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SAFETY WITH HIGH MAGNETIC FIELD SYSTEMS

J. N. Luton, Jr.

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SAFETY WITH HIGH MAGNETIC FIELD SYSTEMS*

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ABSTRACT

Based on a consideration of the laboratory environment and on the physical characteristics of high field magnet coils and of humans, some hazards and safety precautions concerning steady state magnet systems are discussed.

I. INTRODUCTION

There is reason to consider the safe laboratory use of high field magnet coils simply because the number of R&D personnel and the use of magnetic fields continue to grow. A more basic reason is that laboratory use of high fields satisfies the conditions which are statistically conducive to severe injuries:[1] unusual, nonroutine work; nonproduction activities; and sources of high energy.

In R&D, neither the work nor the safety precautions can be successfully pursued by rote or by following prescriptions laid down by someone unfamiliar with the circumstances. Both must rather be based on an understanding of the physical system. Therefore, the next section introduces some of the basic properties of magnet coils.

*Research sponsored by the U.S. Atomic Energy Commission under contract with the Union Carbide Corporation.

II. TECHNICAL BACKGROUND

We are considering systems with field strengths high enough that the augmentation due to iron would not be large, and the simplest magnet type is a single air-cored coil or "solenoid." The coil might, for example, be composed of spirally wound "pancakes" stacked on a common axis. Figure 1 shows a model pancake having an internally cooled copper conductor. The conductor could also have been a flat strip with cooling at the edge of the conductor, a common arrangement in superconducting coils. In either case, a plane containing the coil axis cuts the coil winding as shown in Fig. 2b. If one desires radial access to the coil bore, a mirror field, or a cusp field, then a pair of coils may be used (Fig. 2c). A toroidal field, Fig. 2a, may be produced by a smooth winding (right side) or by a set of discrete coils. In every case, the coil produces at any point in space a flux density B which is proportional to the current and (for resistive coils) to the square root of the power. As indicated below, the coil windings experience forces which are proportional to B^2. The directions of the magnetic forces are indicated by the small arrows on Fig. 2.

A short segment ℓ of a conductor carrying a current $\overline{I}$ in an external magnetic field $\overline{B}$ experiences a magnetic force $\overline{F}$ whose direction and magnitude are given by the vector cross product

$$\frac{\overline{F}}{\ell} = \overline{I} \times \overline{B} . \tag{1}$$

Considering the perpendicular component only,

$$\frac{F}{\ell} \approx 0.57\ I_{kA} B_{\perp\,kG}\ , \quad \text{lb/in.} \tag{2}$$

(When units are not indicated explicitly or by subscripts, RMKS is used.) From Eq. (1) and the Biot-Savart (Ampere's) law it follows that the force between two parallel wires is

$$\frac{F}{\ell} = \frac{\mu I_1 I_2}{2\pi d} . \tag{3}$$

For parallel wires carrying equal currents,

$$\frac{F}{\ell} \approx 0.045 \frac{I_{kA}^2}{d_{in.}} , \quad \text{lb/in.} , \tag{4}$$

repulsive if the currents are antiparallel and attractive if parallel. Equations (2) and (4) describe the magnetic forces on coil leads and show that for a multi-turn coil these forces are moderate. However, if the lead supports are not sufficient and a lead begins to move, it may move so that the magnetic force is larger. In any case, the lead supports should be carefully considered, since if a lead tears loose while still carrying rated or overload current it can be accelerated to lethal velocities as it moves across the field.

The magnetic forces on the coil winding are much larger than those on the leads, because the coil has at least several turns, most of which are in the high-field region rather than in the fringing field. In general, the magnetic forces act to force the coil windings to become more compact and the coil diameter to enlarge. Neighboring coils try to align axes and attract; coils with coincident axes and oppositely directed fields ("cusp coils") repel. Figure 3 gives an indication of the magnitude of the forces. Note that $1/2\ BH \equiv B^2/2\mu$ (μ = permeability of air) has the characteristics of a "magnetic pressure" acting both parallel and

perpendicular to the field lines. Thus, one of the requirements for higher field strengths is a mechanical structure whose strength goes as B^2. Also, as in a pressure vessel, increasing the diameter of the coil increases the load on the structure. Figure 4 shows a structure containing six superconducting coils: four racetrack coils and two mirror coils.[2] Even though the coil cases are massive, they carry such high loads that a special high-strength steel was required.

When the field of the coil is changed, either on purpose or by accident, the changing flux will produce eddy currents in nearby conducting bodies. The magnetic field produces forces on the eddy currents just as on normal currents, and if not considered, these forces may cause damage. For example, remote bodies may be moved, structures in the coil bore may be collapsed (or overheated), and metal dewars may be expelled.

In addition to any eddy current forces, a ferromagnetic body will experience a magnetic force proportional to the field gradient, and this force tends to move the body toward the stronger region of the field where the force would usually be still larger. Therefore, once a remote magnetic body is moved by the stray field, it accelerates rapidly toward the near face of the coil.

The magnetic pressure expression BH/2 also represents the energy per unit volume stored in the magnetic field. At high field strengths this reservoir of energy is quite large, as indicated by Fig. 5, and dangerous amounts of thermal or kinetic energy can result even if the transfer mechanism is inefficient. Except for superconducting coils, one must also add the energy that might be received from the power supply during a fault.

The possibility of voltage breakdown must also be considered. Paradoxically, this is more likely to be troublesome with a superconducting coil than with a resistive coil. This is partly because the superconducting coil is likely to have internal insulation which will withstand less voltage but also because it usually has a much higher inductance. A large superconducting coil should be protected against both high induced voltages and excessive energy release in the dewar, perhaps by a properly sized external resistor[3] ("energy dump") across the coil leads.

Figure 6 is meant to give a feel for high field magnets by displaying some descriptive data for four quite different systems. The first column of data pertains to the large water-cooled magnet of Fig. 7, a coil pair whose mechanical structure is strong enough to restrain the repulsive force (860,000 lb) of cusp operation. The second column of Fig. 6 is for the coil shown partly assembled in Fig. 8, in which each pancake is composed of 12 separate water paths for better cooling. The third column describes the Nb_3Sn superconducting coil shown in Fig. 9. The coil has strip conductor wound into pancakes, and the liquid helium circulates by natural convection through slotted spacers between pancakes, thus cooling the edges of the conductor. The fourth column of Fig. 5 refers to a toroidal device called ORMAK[4] whose field is produced by 56 copper coils with liquid nitrogen coolant. The torus is rather fat, so that the maximum field of 36 kG is considerably larger than the on-axis field. The coil current is pulsed (pulse length $\approx$ 1 1/2 sec) approximately once every 10 min.

The data of Fig. 6 is by no means complete, and the four selected field systems themselves do not span the whole range of high field magnets,

but the variation in the data illustrates that not all magnets are hazardous in the same way. Each proposed system should be scanned with a fresh and systematic eye to detect possible modes of failure and to minimize their probabilities and consequences of occurrence.

III. COMMON HAZARDS

One common hazard is the risk of structural failure, perhaps brought about by increased forces due to over-currents or to mechanical interference due to differential thermal contraction. However, in the example of Fig. 10 it was simply a case of the coil spool piece not restraining its rated load and completely fracturing across three parallel planes.

The possibility of the failure of electrical insulation is always a threat, and such failure may be initiated by mechanical as well as electrical stress. Figure 11 is a postmortem photo of the coil described by Figs. 6 and 8. As might be expected in an electrical failure, there is considerable evidence of arcing, overheated insulation, vaporization of conductor, and loss of coolant. In this particular case it also happened that the current in part of the turns at each end of the coil was reversed by the fault, thus reversing the force and moving these turns inward across the bore of the coil. The appearance of the other end of the coil is remarkably similar to Fig. 11.

Figure 12 shows a superconducting coil which failed by repeated arcing as it and its enveloping coil were driven normal several times without proper protection. The burned area extended radially through both coils, and they had to be completely rewound. Fortunately, most of the conductor was salvageable.

The loss of coolant flow through any part of the coil may also cause failure. Figure 13 shows a coil with the small piece of rubber sheet that largely blocked one water passage and caused it to overheat. A strainer was in place immediately upstream of the coil header; unfortunately "immediately" was far enough that the piping could be opened between the coil and the strainer, and in one such instance a piece of gasket material entered the system.

It should be emphasized that none of the coil failures mentioned above placed any personnel in danger. The coils themselves were damaged extensively, but all the violence was contained within the magnet enclosures.

Other hazards exist which do not involve failure of the coil itself: The field may cause forces on experiments placed within the coil bore, the stray field will interact with any neighboring ferromagnetic body and the time-varying field will produce heat and forces if conductive bodies are nearby. Current leads and connectors may move or become separated. The operation of the coil may involve a megawatt power supply, high pressure coolant system, force structures at cryogenic temperatures, and even liquid hydrogen; and none of these becomes less dangerous merely because we fix our primary attention on the coil. Since one is able to protect himself against all the enumerated hazards, probably the most likely causes of injury are in the categories "things not considered" and "misconceptions." It should be possible to reduce the scope of those two categories by having more than one individual involved in the work.

IV. HUMAN RESISTANCE TO ABUSE

Figure 14 is a medical classification of injuries abridged from the Textbook of Preventive Medicine as quoted by Steere. It can be used as an injury check list. For example, Class II injuries include suffocation and frostbite and should remind one not to locate a rupture disk so as to fill the operator room with inert gas when it breaks. In the Class I injuries, the mechanical injury threshold might be taken[5] as 50 j (30 ft lb), although of course the value depends critically on the circumstances under which the energy is delivered. In any case, the injury threshold is orders of magnitude below the energy stored in most magnet systems (Figs. 5 and 6).

Figure 14 does not include an item for direct injury due to the presence of a magnetic field, and considering the present state of knowledge it would be inappropriate to do so. However, there is now widespread interest in the effects of magnetic fields on living organisms, and we may hope that the effects on humans will be well defined. Present work covers a very wide range of field strengths, gradients, frequencies, and organisms.[6] There may exist subtle or long range changes (good[7] or bad[8]) caused by magnetic fields, but as yet investigators have not found dramatic changes with practical safety consequences analogous to electric shock effects.

The electrical effects mentioned in Fig. 14 are detailed in Fig. 15. The effects are somewhat frequency dependent, but 60 Hz data is customarily given because this frequency is both that of the power grid and that at which shock effects tend to be greatest. The fibrillation region, which in 95% of the cases occurs for an arm-to-opposite-leg current of 80 to 240 mA, is particularly dangerous because the heart will not usually

recover from this state of random twitching even when the shock current is removed. In contrast, below 30 mA and in the 4 A region, the person usually recovers if the current is removed before secondary damage is done. Note that the body internal resistance of 500 Ω is not high enough to limit the current to the paralyzing threshold of 10 mA unless the voltage is 5 V or less.

The conclusion can only be that the unprotected human body is very fragile in comparison to the various hazards of high magnetic field systems.

V. SAFETY PRECAUTIONS

Figure 16 lists some suggested safety precautions. Firstly, in the design of the system it may be necessary in some areas to push design values to the limit, and if so one should consider all failure modes and take steps to render the failures harmless to humans and to other equipment. If necessary, add such weak links as rupture disks so that the system will not fail in a more disastrous manner. However, the fact that a design must be marginal in some areas does not reduce the desirability of making it conservative in the remaining areas.

Secondly, a system of safety interlocks and key-operated permissive sequence should be designed, installed, and checked both periodically and with every change in the system. The checking should be by actual attempted use of the system. For example, one would energize the coil at a very low level, shut off the coolant, and thereby prove that the flow interlock shuts down the system. Again, if there are areas forbidden to personnel during operation, they may be caged, the cage provided with a lock which

will release its key (the only one existing) only when the door is closed and locked, and the key from every door is required to operate the coil; a check of the permissive system would be a deliberate attempt to operate the coil with a cage unlocked.

Thirdly, remove loose metal from around the coil. One should be especially careful about the suitability and restraint of all apparatus within the coil bore, tables and other things on wheels, tools used around the coil, and such things as mechanical pencils and 6-in. metal scales which will fly out of a shirt pocket if one bends over in an appreciable stray field.

Fourthly, shield personnel from the effects of equipment failure. A coil should be enclosed in a shield which will render harmless solid projectiles, steam or cryogenic fluid, and molten metal. If possible, the shield should permit visual inspection of the coil while both coil and shield are in place. One suitable arrangement is Lexan or Lucite sheet backed by expanded metal (stainless, painted black for better vision) held by a framework of stainless angles.

Fifthly, do not permit operation by a single person. Most company policies prohibit working alone if the work involves such hazards as high energy materials, high pressure, cryogenics, electrical equipment, etc. In addition, most magnet coils in research and development are used to provide a field in which experiments are to be performed. The exuberant desires of the various experimenters ought to be restrained as necessary by a second individual whose responsibility is proper operation of the magnet.

Finally, as when operating any potentially hazardous equipment, be alert and aware of the present condition of the system.

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3. See, for example, J. N. Luton, U.S. Patent No. 3,711,744, "Passive Energy Dump for Superconducting Coil Protection," January 16, 1973, for a description of a reliable energy dump whose resistance increases as the dump progresses.
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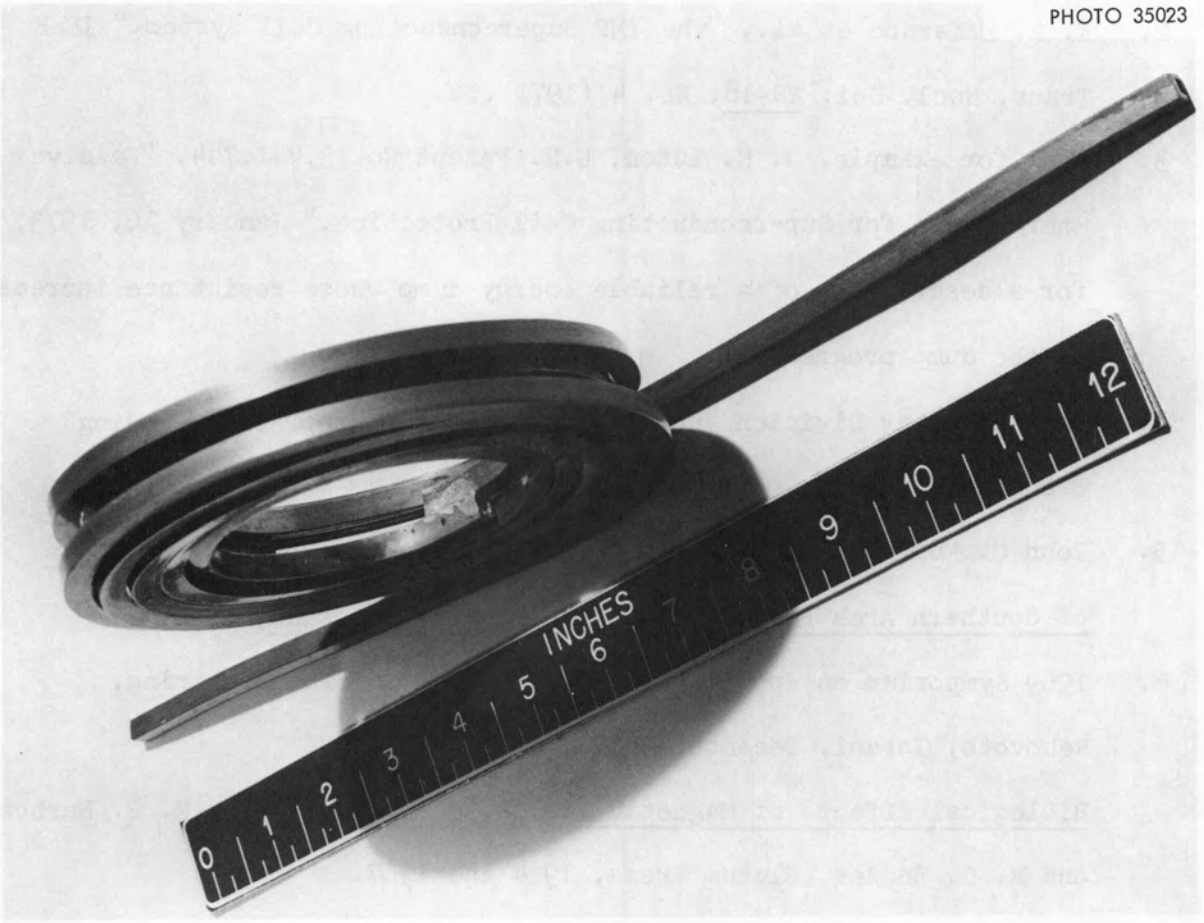
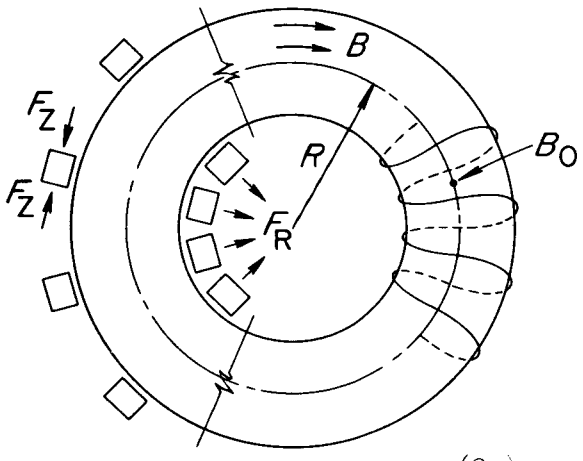


FIGURE 1

ORNL-DWG 73-4594

TORUS

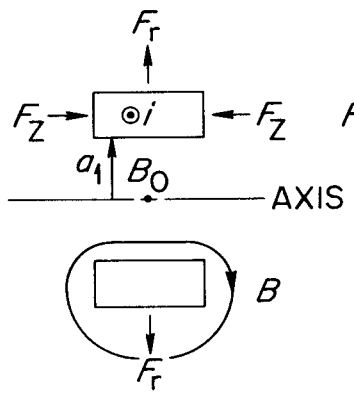


(2a)

$$B_O = \frac{\mu N I}{2\pi R}$$

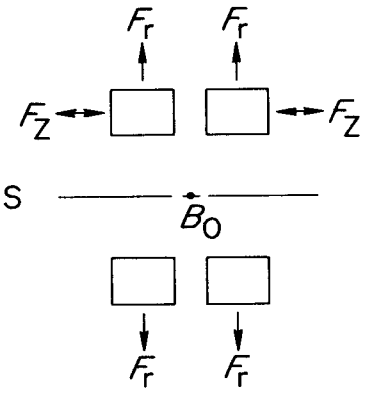
B_O = CENTRAL FLUX DENSITY
NI = TOTAL AMP TURNS

SOLENOID



(2b)

COIL PAIR
(MIRROR OR CUSP)



(2c)

$$B_O = a_1 i F_i = G\sqrt{\frac{P\lambda}{\rho a_i}}$$

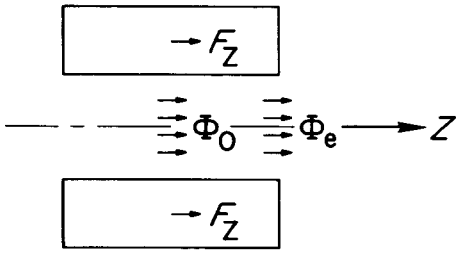
i = CURRENT DENSITY
F_i, G = GEOMETRY FACTORS
P = POWER
λ = PACKING FRACTION
ρ = RESISTIVITY

Common Coil Configurations.

FIGURE 2

ORNL-DWG 73-4595

COIL AXIAL FORCES



$$F_Z = \frac{NI}{\ell}(\Phi_e - \Phi_0)$$

FOR A LONG SOLENOID,

$$F_Z = \frac{1}{2} H_0 B_0 \ \pi r^2$$

COIL RADIAL FORCES

(LONG SOLENOID)

$$\frac{F_r}{\ell} = \frac{1}{2} BH \ 2\pi r$$

MAGNETIC PRESSURE

$$\frac{1}{2} BH$$

MAGNETIC MATERIAL NEAR A COIL

$$F_X = -\frac{1}{2}\Phi^2 \frac{d\mathcal{R}}{dx}$$

Magnetic Forces.

FIGURE 3

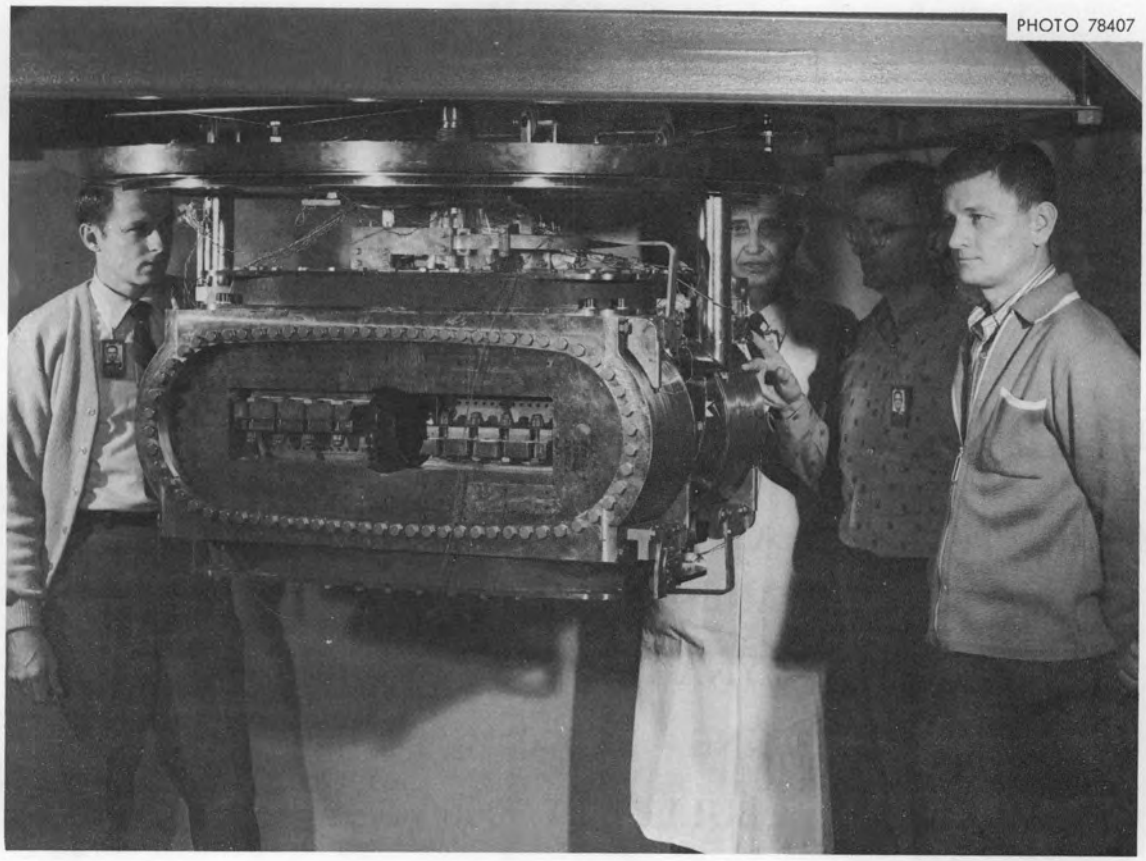


FIGURE 4

ORNL DWG. 73-4607

STORED ENERGY

MAGNETIC FIELD: $W = \frac{1}{2} BH = \frac{1}{2} LI^2 \quad j/m^3$

MAGNETIC FIELD AT 100 kG, $W = 40\ Mj/m^3 = 5\ kj/2''$cube

METHANE – 34. Mj/m^3

TNT, DYNAMITE – 6,000. Mj/m^3

GASOLINE – 35,000. Mj/m^3

180 gr. BULLET AT 3000 FT/SEC – 5 kj

FIGURE 5

ORNL DWG. 73-4616

ILLUSTRATIVE COIL PARAMETERS

				(56-coil torus)[1]
Central Field, kG	63	100	100	21 (36)
Bore, inch	12	2	3	26
Conductor, inch	0.7 Cu	$^3/_{16}$ Cu	$^1/_2$ X 0.008 S.C.	0.5 X $^3/_8$ Cu
Operating Temp.,	45°C	66°C	4.2°K	80°K[3]
Current, A.	9200	4600	440	12,500
Current Density[2], kA/in.^{2}	17	105	85	59
Inductance, h	0.078	0.038	1.65	0.041
Stored Energy, Mj	3.3	0.04	0.16	3.2
Magnetic Pressure, psi	2,300	5,800	5,800	250 (750)
$\frac{dT}{dt}$ w/o Coolant, °C/sec	6.7	475	5000 (180 at 15°K)	25
Power, MW	6.4	3.3	≈ 0	16.5 (peak)
Conductor power density, KW/in.^{3}	0.4	27	0	≈.5

1. Slow pulse device. See text.
2. Over the whole cross section.
3. 110°K at end of pulse.

FIGURE 6

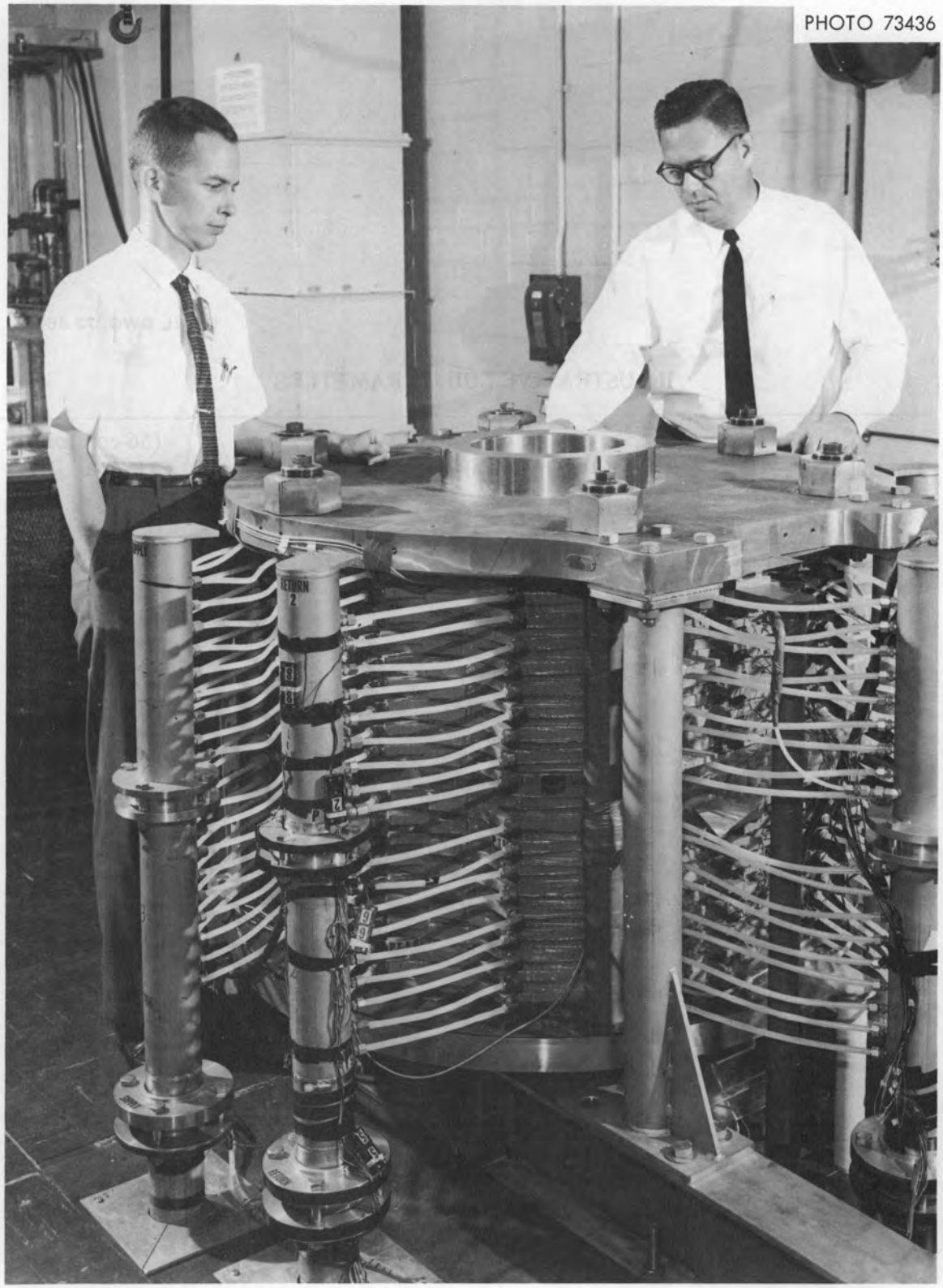
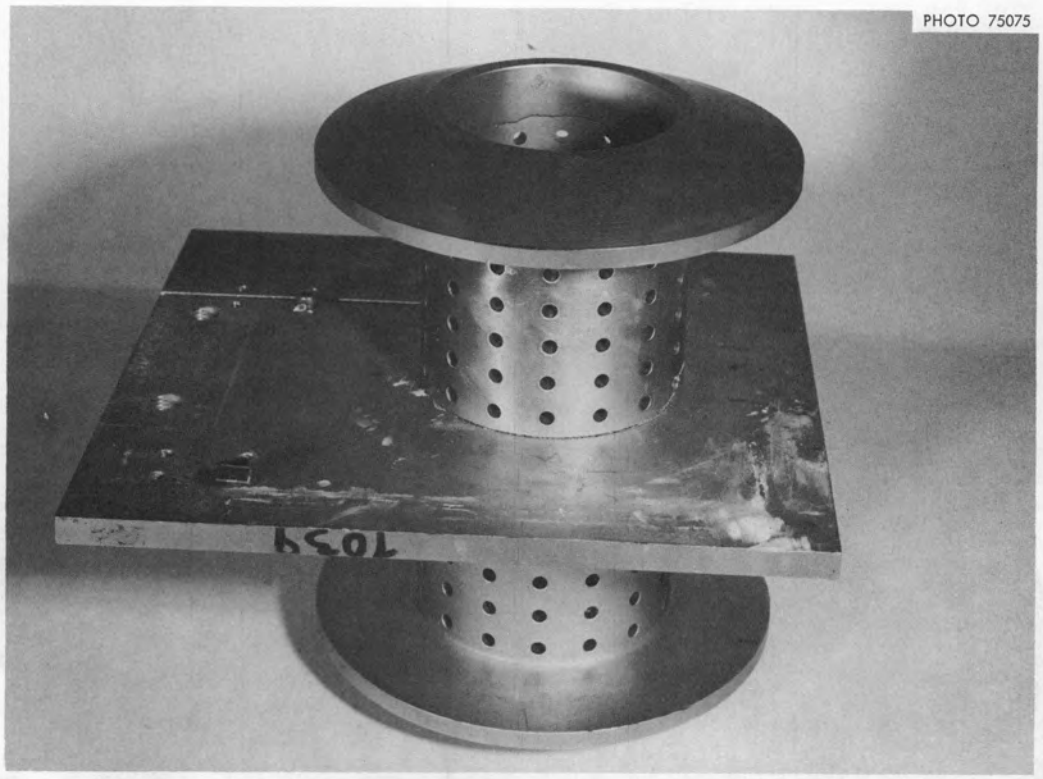


FIGURE 7

FIGURE 8

PHOTO 79549
3" BORE-100 kG
Nb_3Sn SOLENOID
415 AMPS, 1.55 HENRIES

FIGURE 9



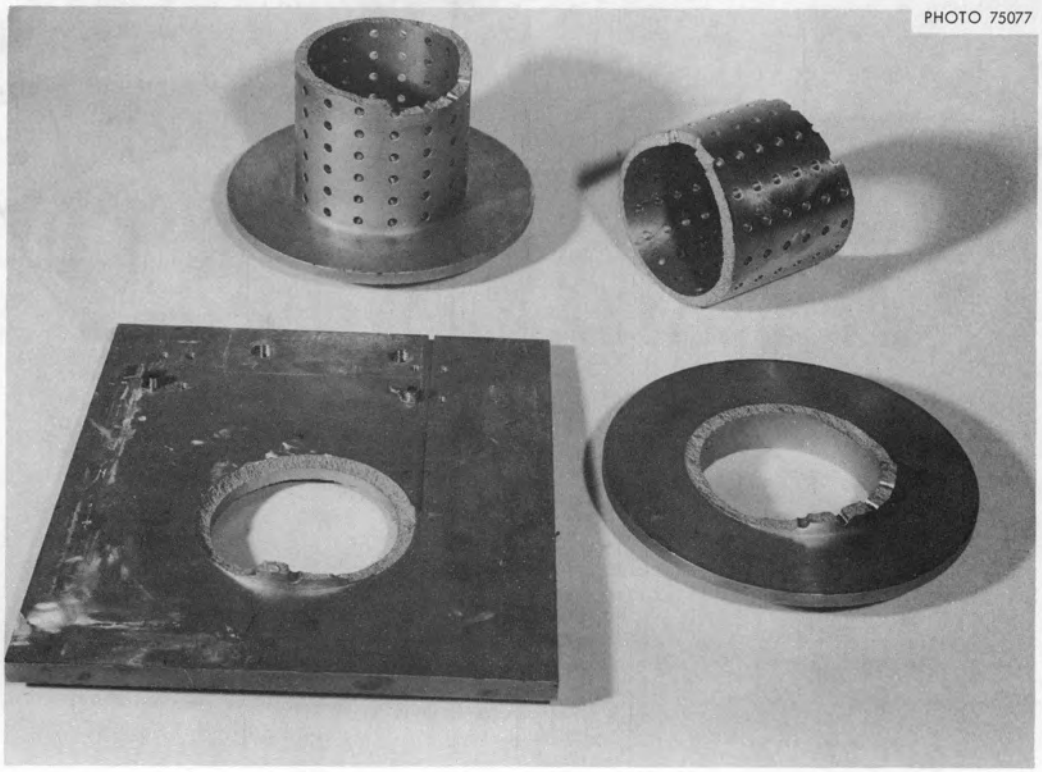


FIGURE 10

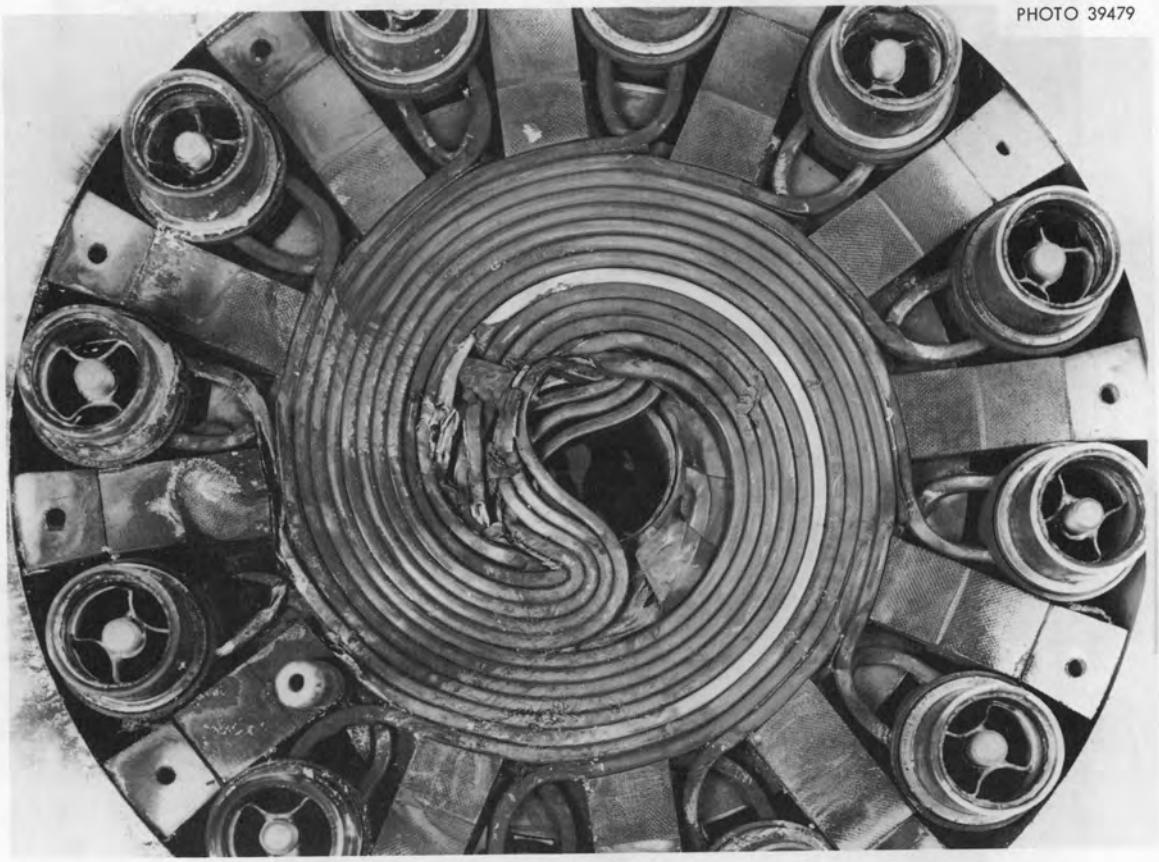


FIGURE 11

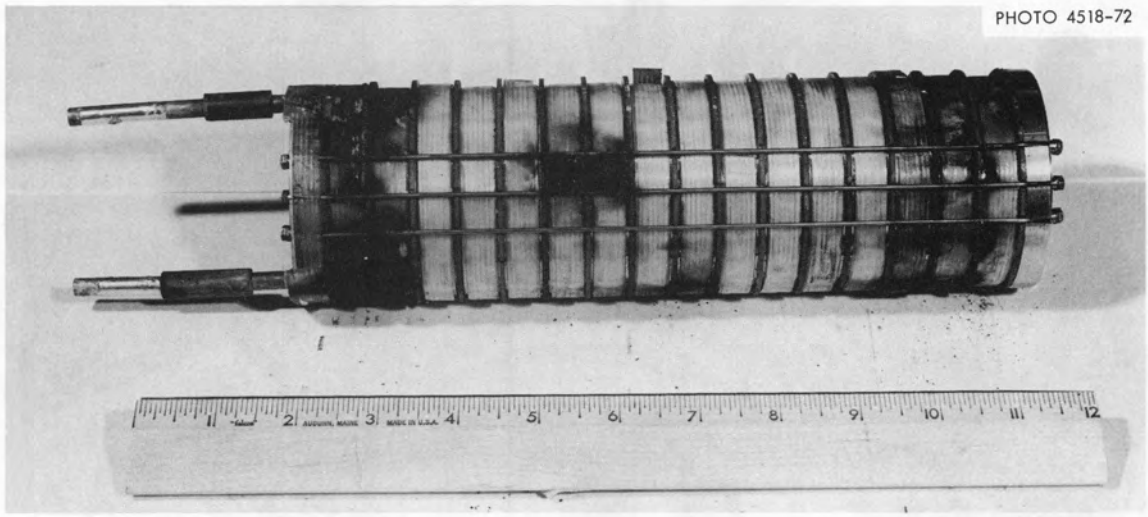


FIGURE 12

FIGURE 13

ORNL DWG. 73-4604

Illustrations of Class I Injuries, Those Due to the Delivery of Energy in Excess of Local or Whole Body Injury Thresholds

Type of Energy Delivered	Primary Injury Produced
Mechanical	Displacement, tearing, breaking and crushing, predominantly at tissue and organ levels of body organization. Majority of injuries are in this group.
Thermal	Inflammation, coagulation, charring, and incineration at all levels of body organization.
Electrical	Interference with neuro-muscular function, and coagulation, charring and incineration, at all levels of body organization.
Ionizing Radiation	Disruption of cellular and subcellular components and function.
Chemical	Generally specific for each group or substance.

From N. V. Steere, *H. of Laboratory Safety*

ORNL DWG. 73-4935

Illustration of Class II Injuries, Those Due to Interference with Normal Local or Whole Body Energy Exchange

Type of Energy Exchange Interfered with	Types of Injury or Derangement Produced
Oxygen Utilization	Physiologic impairment, tissue or whole body death.
Thermal	Physiologic impairment, tissue or whole body death.

From N. V. Steere, *H. of Laboratory Safety*

FIGURE 14

ORNL DWG. 73-4603

60 Hertz Effects on 150 lb Man

Imperceptible	0 – 1 ma
Perceptible, Mild	1 – 3 ma
Annoying, Painful	3 – 10 ma
Paralyzing, "no-let-go"	⩾ 10 ma
Asphyxiation, Unconsciousness	⩾ 30 ma
Fibrillation, Loss of Circulation	80/240 ma – 4a(5 sec.)
Heart Paralysis Threshold	4a approx.
Burning, Heat Damage	⩾ 5a
Electric Fences	10–20 KV, 5 ma Max, 1 pulse/sec
Body Internal Resistance	≈ 500 Ω

Source: R. H. Lee, p. 33 of ISA MONOGRAPH #110, *Electrical Safety Practices*

FIGURE 15

ORNL DWG. 73-4602

RECOMMENDED SAFETY PRECAUTIONS

1. IN DESIGN, CONSIDER ALL FAILURE POSSIBILITIES, & DESIGN CONSERVATIVELY WHERE POSSIBLE.
2. INSTALL & PERIODICALLY EXERCISE INTERLOCKS
3. REMOVE LOOSE METAL.
4. PROVIDE TRANSPARENT PERSONNEL SHIELD.
5. DON'T OPERATE ALONE.
6. IN OPERATION, BE AWARE.

FIGURE 16