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SUPERCONDUCTING MAGNETS IN HIGH RADIATION ENVIRONMENTS: DESIGN PROBLEMS AND SOLUTIONS*

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ABSTRACT

As part of the Stanford Linear Collider Project, three high-field superconducting solenoid magnets are used to rotate the spin direction of a polarized electron beam. The magnets are installed in a high-radiation environment, where they will receive a dose of approximately 10^3 rad per hour, or 10^8 rad over their lifetimes. This level of radiation and the location in which the magnets are installed, some 10 meters below ground in contiguous tunnels, required careful selection of materials for the construction of the solenoids and their ancillary cryogenic equipment, as well as the development of compatible component designs. This paper describes the materials used and the design of the equipment appropriate for the application. Included are summaries of the physical and mechanical properties of the materials and how they behave when irradiated.

INTRODUCTION

Three superconducting solenoid magnets and their associated systems are part of the polarized electron beam facility to be installed at the Stanford Linear Collider. As an intense electron beam passes axially through each solenoid, high magnetic field quality, precise mechanical alignment and long-term stability are essential requirements. The magnets are located some ten meters below ground, in the immediate proximity of other beam lines and in a radiation field that may exceed 10^3 rad per hour at each magnet. All services, monitoring and control must therefore be remote and located above ground, as access to the accelerator housing and magnets is prohibited during operation.

From the beginning of this project, we were much concerned with the high radiation levels and the remoteness of the magnets from occupied service buildings. A closed refrigeration cycle was initially not included in the specifications; nonintrusive weekly batch refilling of local liquid helium storage dewars was mandated, with the option of adding a refrigerator at a later date.

Figure 1 is a schematic representation of one of the solenoid installations. The magnet is supplied with cryogens through a composite transfer line containing both the liquid nitrogen and liquid helium circuits in a common vacuum enclosure, connected to storage vessels above ground.

The environmental parameters of the facility are as follows:

- *Ionizing radiation:* 10^3 rad per hour, or 10^8 rad over the lifetime of the system.
- *Seismic Loads:* California earthquake loads of 0.75 G in any direction, without internal failures or personnel hazards.

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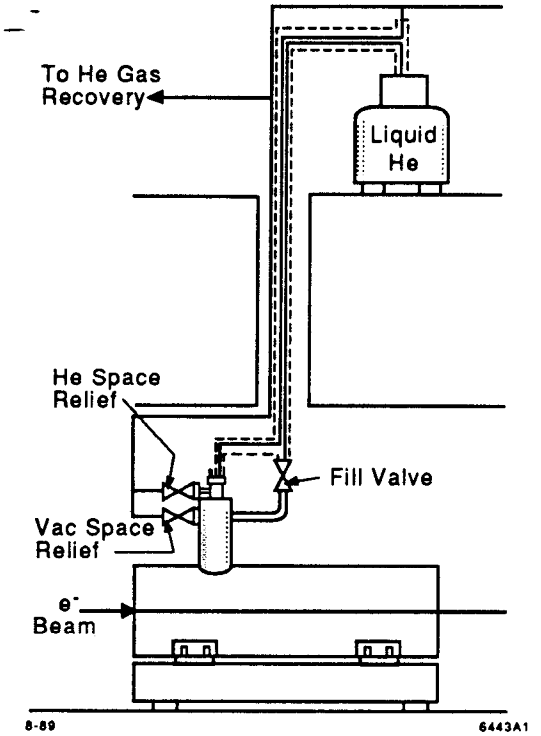

FIGURE 1. Schematic representation of one magnet installation.

- *Access:* Severely limited in space by contiguous beam lines, and restricted in time to a few hours of access every month.
- *Duty Cycle:* 5000 charge and discharge cycles over the lifetime of the system.
- *Thermal Cycles:* One cooldown and one warmup to room temperature per month.
- *Operation:* Remote and automatic for all phases except the periodic refilling of the cryogen storage dewars.

The solenoids themselves were fabricated by a commercial company [1] to exacting specifications determined by the beam optics and the environment described above. The design maximum magnetic field is the same for each solenoid, 4.5 T, with an azimuthal variation of the integrated transverse magnetic field at any radius less than 1.25 cm limited to less than ±0.1%. The current is restricted to 150 A at maximum field so as not to exceed the specified heat inleak of 1 W. This thermal load precluded the use of separate field trim windings or multiple joints in the conductor, so that the field accuracy had to be achieved by precision winding of a single, 18.3 km length of rectangular conductor.

The interplay of these seemingly unrelated requirements led to interesting engineering compromises, some of which are discussed here.

GENERAL CONSIDERATIONS

Initially, we considered the ionizing radiation environment and the limited access to be separate issues in the system concept, but as the design proceeded, we developed a design philosophy to minimize the impact of either constraint:

- Organic materials, unless absolutely essential, to be avoided.
- Organic materials demanded by the construction to have physical and mechanical properties which do not substantially degrade after a lifetime exposure to 10^8 rad.
- The properties of all materials used to be supported by a substantial data base of experimental measurements.
- The peripheral components usually associated with superconducting magnets to be certified for use in the environment or redesigned to have the capability or be relocated to unrestricted areas.
- Cooling of the conductor to be by pool boiling helium, with the added requirement of an *in-situ* reservoir of liquid helium sufficient for one refill every 24 hours.

During this process, we realized that while there exists a considerable body of information on the subject of radiation damage, there is a commensurate unevenness in the level of understanding of the effect of radiation on materials, particularly on magnet components. We therefore ranked our magnet subsystems according to the perceived severity of the problems induced in each by the expected radiation damage:

- Insulation, thermal and electrical.
- Superconductor, stabilizer.
- Instrumentation and control.
- Venting, vacuum and safety.
- Structural components and installation supports.

As the last two items either are constructed from materials not affected by ionizing radiation at dose levels of 10^{10} rad, and at the rather modest implied neutron fluences [2], or else are located in unrestricted access areas, we shall not discuss them further here.

TABLE 1. Industrial insulating materials of interest for cryogenic applications involving radiation.

Commercial Standard or Chemical Name	Trade Name® [3]	Description
NEMA/ASTM G–10	Spauldite G–10 G–10CR G–10–773	Glass fabric, epoxy resin [diglycidyl ether of bisphenol A (DGEBA) cured with dicyanodiamide (DCD)].
NEMA/ASTM G–11	Spauldite G–11 G–11CR G–11–963	Glass fabric, high-temperature epoxy resin [diglycidyl ether of bisphenol A (DGEBA) cured with diamino diphenyl sulphone (DDS)].
Polyvinyl formal	Formvar	
Polyimide	H-film, Kapton	$(C_{22}H_{10}N_2O_4)_n$.
S-glass	S–2, S–901 S–994	Silica-alumina-magnesia fiber (high strength and modulus).
E-glass		Lime-alumina-borosilicate fiber (low modulus, good electrical properties).

INSULATION

Table 1 lists the insulating materials selected for the construction. They are materials whose radiation resistance has been well documented in accordance with our design guidelines, and whose behavior at cryogenic temperatures was well known to us.

Several reviews [4 (and references cited therein), 5] have noted that burried in the wealth of experimental data relating to radiation damage is evidence on secondary phenomena, such as localized nuclear heating exacerbated by the reduction in the thermal conductivity of the material. Studies which reported thermal and electrical properties jointly with measurements of the mechanical properties therefore received special attention. Excellent data on the stability of organic insulations were obtained at Oak Ridge National Laboratory [6]. At doses of 2×10^8 rad (γ) the volume resistivities of a bisphenol A epoxy, an inorganic-filled epoxy, a polyvinyl formal wire coating and an FR–5 type glass-epoxy laminate were found to be virtually unchanged. At higher-dosage levels, the mechanical and electrical properties of glass-reinforced epoxy laminates deteriorated significantly [7]. This is shown in Figs. 2 and 3.

The flexural and compressive strengths of G–10CR and G–11CR laminates fall to 10–15% of their original values after γ irradiation to 2.4×10^9 rad, and even lower after 10^{10} rad. As both irradiations were accompanied by fast neutrons at high fluences, we made this data the reference base for our worst-case irradiation scenario, particularly as the measurements were made following a warmup to ambient temperature. Figure 4 shows data obtained at CERN [8], used to validate our design parameters.

Polyvinyl formal is frequently used where thin, uniform and tough, abrasion-resistant wire insulation is required. Its mechanical properties, as a function of radiation dose, are shown in Fig. 5 [9–11].

Polyimide film developed to compete with mylar, a material unstable in a radiation environment, and has the interesting property that its ultimate tensile strength increases to about 5×10^8 rad while its electrical properties remain essentially unchanged [12].

In the solenoid windings, the turn-to-turn insulation is provided by a 12 μm-thick polyvinyl formal coating applied to the superconductor during manufacture, all ground insulation is made from S-glass reinforced DCD-cured G–10CR, while the layer-to-layer insulation is 50 μm-thick polyimide H-film sheet. No impregnation or overbanding is used to hold the superconductor; the precision winding technique and the tight dimensional specifications ensure that the winding tolerances of ±100 μm are maintained. A byproduct of this method of construction is adequate percolation cooling of the innermost layer.

Each coil-containing helium vessel is supported in its vaccum tank by six race-track-

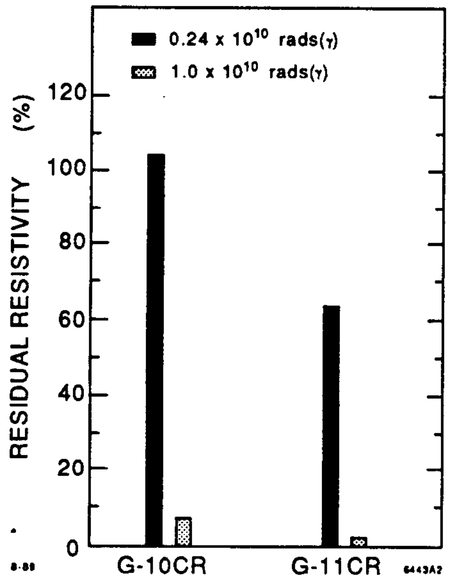

FIGURE 2. Residual electrical resistivity of G-10CR and G-11CR after irradiation at 5 K and warmup to ambient temperature.

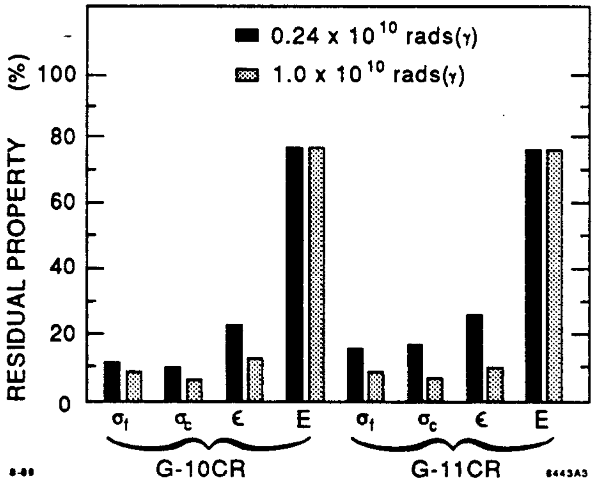

FIGURE 3. Residual mechanical properties of G-10CR and G-11CR (flexural strength σ_f*, strain* ϵ*, and modulus E, and compressive strength* σ_c*) after irradiation at 4 K and warmup to ambient temperature.*

shaped links of unidirectional filament-wound S-glass fibers in a matrix of DDS-cured DGEBA resin. The radiation shields are separately suspended with polydirectionally wound G-10CR rods.

The multilayer insulation blankets thermally insulating the various components inside the cryostat are made from 10–30 layers of 12 μm-thick aluminum foil separated by mats of

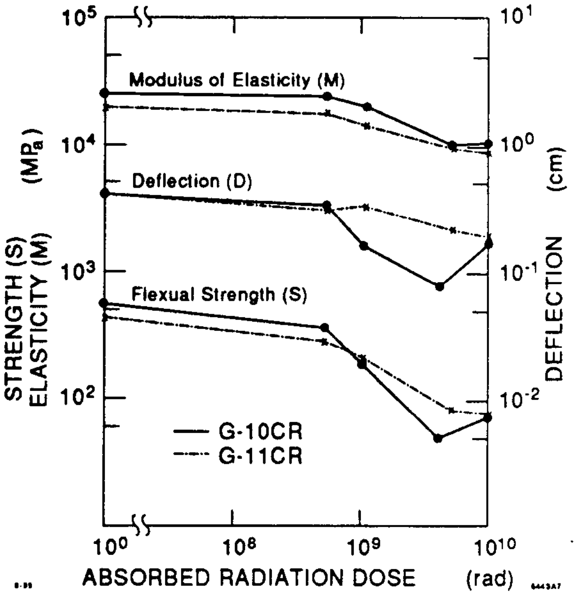

FIGURE 4. The modulus of elasticity, flexural strength and the deflection characteristics of G-10CR and G-11CR at various radiation doses.

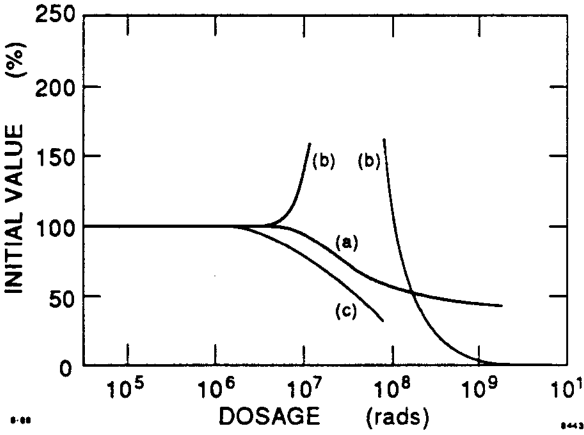

FIGURE 5. Effect of radiation on (a) tensile strength, (b) elongation, and (c) elastic modulus of polyvinyl formal. The initial values are 51 MPa, 2%, and 3.45 GPa, respectively.

unwoven glass fibers. The transfer lines accessing the solenoids are likewise insulated.

SUPERCONDUCTOR AND STABILIZER

There is considerable evidence that the bulk properties of NbTi alloys, T_c and H_{c2} in particular, are decreased very little by irradiation [5]. It also appears that irradiation can enhance the J_c in low J_{c0} materials while in high J_{c0} materials J_c decreases linearly for fluences up to about 4×10^{22} neutrons per m^2, at which point J_c is

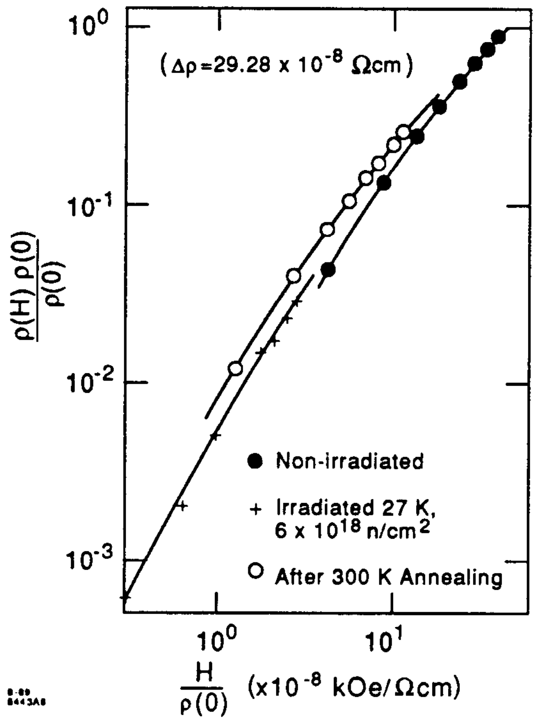

FIGURE 6. Kohler plot for the copper stabilizer in Vacryflux superconducting wire (reference resistivity of the copper = 2.68×10^{-8} *ohm-cm).*

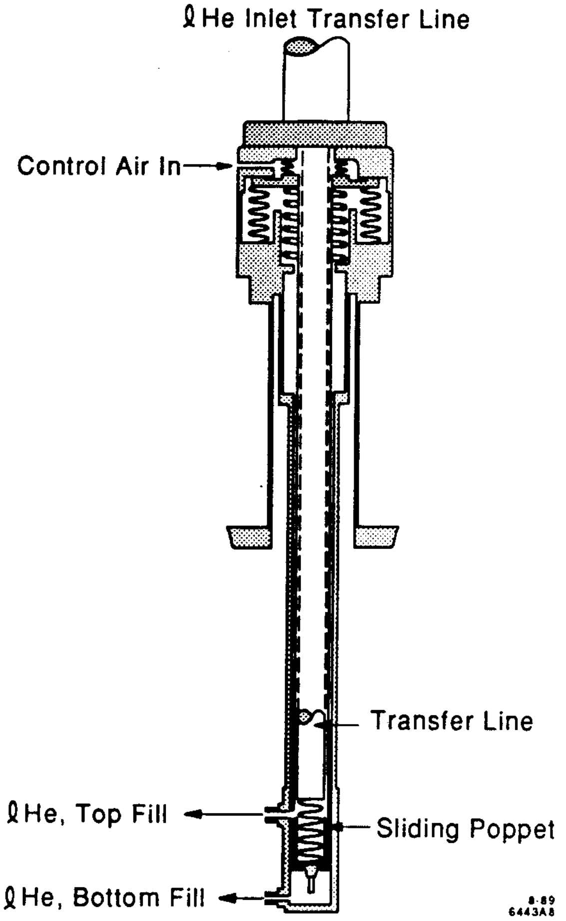

FIGURE 7. The inline three-way cooldown and fill valve.

degraded by about 10%. As the conductor for the solenoids was specified to operate at 60% of its short sample value at maximum field, its performance is not affected.

The magnetoresistance of the copper stabilizer is modified by radiation: the changes due to radiation damage and subsequent treatment are well documented [13]. Kohler's rule is closely obeyed by copper in the magnetic field range of 0–10 T and over a purity range of $200 \leq RRR \leq 7000$ [14]. Figure 6 illustrates the behavior of the copper stabilizer in our Vacryflux® superconducting wire [15,16].

INSTRUMENTATION AND CONTROL

All sensors installed in the magnets are radiation resistant:

- *Temperature:* The surface thermometer gauges are foils of resistance-compensating alloys of nickel and manganin.
- *Pressure:* The magnet-mounted pressure transducers have 17-4PH stainless steel diaphragms to which compensated foil strain gauges are bonded.
- *Vacuum:* The all-metal cold cathode ionization gauges and thermocouple gauges which monitor the vacuum are rated to 10^{10} rad.
- *Control:* Two inline, bellows sealed, three-way valves control the cooldown and fill sequences in each magnet (Fig. 7). No elastomers or composites of any kind are used. The valves are remotely actuated by compressed air.

CONCLUSIONS

Three magnet systems were designed and built according to the philosophy described above. The fully configured solenoids have been tested successfully for several hundred hours each, and are now awaiting installation in the accelerator.

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