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Title: QUASI-CONTINUOUS MAGNETS

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Quasi-Continuous Magnets

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Abstract—The National High Magnetic Field Laboratory (NHMFL) is now completing a quasi-continuous magnet which will sustain a constant field of 60 T for 100 ms in a 32-mm 77 K bore. This magnet consists of nine mechanically independent, nested, liquid nitrogen cooled coils which are individually reinforced by high strength stainless steel outer shells. The coils were wound from rectangular large cross-section, high strength, high conductivity copper conductor insulated with polyimide and fiberglass tapes. After winding, the coils were inserted into closely fitted, stainless steel reinforcing shells and impregnated with epoxy resin. Design, analysis, material, fabrication and operational issues for this class of magnets will be reviewed. Fabrication and quality assurance testing of the 60 T coil set will be covered in detail. Future growth of and possible links from this technology to other magnet systems will be discussed. Needed improvements in design, analysis, materials, and fabrication techniques will be outlined.

I. INTRODUCTION

Quasi-Continuous magnets are controlled power pulsed research magnets. They produce higher fields than hybrid or resistive magnets and have longer field duration than capacitor-driven or explosive driven magnets. The pulse shapes of quasi-continuous magnets can be specified and controlled using commercial power or mechanical energy storage. Fig. 1 shows examples of pulse shapes which may be produced by a high field quasi-continuous magnet. A pioneering 40 T quasi-continuous magnet was in operation for a number of years at the University of Amsterdam. Presently there are two 60 T quasi-continuous magnet development programs underway: the NHMFL magnet being built for operation at Los Alamos National Laboratory and one being built by the University of Amsterdam. The rationale for the construction and operation of this type of research magnet and the design philosophy and specifications for the NHMFL version are given in [1].

II. DESIGN, ANALYSIS, FABRICATION AND OPERATIONAL ISSUES

Quasi-continuous magnet design typically starts with the characteristics of available materials and existing practice in an attempt to produce the required field level, uniformity, duration and bore size. The configuration of conductors and structural reinforcement are the main parameters varied to control mechanical stress and strain and attain a reasonable mechanical fatigue life. Considerations of power requirements and operating voltages and their minimization are included in the design process. The effects of heating, minimizing thermal recovery time between pulses, thermal stress and thermal expansion and contraction are also included. In addition, manufacturability, modularity, assembly, repairs and future upgrade requirements are addressed during magnet design.

Analysis of a quasi-continuous magnet design may begin with a closed form linear elastic orthotropic structural analysis coupled with a circuit analysis of the combined power supply and magnet. After iterations between the structural and circuit analyses which typically include changes in the basic mechanical design and power supply arrangement the process 'closes' with the confirmation of a suitable magnet design and power supply configuration. Analysis continues with finite element analyses of the magnetic loads and magnet structure to confirm the results of the design process and previous closed form analyses. These finite element analyses are typically non-linear to account for thermal effects and elastic and plastic orthotropic behavior of magnet materials; conductors are typically loaded near their yield strength.

Fabrication of a quasi-continuous magnet involves a large investment in magnet coils. There is significant risk of losing a coil during manufacturing. High strength large cross section conductors combined with thin fragile electrical insulation potentially make winding coils difficult. Other fabrication issues of concern are epoxy impregnation of the long and thin coils typical of a quasi-continuous, high repetition rate magnet and the dimensions and weight of the coils. One of the larger coils is 886 mm in diameter and 1145 mm long with a mass of 1460 kg.

The high monetary value, large amount of stored energy and high mechanical loading in a quasi-continuous magnet warrant careful monitoring of the status of the pulse and the coil set. These concerns also justify producing a design which can withstand reasonable power supply excursions from nominal operation, such as a crowbar at the end of a full field flat top pulse. The design should also limit or contain mechanical damage in the event of a coil structural failure.

III. NHMFL 60 T QUASI-CONTINUOUS MAGNET

The NHMFL 60 T quasi-continuous magnet being built at Los Alamos consists of nine mechanically independent, nested coils which are individually reinforced by high strength, stainless steel outer shells. The magnet has a 32 mm diameter usable bore. Fig. 2 shows a sectioned isometric view of a computer solid model of the NHMFL 60 T quasi-continuous magnet. Coils are connected and energized in three electrical circuits. A stainless steel and NEMA G-10 frame supports and positions the coils and busbar within a stainless steel dewar. Coils are liquid nitrogen cooled; liquid nitrogen is drained from the magnet before each pulse. Aluminum oxide dispersion strengthened copper (SCM Metal Products GlidCop AL-15™ and AL-60™) is used for coil conductor and leads and for busbar located in high field regions. Conductors are insulated with E-glass fabric tape and Kapton™ tape. Coils are vacuum impregnated with an anhydride cured epoxy resin (Composite Technology Development CTD-101K™). The reinforcement shells of the inner eight coils are made of seamless, annealed nitrogen-alloyed manganese stainless steel: Fe-21Cr-6Ni-9Mn (Nitronic-40™). The magnet is powered by a 400 MW power supply; a large converted utility generator is utilized for energy storage. These systems have been described previously [2,3]. The magnet stores approximately 90 MJ of inductive energy at peak field. The magnet is designed to withstand a crowbar at the end of peak flat top field without damage. The magnet re-cools to 77 K within one hour following a pulse.

IV. NHMFL 60 T MAGNET FABRICATION AND QUALITY ASSURANCE

A. Coil Fabrication Background

Los Alamos contracted with Everson Electric Company for the prototype manufacture of two of the smallest coils during 1994. These innermost coils were successfully tested at Los Alamos and showed that the insulation scheme and manufacturing methods employed resulted in successful magnet coils. Everson Electric commenced production efforts of all nine coils in January 1995 and delivered the last coils by year end.

The fabrication of these coils posed several significant challenges. During all coil manufacturing operations from winding through final impregnation, tension had to be maintained due to the high degree of springback of the conductor and to maintain very stringent dimensional control. The high yield strength of the conductor demanded that coil forming tooling employ a mechanical advantage. The relatively fragile, thin high voltage insulation scheme required careful handling techniques. The large magnetic loads on the conductors required that all voids within the coil and lead areas be filled with NEMA G-10.

The coils also varied significantly in size ranging from 64 mm to 886 mm outer diameter with masses ranging from 3.4 kg through 1460 kg. Close dimensional tolerances for the coil inner diameters and coil lengths and conductor pitch and camber relative to the mandrels were specified. The locations of transitions or crossovers from layer to layer and lead terminations within the coils were also tightly specified. Achieving these tolerances of size, form and location required very demanding dimensional control of the winding process and careful fit-up of the G-10 fillers and support pieces.

B. Project Management and Quality Assurance

Everson Electric developed comprehensive Manufacturing Process Orders (MPO's) which detailed each step of the manufacturing process, listed all parts and materials, and provided for recording of the completion of each operation. In addition, required dimensional measurements, electrical checks, approvals and inspections by operators, Quality Assurance personnel, engineering and customer representatives were recorded in the MPO documentation.

Everson Electric performed checks of the coil at intermediate steps during the fabrication process. In particular, dimensional conformance and insulation integrity checks were performed during the initial stages of the winding of each coil. The electrical tests consisted of megger and high-pot testing and DC resistance tests. Since the exact dimensions and turn count of the final form of the coils could vary based upon the lay of the conductor, tension maintained, insulation thickness and other factors, the mechanical measurements aided in ensuring that the final required dimensions and turn counts were attained. In addition, these measurements provided information necessary to complete the manufacture of fitted parts used later in the coil fabrication.

C. Fabrication Process Description

A winding train was set up with conductor preparation and insulation stations which were synchronized automatically with the winding machine. The winding train consisted of a pay-off reel which supplied conductor to grit blasting, cleaning, priming and insulation stations prior to the winding machine.

The pay-off reel was mounted on a station which utilized a caliper type braking mechanism to maintain the proper back tension for each coil. A cleaning station removed residual drawing lubricant and dirt. The grit blasting station prepared the conductor surface for better epoxy bonding. A second cleaning station removed residual matter from the grit blasting operation. The priming station sprayed an adhesive primer onto the conductor, again for better epoxy bonding. An automatic taping head applied the half lapped and staggered Kapton™ and E-glass cloth insulation material.

The conductor was then fed to the computer controlled winding machine. The winding machine synchronously traversed across the mandrel and accurately controlled the pitch and lay of the conductor to within thousandths of an inch. Coils one through five were wound utilizing one continuous length of conductor for each coil. Coils six through nine required splices to be made at the ends of each layer of the winding.

In order to maintain tension throughout the winding of the smaller coils, S-bends or transitions to reverse the pitch were made in the conductor just prior to the winding it onto the mandrel. The transition sections were made by the use of forming tools which employed a mechanical advantage to obtain the desired contour. Electrical insulation damaged in the conductor forming process was removed and replaced. The fitted G-10 ramp-up filler pieces were installed to support and position the conductor as it was wound into the coil.

Layer transitions in the larger coils were made by clamping the conductor to the mandrel and then splicing on the conductor from the new reel. A typical splice is shown in Fig. 3. The splices were made by removing the insulation from the conductor in the heat affected zones. Then the joint area surface was prepared and heat sinks and fences were applied to limit the heat effected zone of the brazing operation. The joint was cleaned, re-primed, re-insulated and wound into the coil supported by the fitted G-10 machined filler pieces. Precise location of the transition bends and splices before the winding conductor onto the mandrel was a demanding aspect of the coil manufacturing.

The leads of the coils interlock as shown in Fig. 4; this feature prevents the coils from unwinding. This lead interlocking was accomplished by arranging and winding the coil so that the innermost and outermost layer terminations meet at the same plane from opposite directions. The outer lead was pulled over and past the inner lead then allowed to uncoil slightly against the inner lead with a small G-10 filler block in between. This lead arrangement also served to return a significant portion of the mechanical loads into the conductor and then to the external support shell. This reduced the dependence upon the shear strength of the electrical insulation and epoxy system at the end turns.

The mandrel or coil winding form for each of the coils also acted as the inner wall of the potting mold; the mandrel was wrapped with mold release prior to starting the winding process. The reinforcing shell inner surface served as the outer wall of the potting mold. Upon completion of the winding, the coil was measured and the inner bore of the shell machined to accurately match its outer diameter. In some cases the shell was heated to 125 °C to obtain additional clearance for assembly. Centering rings were installed on the ends of the coil to ensure proper axial placement of the coil relative to the outer shell and mandrel during potting. End caps were placed and sealed onto the tops and bottoms of the mandrel and reinforcing shell to complete the potting mold.

The coil was vacuum pressure impregnated with CTD-101K™ epoxy resin. The resin was mixed and heated under vacuum then pushed under pressure into the mold until resin could be seen in a clear riser tube above the top most point of the coil. The coil assembly was then cured and post cured at specified temperatures and pressures.

The mandrels for the smaller coils were removed by collapsing the mandrel. The larger coil mandrels were machined with a slight taper to ease in removal. A combination of axially applied hydraulic press force and thermal contraction of the mandrel also aided in the removal of the mandrel from the larger coils.

A final series of electrical tests were performed which included DC resistance measurements, megger, high pot and impulse tests. The smaller coils were tested to 4 kV and the larger coils to 8 kV for ground insulation integrity. Electrical acceptance tests at Los Alamos were performed on each coil to 90 % of the factory levels.

V. FUTURE GROWTH OF QUASI-CONTINUOUS MAGNET TECHNOLOGY

Fields of 70 to 80 T in quasi-continuous magnets may be realized by replacing the small inner coils with improved coils incorporating better materials. A second approach would be to install short pulse capacitor driven coils in place of small inner coils. An effort to attain 100 T non-destructively utilizing the second approach in an entirely new magnet has been funded by the United States Department of Energy and is underway in cooperation with the National Science Foundation's NHMFL quasi-continuous magnet efforts.

VI. LINKS TO OTHER MAGNET TECHNOLOGY

Quasi-continuous magnet technology may be applicable for solenoids or other types of magnet coils operating at low or high temperatures or under high stress conditions. One possible application for this technology is electromagnetic pumps for molten sodium; electromagnetic pump coils operate under high temperature and moderate stress conditions. Other magnets like Tokamak type fusion machine central solenoids, high repetition rate pulsed high field magnets for neutron scattering experiments and high field, superconducting, NMR solenoids experience loading conditions similar to quasi-continuous magnets. Quasi-continuous magnet technology may be of some benefit in these areas.

VII. DESIRABLE TECHNOLOGY AND MATERIAL IMPROVEMENTS

In the area of design, a better linkage of power supply, mechanical arrangements, stress, strain and thermal management issues in the design iteration process is needed. The rigor of design process needs improvement; it is now very discontinuous and non-linear. It is difficult to determine optimum design points when rendering a quasi-continuous magnet design.

Analysis of quasi-continuous magnets would benefit from increased material property data especially at temperatures at and slightly above 77 K. Analysis accuracy would also be improved if finite element modeling of orthotropic conductor properties combined with plasticity is realized. This requirement of orthotropic plasticity finite element modeling will be increasingly important with the use of the higher performance micro-composite conductors which are likely to have highly orthotropic mechanical properties.

Advances in quasi-continuous magnet technology requires higher strength conductors with adequate cross-sections and lengths. Currently, the more promising candidate materials for these conductors are CuNb, CuAg and GlidCop™ with Nb. Higher strength and stiffness reinforcement materials are also needed. Candidates are carbon fiber composites, maraging steels toughened by grain refinement heat treatment and Nitronic-40™ strengthened by cold working. Coils for quasi-continuous high field magnet service could be improved by using insulating resins with good thermal shock resistance and low viscosity for vacuum impregnation. Resins with these properties are not currently commercially available.

Better methods of splicing and lead attachment for high strength micro-composite conductors and for zones near electrical insulation need to be developed. Available low temperature solders are brittle at quasi-continuous magnet cryogenic operating temperatures. The temperatures required for brazing destroy the high performance metallurgical structure and damage adjacent electrical insulation. Mechanical conductor joints are bulky and potentially unreliable over the operating temperature range and under the mechanical loads experienced.

VIII. SUMMARY

Quasi-continuous magnet technology is being extended to reach fields of 60 T through the use of improved designs and better materials. The NHMFL 60 T magnet coil set has been successfully fabricated and the magnet is being assembled with commissioning scheduled for later this year. The materials and technology developed for quasi-continuos magnets may be applicable to other magnetic systems. There is potential for improvement of quasi-continuous magnet performance with better materials and technology developments.

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[3] J. B. Schillig, H. J. Boenig, J. D. Rogers, and J. R. Sims, "Design of a 400 MW power supply for a 60 T pulsed magnet," *IEEE Trans. Magn.*, pp. 1770-1773, July 1994.

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Quasi-Continuous Magnets

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Answers to Discussion Questions:

Question—Please comment on the effectiveness of load transfer from windings to cylindrical shell. Assuming that radial tightness is important, how is that achieved in your manufacturing process? John Miller, NHMFL.

Answer—Significant portions of the axial and radial magnetic loads in the NHMFL 60 T quasi-continuous magnet coils are transferred from the windings to the external shells. Load transfer occurs by means of radial interface pressure and traction forces between the windings and the shells. The amount of load transfer is governed by the relative stiffnesses of the windings and the external reinforcing shells and by the amount of low stiffness material such as electrical insulation or epoxy resin located between the conductors of the windings and the shells. Clearance between the windings and the shell reduces the load transfer by reducing the effective radial stiffness of the shell. Sources of winding to shell clearance are differences in thermal contraction upon cooling from room temperature to 77 K, fabrication tolerances and clearance allowances for assembly of the windings into the shells. Radial tightness of the winding to shell interface is very important and was achieved in the manufacturing of the NHMFL 60 T quasi-continuous coils by measuring the outside diameter of the winding upon completion and then finishing the bore of the shell to match with only a small amount of allowed clearance. Allowed clearance increased as the diameters of the coils increased. It is important to note that the insertion of the winding into the reinforcing shell was done before epoxy impregnation. The unimpregnated winding is still relatively compliant and may be inserted into a shell with less concern for matching shapes and roundness of the contact interface and with no concern for damaging the epoxy.

Question—How do you handle coil/support interface? There are clearly very large cool-down and energization relative displacements? Bruce Montgomery, MIT.

Answer—The coil/ support interface is made tight but the coil impregnation epoxy is not allowed to bond to the support or reinforcing shell inner surface. The reinforcing shell inner surface is machined to a smooth finish and the coil is covered with a Tedlar™ release film to prevent bonding at the coil/support interface. This arrangement allows the coil to thermally contract relative to the support in both the axial and radial directions. Axial contraction of the coil relative to the support due to energization is also allowed. During coil energization axial contraction is eventually limited as axial forces reach equilibrium with the traction forces produced by radial pressure and interface friction.

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Answers to Discussion Questions continued:

Question—Are eddy currents any problem in the steel support cylinders? Bruce Montgomery, MIT.

Answer—The Nitronic-40™ steel support cylinders have an electrical resistivity similar to that of 304 stainless steel and this relatively high resistivity combined with the comparatively slow rise of current and field in the magnet reduces eddy current heating and losses. It is calculated that the larger and thicker shells in the magnet will experience an increase in temperature of approximately 8 K during field rise and again during field decline.

Question—Is there any trouble with the wicking of the resin in your Kapton™/S2 glass? Does the Kapton™ act as a resin blocker? Comment— On the TPX project, Westinghouse found that this method didn't bond as well. Everson Electric should have all the information. Chris Rey, Babcock and Wilcox.

Answer—The Kapton™ tape and E-glass cloth tape were arranged staggered and lapped to ensure a wicking path for the epoxy to reach the conductor surface. In addition, there is a layer of E-glass cloth between each layer of conductor in the coils to provide a 'manifold' for axial and tangential distribution of epoxy resin throughout the coil. These features combined with a low viscosity, long pot life epoxy resin greatly reduced the possibility that the epoxy resin could be blocked from reaching all parts of the insulation system. This system has been used extensively by a commercial coil manufacturer and when implemented in its entirety produces good bonding to the conductor combined with the good electrical insulation properties of Kapton™.

EXAMPLES OF PULSE SHAPES FROM QUASI-CONTINUOUS MAGNET

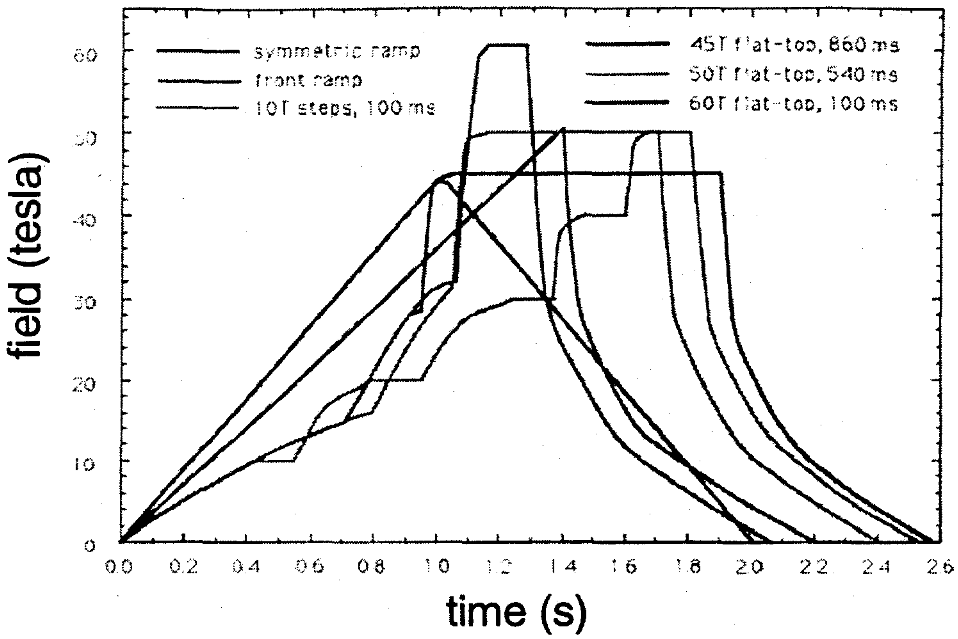

Figure 1

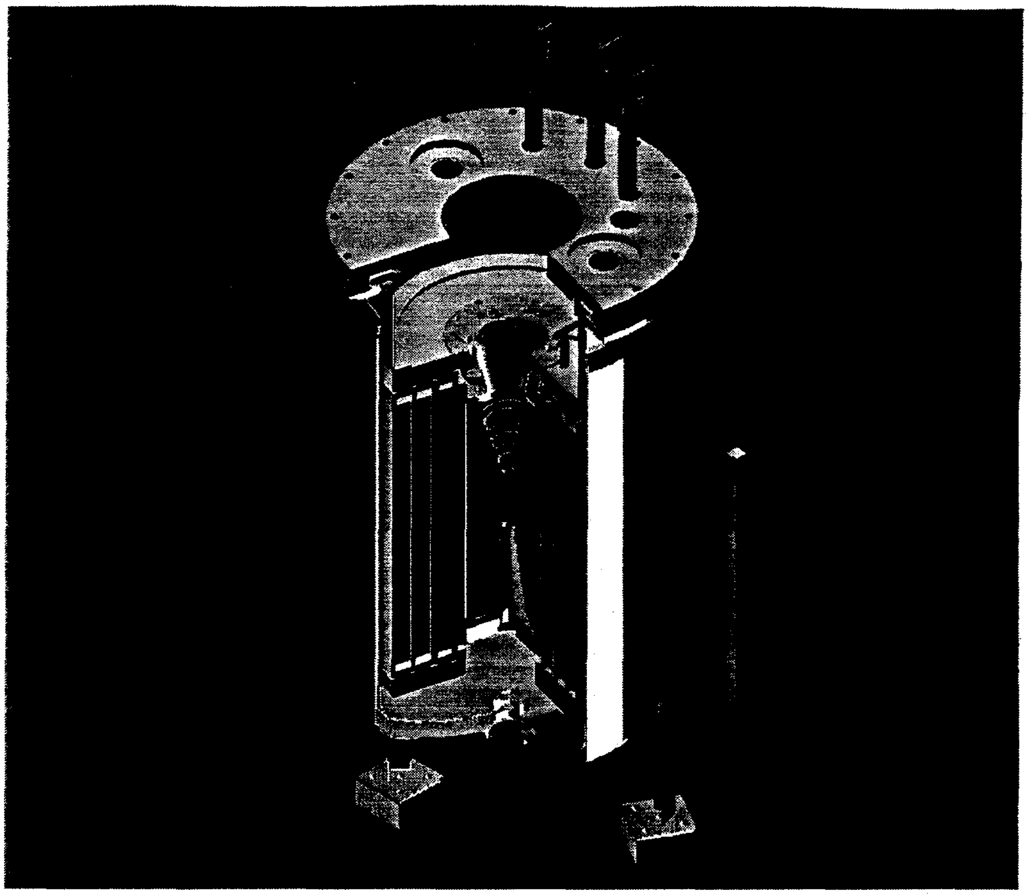

Figure 2

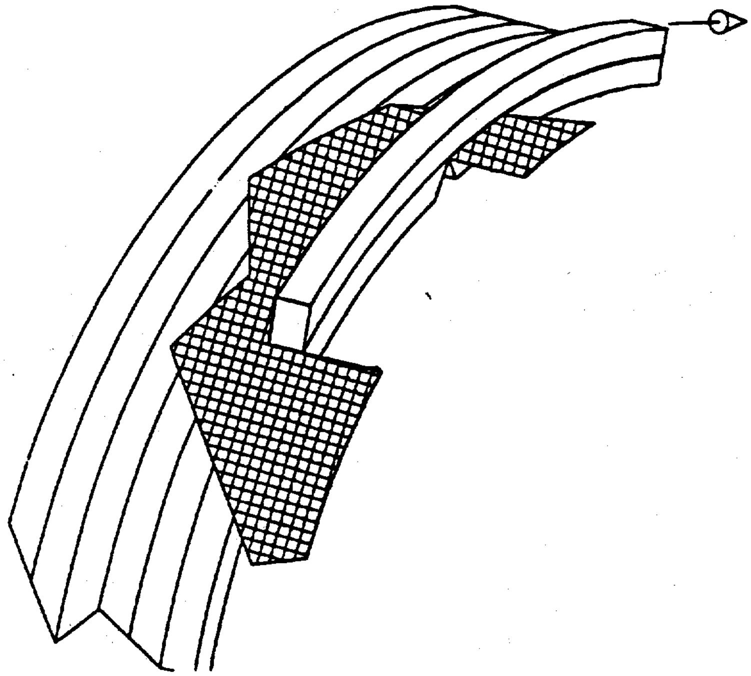

Figure 3

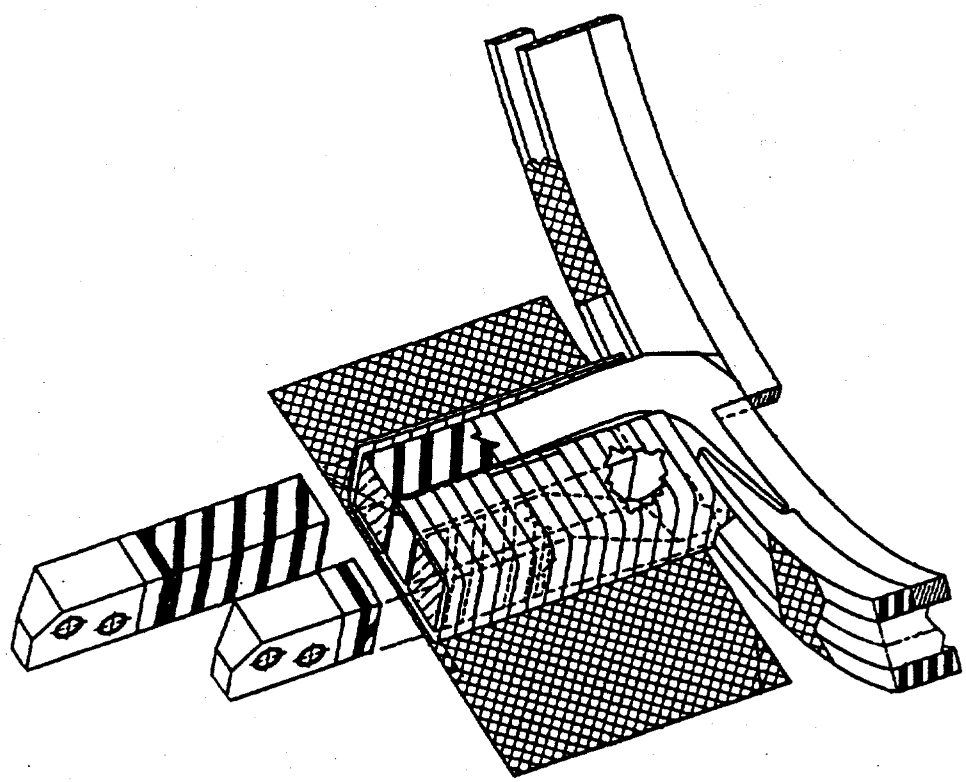

Figure 4