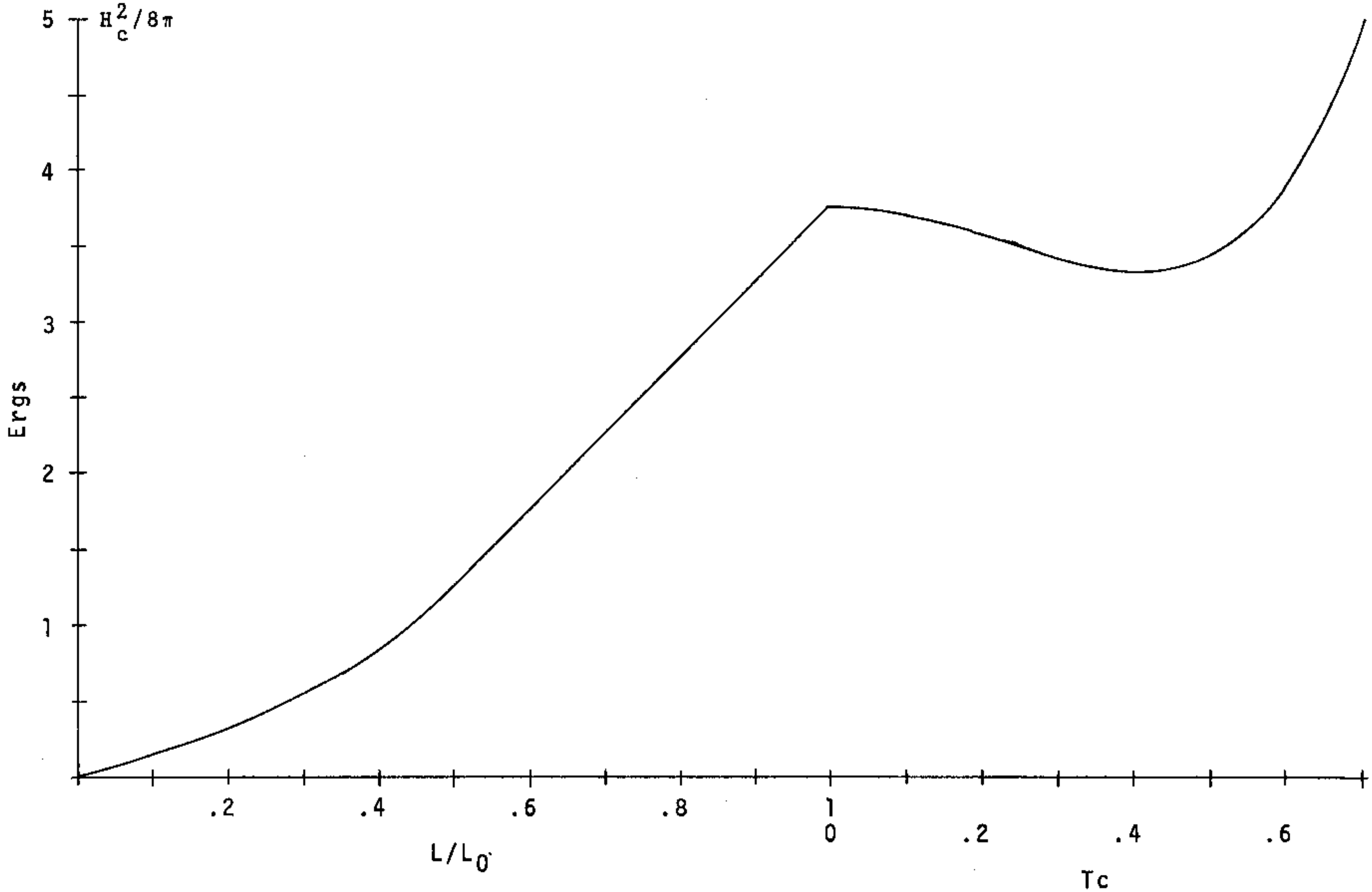



Fig. IV-2. Total Work of Normalization

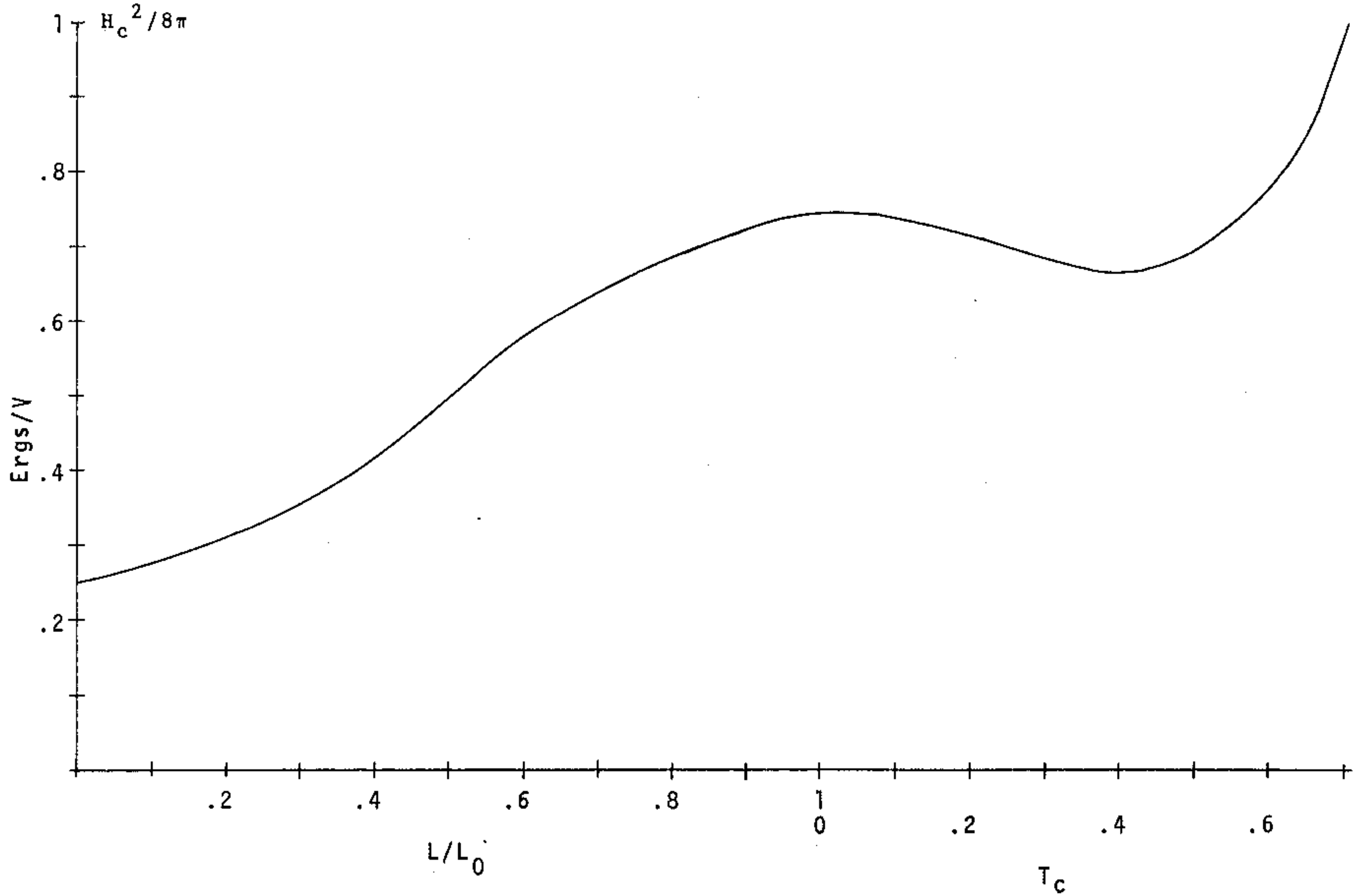



Fig. IV-1. Total Work per Unit Volume

IV.

A THERMODYNAMIC COMPARISON BETWEEN THE MAGNETO-MECHANICALLY AND MAGNETO-CALORICALLY INDUCED SUPERCONDUCTIVE PHASE TRANSITION IN A TYPE I SUPERCONDUCTOR

II. Magneto-Mechanical Work @ $.5H_c$ & 0°K @ 5 cc:

Mechanical Work: ..... $.75H_c^2/8\pi$

III. Magneto-Caloric Work @ $.5H_c$ & 0°K to $.7071T_c$ @ 5 cc:

Specific Heat: ..... $-.1363H_c^2/8\pi$

Latent Heat: ..... $.3863H_c^2/8\pi$

Caloric Work: ..... $.25H_c^2/8\pi$

IV. Work of Normalization (II + III) : ..... $H_c^2/8\pi$

Fig. IV-3. A summary of experimental results.

# IV. ACCEPTED CALORIMETRIC AND MAGNETIC DATA:

| Element | $T_c$ Cal. | $T_c$ Mag. | $H_c$ Cal. | $H_c$ Mag. |
|---|---|---|---|---|
| Al ... | 1.183 | 1.196 | 104 | 99 |
| Hg ... | 4.16 | 4.154 | 380 | 410.9 |
| In ... | 3.407 | 4.303 | 282.7 | 293 |
| Nb ... | 9.17 | 9.26 | 1,944 | 1,980 |
| Pb ... | 7.23 | 7.193 | 803 | 803 |
| Sn ... | 3.722 | 3.722 | 303 | 305.5 |
| Ta ... | 4.39 | 4.483 | 780 | 830 |
| Ti ... | .42 | .38 | 56 | 100 |
| Zn ... | .852 | .875 | 51.8 | 53 |

Fig. IV-4. Calorimetric and magnetic data for the superconductive critical temperature and field. (Data taken from *Handbook of Chemistry and Physics*, The Chemical Rubber Co., Cleveland, Ohio.)

# A PROPOSAL FOR A NEW TYPE OF SUPERCONDUCTIVE MOTOR

We have in the foregoing sections analyzed the mechanical and caloric energy functions, which, because of their unitized consistency, yield a viable thermodynamics for superconductivity.

Taking the information we have available, it seems that a superconductor affords a rather unique opportunity to harness mechanical energy from thermal energy via the Meissner Effect.

To this end, this final chapter will deal with the practical application of the whole of the phenomenon.

A. Basic Hypothesis

A free energy difference of $H_c^2/8\pi \cdot V$ has been found to exist at absolute zero for a metallic conductor between the superconductive and normal states. Hence, a field of application of $H_c$ is required to effect normalization, or in essence, raise the free energies of the superconductive phase to that of the normal phase at absolute zero.

To complement the above, superconductivity can exist until some critical temperature, $T_c$, is reached, whereupon the free energy difference between states has decreased to zero, from its maximum of $H_c^2/8\pi \cdot V$ at 0°K.

We have seen that Tuyn's Law correlates the critical field to an applied temperature value. It is possible, then, to control the state of a sample either by a variation in magnetic field or in ambient temperature.

I wish to invent a scheme by which mechanical energies of output might be derived from thermal energies of input via some appropriate device construct employing a judicious control of the phase of some cyclable superconductive substance.

This can be most expediciously accomplished by utilization of the following cyclical technique: See Figure AA.

a) A normal superconductive material at an applied temperature of $T_c$ is inserted into a magnetic field of $H_c$. No work is done.

b) The temperature is reduced to 0°K from $T_c$. No work is done.

c) The material expels the field and gains a magnetization of $-H_c/4\pi$ when it goes superconductive at 0°K (we cross the Tuyn curve).

d) The sample is removed entirely from the applied field. Work $H_c^2/8\pi$ V is done by the superconductor.

e) The temperature is raised to $T_c$ from 0°K. Work is done on the material on the order of $H_c^2/8\pi$ V.

f) The sample goes normal at $T_c$, whereupon we are back to a).

B. Attendent Problems:

a) The device will properly be termed a motor, in that mechanical energy is the final product of some energy input. A familiar design encompassing stator and armature components will be required, the armature consisting of the cyclable substance and the stator of magnetic field producing materials.

b) The stator magnetic field of production must vary in cyclic fashion from zero gauss to $H_c$.

c) The armature must rotate freely and some shafting technique should be employed for room temperature utilization.

d) The cyclable substance must be switched normal and superconductive at appropriate stator field values.

e) The temperature must vary at local points on the armature so that the phase of the cyclable substance may be controlled. Supportive refrigeration equipment being required.

f) A proper magnetic circuit must be devised.

C. The Literature:

a) Newhouse[1] reports that Schock (1961) has operated a superconductive motor at speeds of up to 20,000 RPM using radiation cooling techniques.

The mechanism relied on the surface pressure that magnetic fields exert on superconductors. An octagonally shaped superconductive armature was caused to rotate by sequential energization of regularly spaced electromagnets located close to its circumferential periphery. See Figure F-1. The stator windings are at best 100 percent efficient when superconductive wire is used, so that some losses occurred due to AC dissipation effects. (Not including outside electrical losses.)

b) T. A. Buchhold[2] proposed that the superconductive diamagnetic properties may be successfully employed in mechanical bearings where losses must be held to an absolute minimum. Here, no actual contact between surfaces is made; the field acts as the "unseen ball or roller component". See Figure F-2.

c) M. Chester[3] analyzed the possibility of utilizing the Meissner Effect for direct conversion of heat into electrical energy. He assumed ideal operating cycles and based his calculations on reversible processes. His analysis is somewhat burdened by the requirement of a zero demagnetization factor.

His idea was to wrap an infinitely tight coil about a superconductive sample and cycle its phase by temperature regulation while in a constant applied magnetic field. A current would be induced in the coil as the magnetization of the sample varied and flux was admitted into, or expelled from, the interior of the material. See Figure F-3.

The papers cited above are essentially intended for instruction. Due to the rather narrow scope of these presentations, we are unable to draw upon them for any solutions to our problems.

D. A Superconductive Motor: *The Cryoengine*

Design:

The motor will be designed utilizing stator and armature components. The stator is stationary, attached to the cryostatic system, and supplies the required magnetic fields. The armature is free to rotate or move in linear fashion, coupled by low loss bearings to the stator with power transmitted via some convenient shafting technique. It is composed of a superconductive material which is cycled normal and superconductive in phase during operation, as one would cycle the armature magnets of an electric motor north and south in polarity, thereby achieving motive energy.

Please refer to Figure A.

1. Stator: This component is designed to supply a magnetic field, the intensity of which cyclically varies from $0H_c$ to $H_c$ to $0H_c$, etc. The magnet is continuous, that is, if the motor were developed

for rotary motion, the stator magnet would continuously supply a cyclical $OH_c$ to $H_c$ to $OH_c$, etc. over $2\pi$ radians. Any number of such cycled field values may be incorporated depending on over-all dimensions. Two such magnetic units are required within the stator, of opposing polarity and synchronous field values. The actual magnetic agencies would be constructed from superconductive permanent magnets. (See page 44).

2-3. *Envelopment:* This component is designed to be a cyclable superconductive substance which essentially constitutes the major part of the armature. The substance is continuous, ie., in the rotary design, it would be present over a full $2\pi$ radians revolution. The critical field and temperature will be $H_c$ and $T_c$ respectively. The *envelopment* is placed between the opposed stator magnetic units and actuates within those confines. In case 2. it is superconductive and in case 3. it is normal.

4-5. *Sheath:* This component is designed to control the magnetic field generated by the stator as it applies to the immediate environment about the *envelopment*. The *sheath* occupies the region directly between the stator and *envelopmentic* assemblies. When the *envelopment* is superconductive, the field can not penetrate, hence it must go around this armature component, thereby creating field inhomogeneities on the stator facing surface of the *envelopment*. The *sheath* is composed of a highly permeable ferromagnetic material which is easily capable of "routing" the flux in a homogeneous manner. In case 5. when the *envelopment* is normal, the *sheath* renders little service except to reduce to a minimum the over-all field generation requirements on the stator by reducing the total air-gap space of the magnetic circuit.

6-7. *Transmissor:* This component, composed of highly permeable ferromagnetic material, is designed to route the return flux from the stator magnets. It is essential to regulate the reluctance such that a constant value prevails throughout the entire circuit. In case 7. the *transmissor* is routing flux around a presently superconductive *envelopment;* here the reluctance must be equivalent, in final form, to the air-gap reluctance created when the *envelopment* is normal. This component (7) is called the *envelopmental-transmissor.*

8. *Cylindrical:* This component is designed to confine the magnetic field to well defined regions of space. It is composed of layer wound filamentary (or Type I) superconductor sheet. See pages 42 and 43.

Additonal supportive apparatus include:

a) Superconductive bearing and shafting assemblies. On the former see Buchhold (1961) and Figure F-2. On the latter see Figure G; these designs are intended for shafting of motive energies from the cryogenic environment for room-temperature applications.

b) Cryostatic apparatus and cooling equipment (See page 41.).

The latter further incorporates the temperature regulation apparatus for the *envelopment;* specifics will be discussed in the section on "Conditions of Operation".

Operation:

Starting at a local point in which the field is $0H_c$ and the *envelopmental* temperature is $T_c$, a cycle will be described for an elemental *envelopment* volume, dV.

A) Being that $T_c$ is the temperature of the *envelopment,* it is normal even though the applied field is zero gauss.

The *envelopment* is rotated in the direction of increasing field, as per the cyclic generations of the stator. As this motion occurs, the temperature of the *envelopment* is lowered in a controlled fashion such that the critical temperature is maintained according to Tuyn's Law as per the presently applied magnetic field.

The *envelopment* continues moving in the direction of increasing field while the local temperature decreases until a field value of $H_c$ is reached and the temperature becomes 0°K.

During the above the following has occurred:

a) No work was expended inserting the *envelopment* into the field.

b) The magnetization of the *envelopment* was a constant, zero.

c) The *envelopment* remained at all times normal.

d) Magnetic flux passed directly through the *sheath* and *envelopment* and back via the *transmissor*.

B) The *envelopment* upon reaching the $H_c$ field value, assumes the superconductive state since the temperature is 0°K, as per the Tuyn Law.

The following occurs:

a) The *envelopment* gains a diamagnetic magnetization of $-H_c/4\pi$.

b) All magnetic flux is expelled from the interior of the *envelopmental* element.

c) The free energy difference between states, $H_c^2/8\pi \cdot V$, accounts for the work done to exclude the field.

d) A magnetic pressure of $H_c^2/8\pi \cdot A$ appears upon the boundary superconductive face between phases.

C) The *envelopment* continues moving in the same direction as before, however, now the applied field is decreasing as per the stator cyclics, and the local temperature is increasing. This continues until the applied field is again zero gauss.

During the above the following has occurred:

a) Work $H_c^2/8\pi \cdot V$ has been performed as a mechanical output.

b) Energy $H_c^2/8\pi$ has gone into the *envelopment* as a heat input.

c) The magnetization has varied as per the applied field: $-H_a/4\pi$.

d) The *envelopment* has remained at all times superconductive.

e) Magnetic flux passed through the *sheath*, around the *envelopment*, through the *envelopmental-transmissor*, and back via the *transmissor*.

D) The *envelopment*, upon reaching the zero gauss field, assumes the normal state, since the temperature is $T_c$, as per the Tuyn Law.

The following occurs:

a) The *envelopment* smoothly looses its magnetization: $-H_a/4\pi$ to zero.

b) All magnetic flux can pass through the *envelopment* since it is now completely normal.

c) The free energies between states are smoothly joined at $T_c$, so that no latent heat occurs.

d) There is no magnetic pressure at the interphase boundary, as there is no applied magnetic field.

In essence, $H_c^2/8\pi$-$0H_c^2/8\pi$ are the pressures at the interphase boundaries, the net value of which results in a mechanical work output.

Analysis of Operation:

A. The thermodynamics of a complete cycle:

Process A), in which the *envelopmental* volume, dV, moves in the direction of increasing field and decreasing temperature involves no relevant thermodynamics. We are solely interested in $C_n$-$C_s$, the difference in specific heats between phases. We consider $C_n$ to be the guide by which to measure $C_n$-$C_s$ and, as if we were considering gravitational potential energy, where $C_n$ would be analogous to the elevation of zero potential, we will call $C_n$ zero. The magnetization is zero, therefore, no magnetic mechanical work is done in order to insert the volume. (See pages 70 and 16 .)

Process B) involves a phase transformation, the normal state becoming the superconductive state. There is a free energy difference between states equal to $H_c^2/8\pi \cdot V$ when the temperature is 0°K. The Meissner-Ochsenfeld Effect (See pages 13-14) occurs when a sample crosses the Tuyn curve becoming superconductive in an applied field. The free energy difference is just sufficient to expel a critical magnetic field. In our case, the *envelopment* becomes superconductive and the entire free energy is used to expel the magnetic field. This is electronic energy (ie, Cooper pairing energy -- see pages 30-74. ) which is now converted into macroscopic magneto-mechanical potential energy. Since this free energy exists, no latent heat occurs and, to present, no external work has been done. A pressure of $H_c^2/8\pi \cdot A$ exists on the superconductive state side of the interphase boundary. This occurs since the magnetic field in the normal region is confined at the interphase boundary to only the normal region, causing a diamagnetic surface pressure. This boundary shall be known as the *Transmogrification Point.* See pages 28-29.

Process C), in which the *envelopmental* volume, dV, moves in the direction of decreasing field and increasing temperature, involves several thermodynamic functions. Primarily, the mechanical energy output comes about through the pressure that is developed upon the interphase boundary discussed above. (*Transmogrification Point* boundary.) The final energy is:

$$\int H \cdot dM \cdot \int dV = H_c^2/8\pi \cdot V = \text{Mechanical Work Output.}$$

Further, as the temperature increases, the specific heat of the superconductive phase is involved and now $C_n - C_s$ is important. This difference in heats constitutes a heat energy of input, which is the actual *fuel* for the mechanical work.

The specific heat input energy is:

$$C_n - C_s = -T/4\pi \cdot (H_c(d^2H_c/dT^2) + (dH_c/dT)^2) \cdot V$$

$$\int (C_n - C_s)dT = H_c^{\,2}/8\pi \cdot V = \text{Thermal Energy Input.}$$

The above represent the energies involved in a change of magnetization while a sample is superconductive. See pages 30 & 70.

Process D) involves a phase transformation, the super - conductive state becoming the normal state. The free energy difference between states is zero at $T_c$ due to the fact that super-electrons were being raised to normal electrons throughout this process and that the number of super-electrons smoothly went to zero. (All electrons are now normal, hence the *envelopment* is normal.) See pages 32-56. This process involves no latent heats. See pages 74 & 77.

B. The Work Cycles: See Figure E.

A magnetization versus applied field curve (Figure E-1) indicates the magnetic status of the *envelopment* at any cyclic point. Starting where H and M equal zero, the field is increased with the magnetization a constant, zero. At $H = H_c$ the magnetization is increased to $-H_c/4\pi$, ie, the *envelopment* becomes superconductive. The *envelopment* then leaves the field while the attendant magnetization also decreases. This constitutes a work output; the area under the curve being the actual mechanical output work.

An applied field versus ambient temperature curve

(Figure E-2) relates the thermodynamic state of the *envelopment* at all times. Starting at $T_c$ and zero gauss, the *envelopment* is cycled just above the Tuyn Curve at all points until $H_c$ and 0°K are reached. This implies that at all times the *envelopment* is normal. Upon reaching $H_c$ and 0°K the *envelopment* becomes superconductive. The *envelopment* is then cycled back just below the Tuyn Curve to the starting point of $T_c$ and zero gauss. This implies that at all times the *envelopment* is superconductive. As per the magnetization curve work $H_c^2/8\pi \cdot V$ is performed during the return cycle and thereby thermal energies related to $C_n - C_s$ occurs as an input also during this return superconductive portion of the full cycle.

Figure E-3 is an alternate form of the applied field versus ambient temperature curve.

The *envelopment* is placed into a magnetic field of $H_c$ gauss while at $T_c$°K. The temperature is lowered to 0°K with the field constant. The superconductor is at all times normal. The *envelopment* then leaves the field at T = 0°K. Finally, the temperature is raised to $T_c$ while H remains zero. The superconductor is at all times superconductive. At $H_c$ and 0°K, and at zero gauss and $T_c$ phase changes occur.

A second operating cycle based on supercooling is shown. Here the superconductor retraces the same paths. First, the temperature reduces from $T_c$ to 0°K at zero gauss then the field increases to $H_c$ at 0°K, a hysteritic phase change to the superconductive state occurring at $H_c$. Finally, the superconductor retraces these steps, now superconductive instead of normal. See the section "Conditions of Operation".

C. The Efficiency of the Work Cycle:

The *Cryoengine* is designed to utilize the Meissner-Ochsenfeld Effect of superconductors. Maximum energy conversion of heat into mechanical work will be when the entire free energy difference between states is utilized. This can only occur when the operational cycle ranges from $T_c$ to 0°K and zero gauss to $H_c$, respectively. In the event this occurs the efficiency is then:

$$\eta = W_{out}/W_{in} = (\int_0^{H_c} H \cdot dM \cdot \int_0^{V} dV)/(\int_0^{T_c} (C_n - C_s) dT = 1, \text{ ideally.}$$

The actual efficiency will depend on refrigeration inefficiency, which may be included as Wr:

$$\eta = (\int_0^{H_c} H \cdot dM \cdot \int_0^{V} dV)/(\int_0^{T_c} (C_n - C_s) dT + W_r).$$

In the event that the engine is not operated within full critical limits, then the full free energies available will not be utilized and the additional factor of the Latent Heat must be considered. See pages 75 & 76. At the points where transition occurs, the latent heat, *L*, will be exhibited. Further, a back pressure will be present at the low field phase boundary since the magnetic field is not now zero. The efficiency will now be given as:

$$\eta = (\int_{H_1}^{H_2} H \cdot dM \cdot \int_{V_1}^{V_2} dV)/(\int_{T_1}^{T_2} (C_n - C_s) dT + W_r - L_1 + L_2).$$

for the general case of *Cryoengine* operation between any arbitrary field and temperature values. The latent heat is negative on the superconductive to normal transition, positive on the normal to superconductive transition. See pages 75 and 76. Finally, if losses, E, occur, due to eddy currents, Joule heating, inefficient bearings, etc., then the efficiency becomes:

$$\eta = ((\int_{H_1}^{H_2} H \cdot dM \cdot \int_{V_1}^{V_2} dV) - E)/(\int_{T_1}^{T_2} (C_n - C_s) dT + W_r - L_1 + L_2).$$

Conditions of Operation:

The general electric motor depends upon an external electric power source to act as a fuel to supply the armature electromagnets and a commutator to so direct this energy as to reverse the polarity of these magnets so that induction or repulsion of a stator magnet can be effected. This results in a net electrical energy input and mechanical energy output.

The *Cryoengine* relies upon the Meissner-Ochsenfeld Effect to transform heat energy into mechanical energy. This is accomplished by controlling the phase of the armature (*envelopment*) (this is akin to polarity above) and regulate the local temperature of the *envelopment* (by some means akin to the commutator above). This results in a net thermal energy input and mechanical energy output.

Proposition #1.

The phase-temperature regulation may be controlled by maintaining a cyclic temperature in accordance with stator magnetic field values, as per 0°K at $H_c$, $.707T_c$°K at $.5H_c$ and $T_c$ at zero gauss. An *envelopmental* element is then constantly undergoing temperature variation during operation. There is, however, no abrupt temperature change so that the over-all temperature gradient maintained in the *envelopment* is fairly manageable.

Proposition #2.

The phase-temperature regulation may be controlled by establishing constant temperatures over each cycle, ie, 0°K from H equal to zero gauss to $H_c$ and back to zero gauss, then an abrupt temperature change from 0°K to $T_c$ to 0°K between cycles in the *envelopment*. This procedure involves employment of the somewhat fickle supercooling effect so well described by Faber[4] (See page 19 ). Provided the supercooling can be assured, which seems plausible, then a point between cycles can exist where the temperature is maintained at $T_c$. This point can be as sharply defined as desired and will in every way effect the same net result as Proposition #1. See Figure E-3.

In operation, the magnetic flux must be rigidly controlled. This is accomplished via the *cylindrical* and *transmissor* components. No energy is utilized to generate the screening currents on the surface of the *cylindrical*. This may be exemplified by generating a larger than critical field on the *cylindrical* surface. The energy of normalization comes from the requirement on the stator magnets to generate a larger field to maintain that value present before the wall normalized, due to the now large fringing field. These flux path components then do not enter into the calculation of any work functions.

The requirements on the refrigerational apparatus are rather extreme since the local *envelopmental* temperature must be regulated to very close tolerances, while latent and specific heats are present. Use of heat sinks is suggested. Liquid Helium II (See foll.) may be a rather excellent answer to control heat transport problems. Heat insulators should be adequately employed in Proposition #2 operation.

$10^{12}$ Hertz is the limit below which AC dissipation effects become objectionable; this is the upper theoretical limit on the Revolutions per Second possible. Considering that no load is placed on the motor, the unit will accelerate until some back EMF is generated or superconduction breaks down completely. This may very well occur due to eddy currents generated in the normal regions. With a load placed on the engine, speed and power will be predictable depending on over-all engine dimensions, ie:

$\int dW = \int F \cdot dx = \eta \cdot \int H \cdot dM \cdot A \cdot \int dx$, where F is the load and dx is the circular or linear distance of *envelopmental* motion.

The phase boundary at the $H_c$ field value (*Transmogrification Point*) has an unbalanced force since the magnetic pressure is only directed against the superconductive side. (The normal side "supporting" the pressure by virtue of the magnetic field.) Throughout any cycle, this is the only point where forces can act; hence, if any useful work is being generated, it is coming from this locality.

In the design of a particular machine, the reluctance must be constant in the magnetic circuit. At the *transmogrification point*, motive pressures will only be generated if the components comprising the circuit, ie, *transmissor* and *cylindrical*, are so designed that no field density changes result from the *envelopmental* phase change. If such inhomogeneities occurred, then: a) only part of the local generated field might contact the *envelopment* (some being routed via the *transmissor*), b) a back pressure could develop on components due to an improper flux routing technique (thus the effort to cycle the *envelopment* would be neutralized, in effect), and c) two components could alternately undergo phase change (*envelopment* and some *cylindrical* unit which is part of the armature) resulting in a net reduced mechanical output. The main procedure in design is to maximize the boundary pressure and minimize back pressures and fringing losses due to inefficient techniques.

At present, refrigeration efficiencies are discouragingly low when extreme cryogenic temperatures are concerned. Although there is a net heat flow into the engine, this comes about only through the specific heats--not some mysterious form of latent (automatically refrigerating) heat. The heat present at high temperature must be extracted mechanically to gain the necessary periodic low temperature. (Raising the temperature is easy--just let some heat leak in.) This is usually accomplished via techniques discussed on pages 41 and 47.

Newhouse[5] reports that Yaqub (1960) proposed utilizing the latent heat of transition of a superconductor to achieve cooling. He found that a tin alloy cooled to .8°K and then driven normal by the application of a strong magnetic field dropped in temperature to just .18°K. In this procedure, mechanical work was converted directly into refrigerational cooling work. Efficiencies are rather high, depending widely on the particular substance used.

The latent heat of transition may afford a highly attractive refrigeration mechanism provided the vicinity of 0°K is not the final cyclic goal. A sample would be forced normal by a magnetic field, thereby lowering its temperature via the latent heat (See pages 74-77 ). The sample may then be removed from the field, while contact is now broken with the motor and established with the cooling bath. Transition will involve a latent heat evolution which can be taken away via the liquid helium bath. This procedure involves a recoverable mechanical work, ideally. Its best utilization would be to regulate local envelopmental temperatures, exhausting waste heat to the bath.

If the motor should be utilized in an exotic environment where near 0°K subtends naturally, refrigeration is of no concern; rather, the generation of heat is. The high temperature cycle value may be achieved directly by the latent heat of transition (normal to superconductive) or some chemical, electric, or mechanical, etc., means. If some perfect heat source could be found, the motor would be essentially 100 percent efficient (at low RPM).

Observations:

A cryogenic environment is required so that the component superconductive constituents may be exposed to the temperatures which are associated with the superconductive state. In order that the full energy cycle may be employed, 0°K must be approximately attained. (Thus irrespective of how high the $T_c$ of superconductors becomes (See page 5 ) in the coming years, cryogenics will remain an integral part of what I call *Cryoengenics* or the study of engines in cryogenic environments, especially superconductive motors.) At present, cryogenic engineering is sufficiently advanced to regulate, to high measure, heat losses to minimum acceptable levels. See Page 41 , Figure I-3.

Shafting techniques are shown in Figure G after works by the author dated 9/4/68.

Due to the fact that the armature unit must rotate freely, minimum drag must be present. To accomplish this goal, radiation techniques (See page 41) may be employed. A more acceptable means is to use liquid helium-four below the lambda point (2.19°K), which is then a "super-fluid",[6] conducting heat almost instantaneously and having virtually zero viscosity as the contact medium between the cooling bath and the motor.

The *envelopment* should be constructed from Type I materials, which show essentially zero losses below $10^{12}$ Hertz. This being a guide, all components should be designed for low loss and high reliability.

Use of the *Cryoengine* shall be in existing areas of power employment, where factors of size, weight, cost, and power output make it most attractive over conventional systems. As exceedingly pure crystalline structures exhibit no losses, production costs will depend on loss tolerances.

The work cycle of the *Cryoengine* is innately dissimilar to that of the Carnot Engine.

The Carnot cycle is based on four processes incorporated to achieve a closed cycle of operation: (1) an isothermal expansion, (2) an adiabatic expansion, (3) an isothermal compression, and (4) an adiabatic compression. The work invested in (4) is equal to the work gained in (2), so that the efficiency of a Carnot engine depends on how large (3) is compared with (1).

(3), defined as: $Q_3 = W_3 = \ PdV = -RT_L(dV/V)$, for a gas, is utilized solely to return the system to the starting point of the cycle. Notice that if $T_L=0$, then $Q_3=W_3=0$ and the efficiency becomes: $\eta = 1$ ($\eta = [(1)-(3)]/(1)$ where (1) is defined as: $W_1 = \ PdV = RT_H(dV/V)$).

For the *Cryoengine*, we achieve a closed cycle by: (1) an isothermal de-magnetization, (2) an isomagnetic heating, (3) an isothermal magnetization, and (4) an isomagnetic cooling.

In this case no work is performed in (3), the heat invested in (2) is at least equal to the heat evolved in (4) ($C_n-C_n = 0$), and the work gained in (1) is equivalent to the energy invested in (2) (in addition to that involved in $C_n$ above, ie, $C_n-C_s = E$). Hence, there is here no limitation on reservoir temperatures and operation of the ideal *Cryoengine* between any two arbitrary temperatures is 100% efficient.

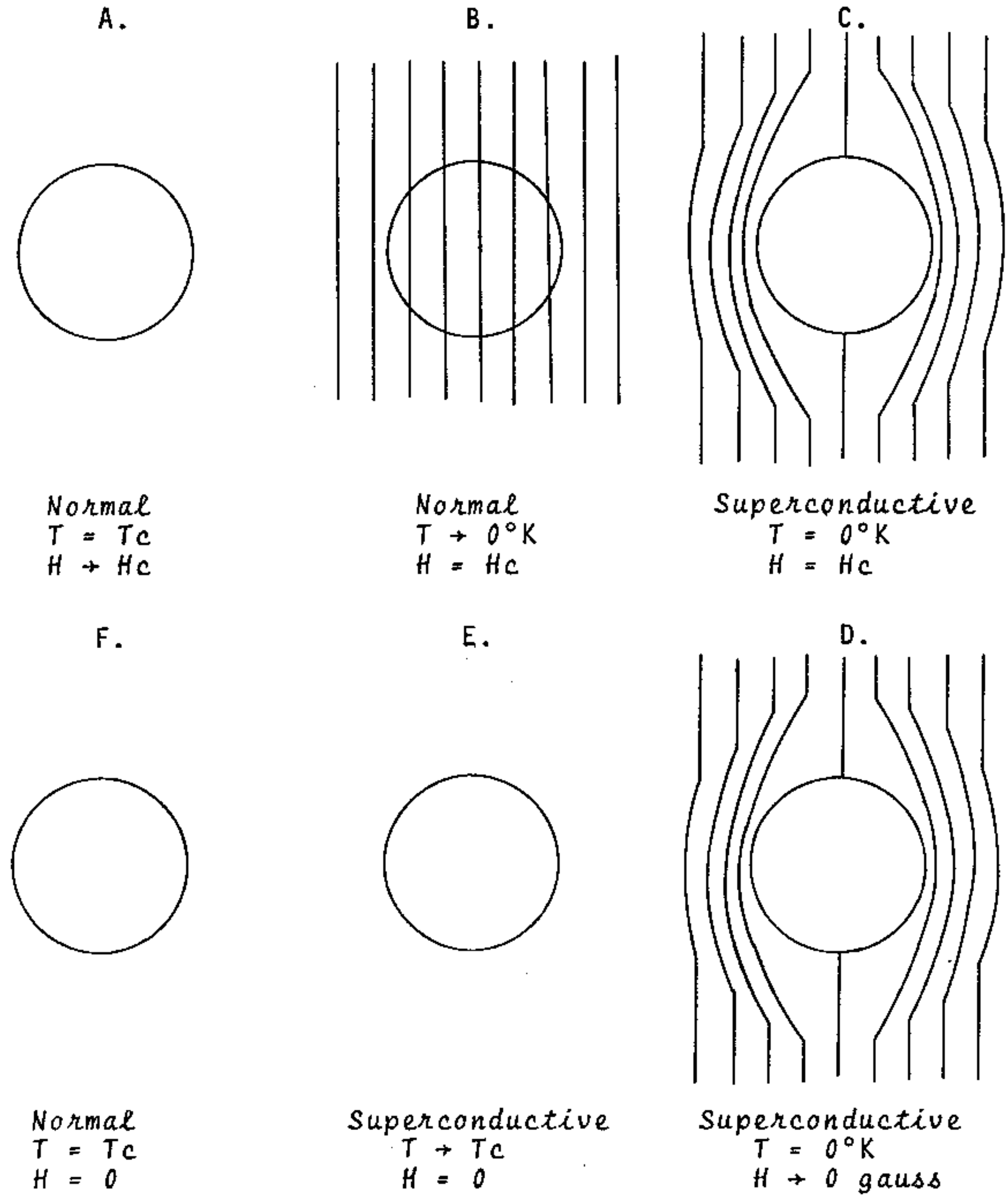



Fig. AA. Basic Hypothesis.

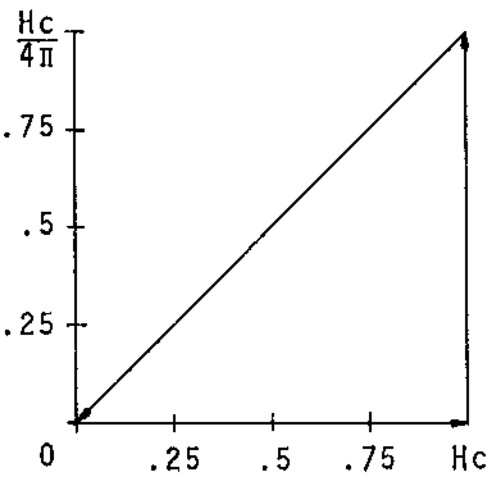



Fig. 1

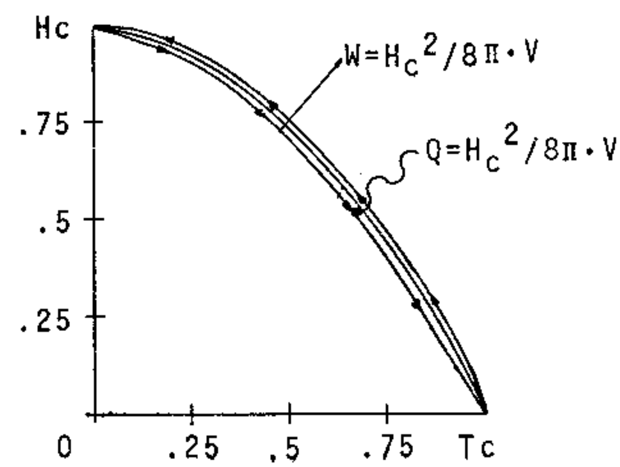



Fig. 2

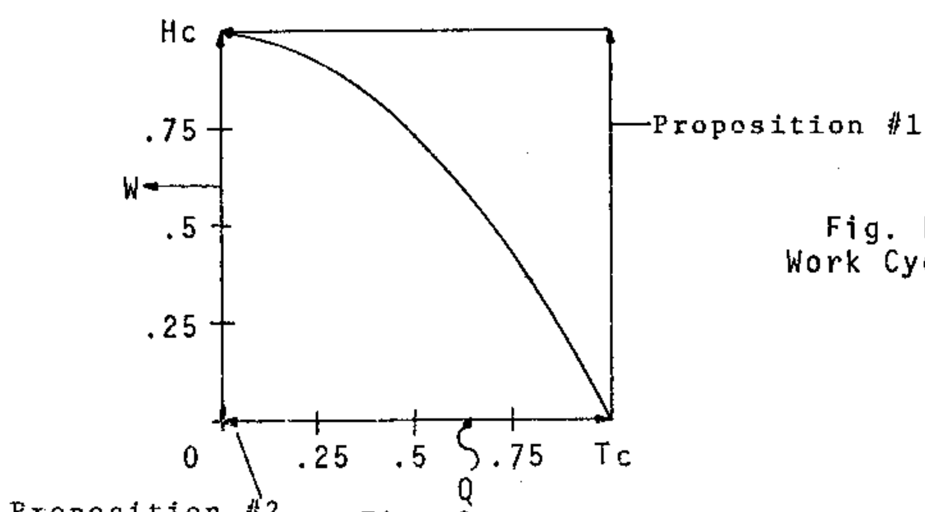
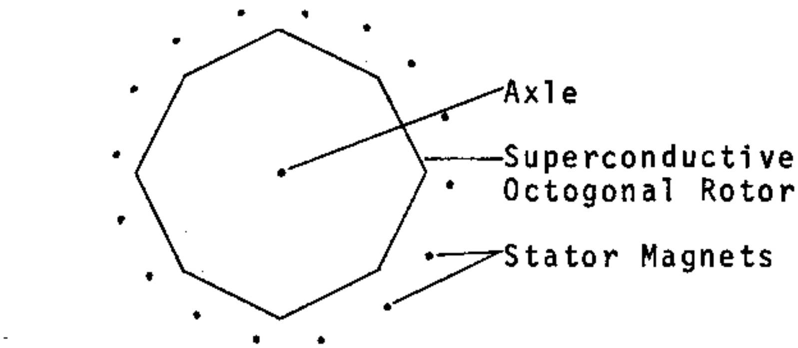
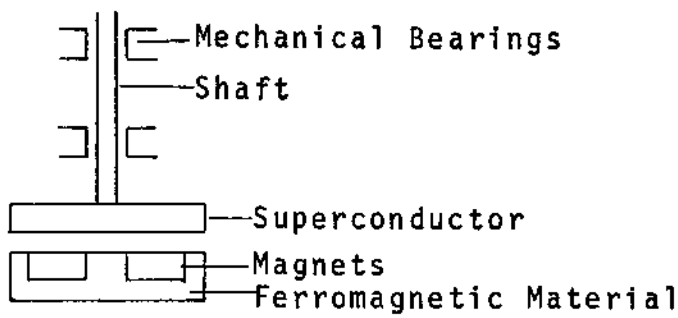



Fig. 3

Fig. E.
Work Cycles.


Axle
Superconductive
Octogonal Rotor
Stator Magnets


Mechanical Bearings
Shaft
Superconductor
Magnets
Ferromagnetic Material

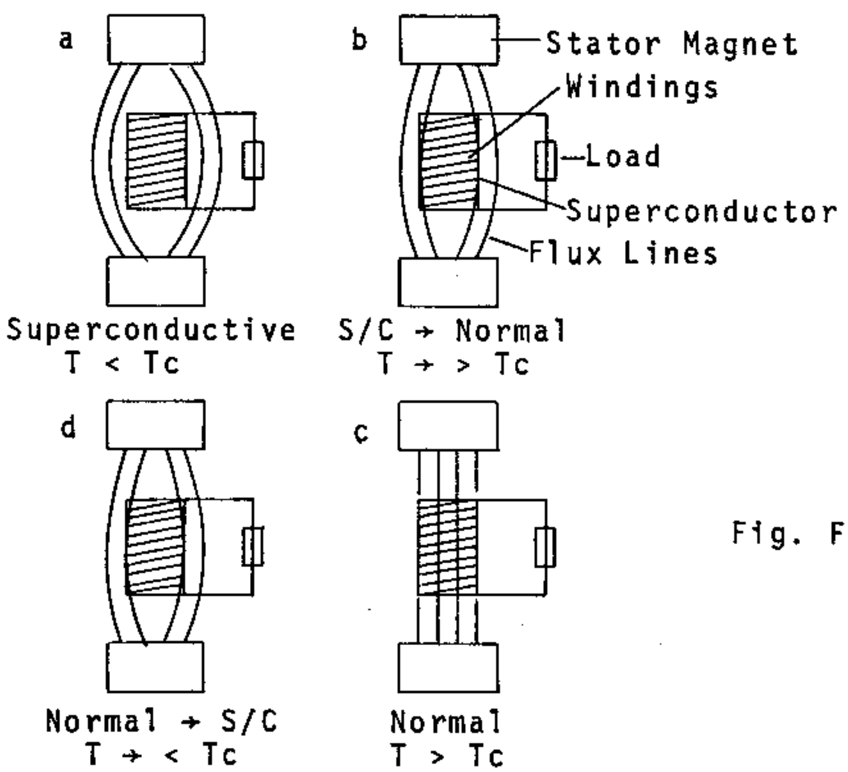
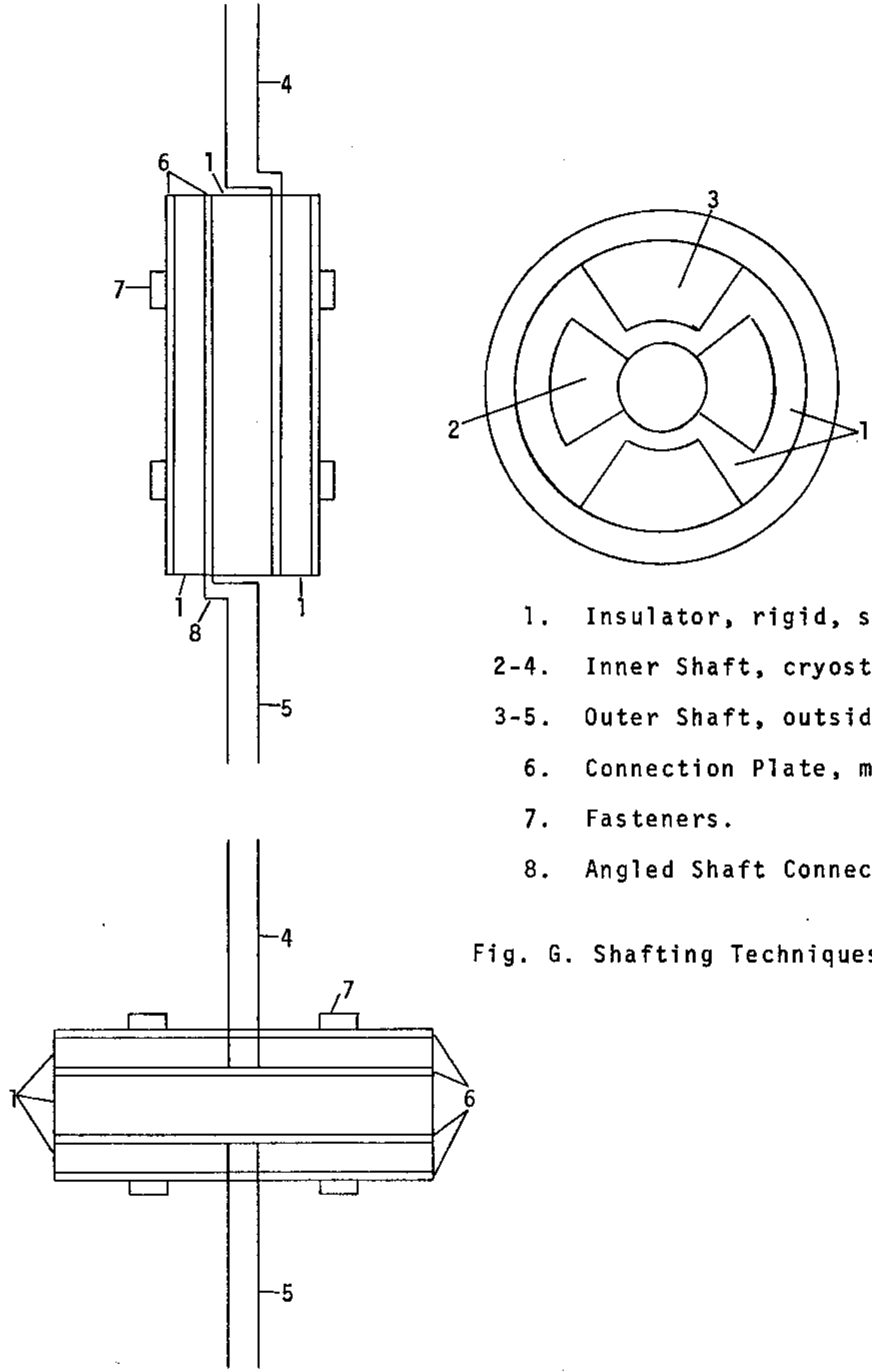

a
b
Stator Magnet
Windings
Load
Superconductor
Flux Lines
Superconductive
T < Tc
S/C → Normal
T → > Tc
d
c
Normal → S/C
T → < Tc
Normal
T > Tc

Fig. F.




1. Insulator, rigid, strong.
2-4. Inner Shaft, cryostat.
3-5. Outer Shaft, outside.
6. Connection Plate, metal.
7. Fasteners.
8. Angled Shaft Connection.

Fig. G. Shafting Techniques.

DESIGN ELECTIVES:

Pursuant to the creation of a *Cryoengine*, a design must incorporate a net magnetic pressure discontinuity at the *transmogrification point* in order to achieve a net motive energies output from a net heat energies input.

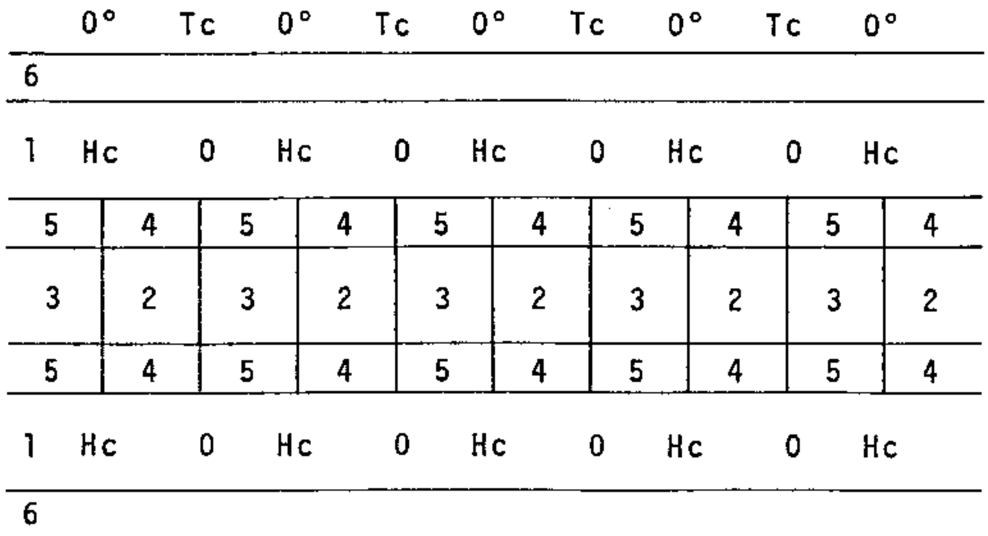



Fig. 1

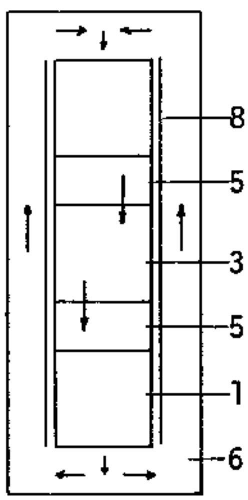



Fig. 2

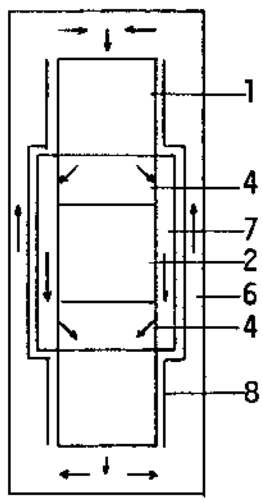



Fig. 3

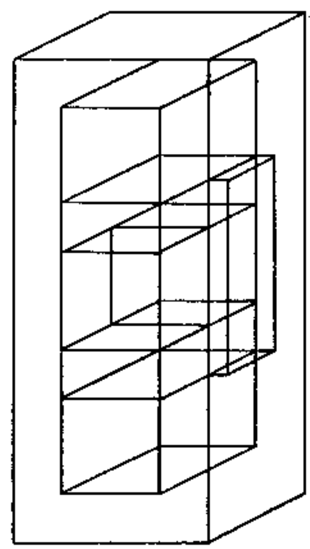


Fig. 4

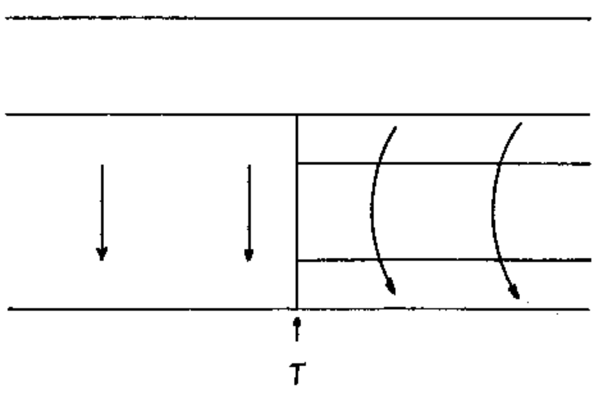



Fig. 5

Fig. A.
Design Elective A.

Design Elective A:

The over-all cyclic hypothesis is presented in Figure A, as elaborated previously. The *envelopment* moves in a linear manner to the right. Rotary operation can be accomplished by designing the whole of Figure 1 as a torus. Operation under mode Proposition #1 is there indicated.

In Figure 2 the stator magnetic field passes directly through a normalized *envelopment*, returning via the *transmissor*.

In Figure 3 the *envelopment* is superconductive. The stator field passes around via an *envelopmental-transmissor* (7), returning via the previously mentioned return path (6).

Figure 4 is the three dimensional view.

Figure 5 demonstrates the nature of the field pressure discontinuity at the *transmogrification point*. The magnetic field to the left of ($T$) is self-supporting, ie, the field diminishes smoothly and naturally, as per $H/r^2$, where r is the distance from ($T$) to the left. To the right of ($T$) is a superconductive *envelopment*. This permits no field entry and sustains the pressure of the external field to the left by diamagnetic screening currents flowing on the boundary surface. This constitutes a pressure, analogous to the form commonly found in hydrostatics, which is of a singular, unidirectional sort. Motion of the *envelopment* to the right, while the boundary location is fixed, results in a force of $H_a^2/8\pi \cdot A$ acting over such motional distance, ie, $dW = F \cdot dx$. The final work in a full cycle is then just: $\int_1^2 dW = A \cdot \int_0^{H_c} \mathrm{H} \cdot dM \cdot \int_0^x dx = H_c^2/8\pi \cdot V$.

At the *transmogrification point* field commences to route through the *envelopmental-transmissor* (7). The flux passing through the *envelopmental-transmissor* must now, in some locality, produce a field pressure directed to the left, since now the situation is exactly the reverse of that described for the *envelopment*. This is because the field is now maintained by a diamagnetic *cylindrical* wall to the left of the *envelopmental-transmissor* field boundary. The pressure is equivalent to that created on the *envelopment*, ie, $-H_a^2/8\pi \cdot A$. This is of no consequence since the *transmissor* and *cylindrical* components are stator constituents. Since they are stationary, no work is performed as $dW = F \cdot dx$ and dx equals zero.

The total circuital reluctance is maintained constant by adjusting the *transmissor* in each phase case of the *envelopment*.

If Proposition #2 is utilized, then at each locality where $H_a$ equals zero gauss, the local *envelopmental* temperature is $T_c$. This temperature value extends over a very narrow spatial volume. Temperature 0°K is ambient over the cyclic regions: zero gauss to $H_c$ to zero gauss.

Supercooling will create a normalized state for entry into the field, where the *envelopment,* as per Tuyn's Law, would normally be superconductive. At $H_c$, the *envelopment* becomes superconductive, expelling the field. The temperature must be raised to $T_c$ between cycles to return to the same thermodynamic coordinates before each new cycle.

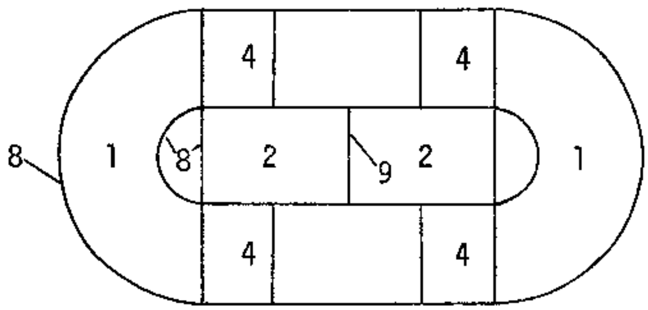



Fig. 1

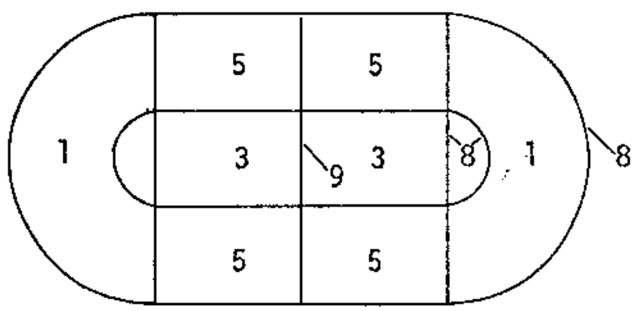



Fig. 2

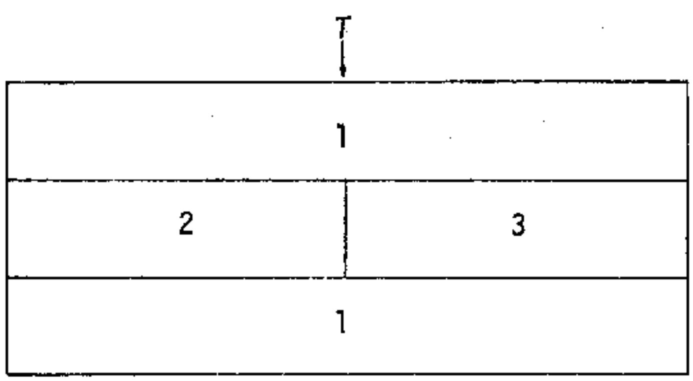



Fig. 3

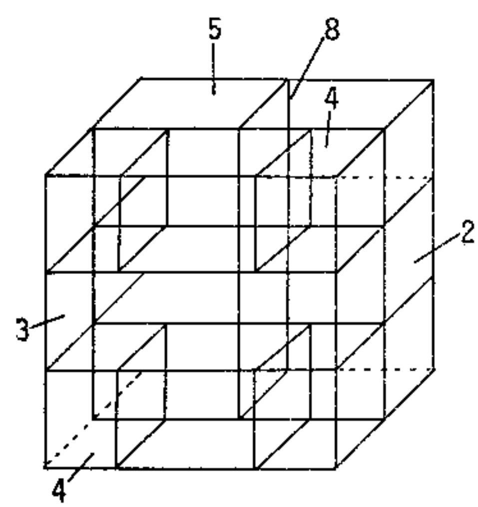



Fig. 4

Fig. B. Design Elective B.

Design Elective B:

In Figure B-1 the stator component is designed in the form of a "horse-shoe". This results in elimination of the return path *transmissor;* the spatial volume being entirely occupied by a field producing construct. The *envelopment* is now superconducting. In order to maintain the reluctance constant, an air-gap between *sheath* components simulates a normal *envelopment* volume.

Figure B-2 shows the *envelopment* component in the normal state. The *sheath* extends over all space between stator units and the *envelopment.* In order to facilitate creation of a homogeneous field in the *envelopmental* volume, a *cylindrical* wall (9) symmetrically divides the *envelopment* into longtitudinal half sections, thereby separating the opposite stator fields. This *envelopmental-cylindrical* (9) is present at all times in the *envelopment,* always superconductive, ie, its $H_c$ is greater than that of the *envelopment.*

Figure B-3 demonstrates the field distribution at the *transmogrification point.*

Figure B-4 is the three dimensional view.

Propositions #1 and #2 and the net forces may be described as per that presented in Elective A.

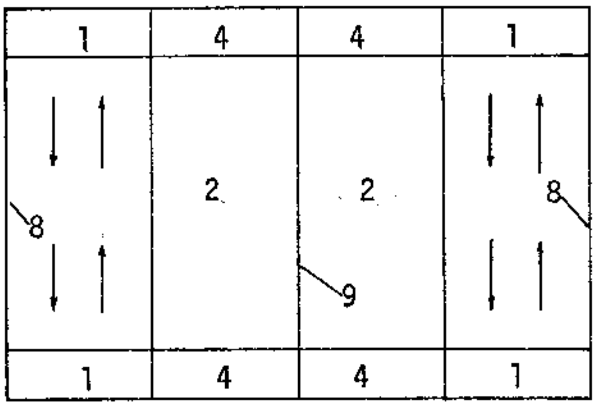



Fig. 1

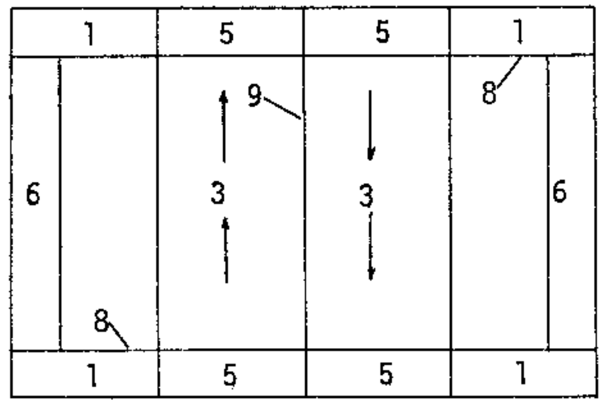



Fig. 2

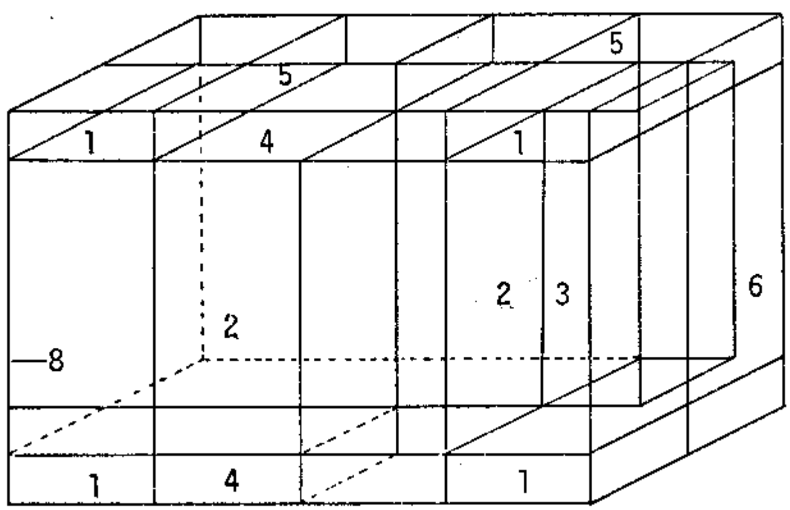



Fig. 3

Fig. C. Design Elective C.

Design Elective C:

Figure C-1 shows a superconductive *envelopment* with the stator magnetic field being routed around through an air-gap volume, the same spatial size as the *envelopment*. In this concept, the stator magnets are oriented "on side", thereby eliminating need for a *transmissor* in this *envelopmental* mode. This is so because here two entirely separated stator magnets constitute each of the two units of the stator assembly. The *sheath,* which is shown, is rendered inoperative to route flux due to an *envelopmental-cylindrical* which is placed in the symmetrical center of the *envelopment* and as in Design B, extends throughout the entire longtitudinal dimension of the *envelopment.* This component (9) is at all times present during operation and extends through to and including the *sheath.* Since the *sheath* is not needed, it need not be employed here; thus, while the *envelopment* is superconductive, all flux is contained in the adjacent air-gap and no *transmissor* or *sheath* is employed. (The *sheath* assembly can be installed, if desired, so that its extension is continuous over all cycles.)

In Figure 2, the *envelopment* is normal with field passing through it. A *transmissor* is employed to route flux around the air-gap which is now insulated, to prevent fringing, by a *cylindrical.* The *sheath* will route flux so that a homogeneous field passes through the *envelopment.*

The *envelopmental cylindrical* is always present.

Figure C-3 is the three dimensional view.

Propositions #1 and #2 and net forces may be described as per that presented in Elective A.

Fig. D.
Design Elective *D*

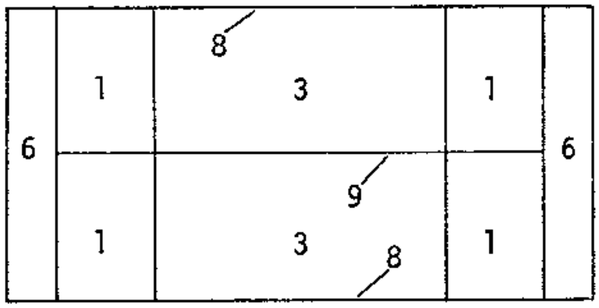



Fig. 1

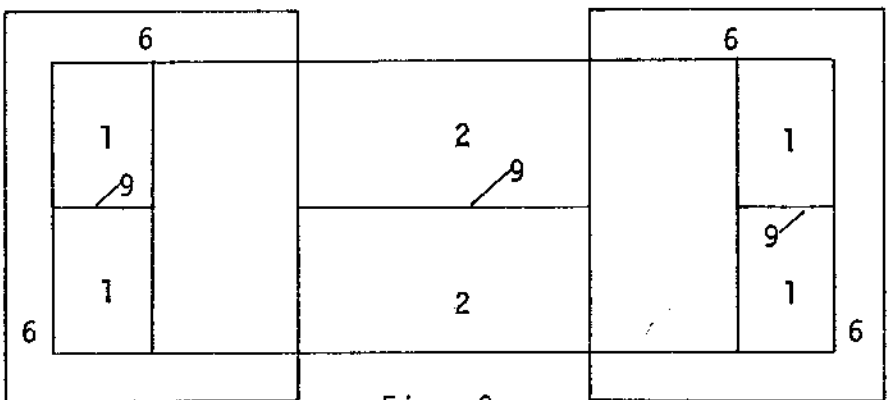



Fig. 2

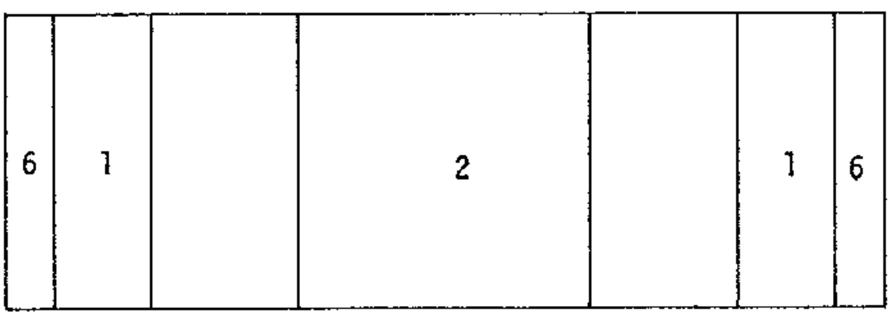



Fig. 3

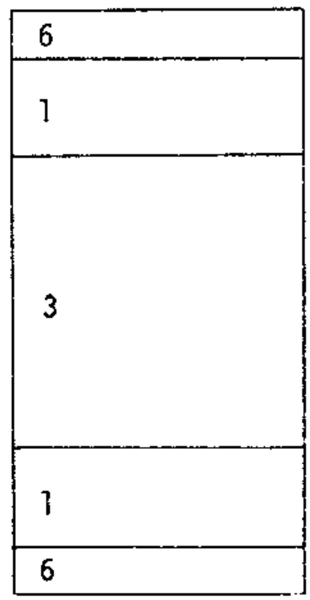



Fig. 4

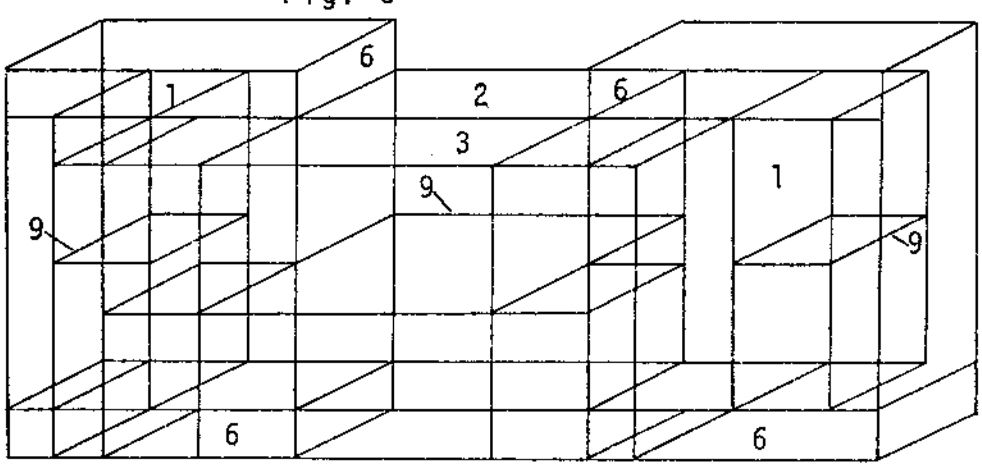



Fig. 5

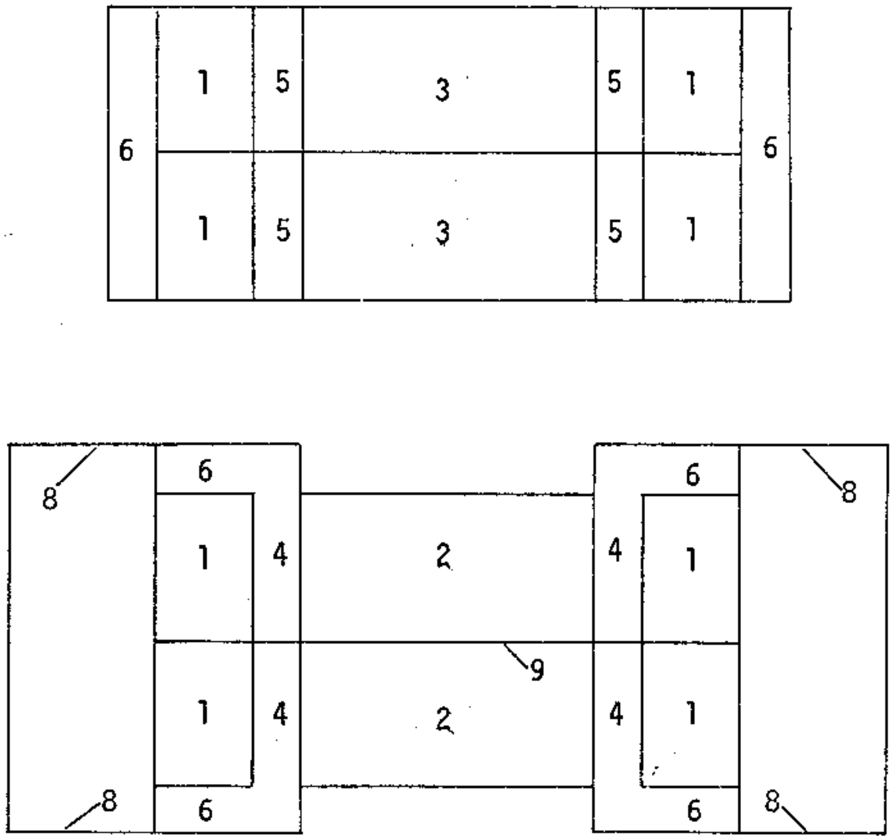



Fig. D-6. Design Elective D.

Design Elective D:

In Figure D-1 the *envelopment* is normal, flux passing directly there through. A permanent *envelopmental-cylindrical* is located in the symmetrical *envelopmental* center, and extending as described in Electives B & C. This component (9) extends into and including the stator magnets, thereby insulating them from one another. The stator assembly then consists of two units of two separated magnets each. A *transmissor* routes the return flux. The *cylindrical* is placed entirely around the whole of all components from *transmissor* end to *transmissor* end, thereby containing the *envelopmental* air-gap.

Figure B-2 shows the situation when the *envelopment* is superconductive. The stator magnets are moved back establishing an air-gap between magnet and *envelopment* of the same spatial volume as the *envelopment*. This means retaining constant reluctance can also be accomplished by retaining the original magnet locality with a *sheath* between *envelopment* and magnet and establishing a confined, *cylindrically* introduced, air space opposite in position to the magnet side of the stator now shown. See Figure B-6. The *envelopmental-cylindrical* is located only in *envelopmental* and magnet areas as a permanent feature. As in all cases where it is utilized, the limit on thinness depends on the penetration depth.

Figure B-3 and B-4 show top views; Figure B-5 shows the three dimensional view.

Propositions #1 & #2 and net forces may be described as per that presented in Elective A.

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