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GENERAL DYNAMICS CONVAIR DIVISION APPROACH TO STRUCTURAL ANALYSIS OF LARGE SUPERCONDUCTING COILS

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Summary

The analysis and design of large superconducting magnets for nuclear fusion reactors involves a broad spectrum of engineering disciplines. To ensure structural integrity of these large magnets, in-depth interface and close coordination with all members of the design team are essential. Operational electromagnetic forces generally provide the most significant structural design condition. Temperature gradients which exist during magnet cooldown, warmup, and quench conditions can also create significant design conditions. In addition, manufacturing aspects such as winding preloads, internal winding gaps, and residual welding stresses must be considered. Frequently, geometric constraints exist that create competitive struggles for the space available for structure. This necessitates detail optimization to satisfy design specifications.

To meet these challenging demands, General Dynamics Convair Division has developed integrated analysis procedures to predict structural deformations and material stresses induced during magnet fabrication and operation. These procedures have been successfully used to support the detail design of the General Dynamics Large Coil Program (LCP) for Oak Ridge National Laboratory, and the Mirror Fusion Test Facility (MFTF) magnet system for Lawrence Livermore Laboratory.

This paper describes the overall integrated analysis approach and highlights the results obtained. Most of the procedures and techniques described were developed over the past three years. Starting in late 1976, development began on high-accuracy computer codes for electromagnetic field and force analysis. This effort resulted in completion of a family of computer programs called MAGIC (MAGnetic Integration Calculation). Included in this group of programs is a post-processor called POSTMAGIC that links MAGIC to GDSAP (General Dynamics Structural Analysis Program) by automatically transferring force data. Integrating these computer programs afforded us the capability to readily analyze several different conditions that are anticipated to occur during tokamak operation. During 1977 we initiated the development of the CONVERT program that effectively links our THERMAL ANALYZER program to GDSAP by automatically transferring temperature data. The CONVERT program allowed us the capability to readily predict thermal stresses at several different time phases during the computer-simulated cooldown and warmup cycle. This feature aided us in determining the most crucial time phases and to adjust recommended operating procedure to minimize risk.

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1. Introduction

Integrated procedures have been developed and applied by General Dynamics to analyze large superconducting magnets for nuclear fusion research (Figure 1). Each of the blocks shown on this flow diagram depict a major phase for analyzing a superconducting magnet. The computer programs which are currently employed to support each of these phases are specified in parentheses within each respective block. In actual practice, this cycle usually must be iterated several times to create a cost-effective magnet design meeting all specification requirements. Our objective in developing this intergrated analysis approach was to improve both efficiency and accuracy of analysis.

The main computer program for structural analysis is GDSAP (General Dynamics Structural Analysis Program)[1]. GDSAP performs a linear-elastic, finite-element analysis of three-dimensional structures. GDSAP is based on a family of SAP programs developed by Professor E.L. Wilson of the University of California at Berkeley. The theoretical development of the elements and the solution scheme are essentially the same as SAP II and SAP IV. General Dynamics has added extensive data generation and checking capability and installed a bandwidth minimization module (BANDIT) in the program. In addition, an interactive graphics system allows display of a structural model in both its undeflected (input) shape and in the loaded deflected position.

The primary input data for structural analysis (Figure 1) are coil geometry and specifications, electromagnetic operating forces, and the cooldown/warmup temperature gradients. Computer programs used to develop the latter two items will be described in Sections 2 and 3. Since the magnet structure experiences cyclic stresses during charge/discharge and cooldown/warmup phases, fracture mechanisms analysis is subsequently performed using the FLAGRO (flaw growth) computer program [2]. FLAGRO is a linear-elastic fracture mechanics computer program developed by Rockwell International Corporation for the Space Shuttle program. These procedures have successfully supported the detail design of the General Dynamics Large Coil Program (LCP) for Oak Ridge National Laboratory, and the Mirror Fusion Test Facility (MFTF) magnet system for Lawrence Livermore Laboratory. Highlights of the results obtained have been included. Details pertaining to the structural analysis for both of these major programs can be found in References [3] and [4], respectively.

2. Large Coil Program (LCP)

We are presently under contract to Union Carbide Corporation — Nuclear Division, Oak Ridge National Laboratory (ORNL), to design, develop, and manufacture a large toroidal field magnet to be delivered to ORNL in November 1980. This magnet, plus two others manufactured in the USA and three additional coils from foreign countries, will be tested in the large coil test facility at ORNL. These tests will verify design parameters on six different coil designs and provide sound design information for future tokamak devices such as Engineering Test Facility (ETF) for fusion research.

In the General Dynamics design, the large coil is wound and sealed in approximately 7.6 cm (3.0 inches) thick plate 304L stainless steel case. Case construction including closeout, is accomplished by welding. Much of our development test program has concentrated on the low temperature mechanical properties of the welds and parent materials and reduced weld distortions. An exploded view of the LCP coil is shown in Figure 2.

LCP Coil Characteristics

• **Weight**	**— 42,600 Kg (47 tons)**
• **Size**	**— 5.3m high** **— 3.5m wide** **— 0.75m thick**
• **Operating Current**	**— 10,000 amps**
• **Stored Energy**	**— 137.5 MJ**
• **Cooling**	**— Liquid helium pool boiling at 4.2K**
• **Peak Field**	**— 8 Tesla**
• **NbTi superconductor cable in cop**	**per stabilizer**
• **All-welded 304L steel case**	

Electromagnetic forces generally establish the main structural design requirements for superconducting magnets. The worst-case in-plane forces acting on the LCP coil for the normal operating condition and the three most severe alternate load conditions are shown in Figure 3. Whenever the currents in all of the tokamak coils are not equal (Figure 3), out-of-plane forces also exist. Figure 4 shows the worst-case out-of-plane loads occurring for alternative load case B. While the magnitude of these out-of-plane loads is small compared to the in-plane loads, their effects are as severe as the in-plane effects and require careful attention in the coil case design to react them efficiently.

During 1977 we developed the MAGIC (MAGnetic Integration Calculation) described in detail in Reference [5] to accurately predict the electromagnetic forces associated with tokamak operation. The inherent accuracy of the program stems from its basic mathematical model in which every conductor of each coil can be modeled as individual current filaments. MAGIC program results have been compared to similar programs which utilized arcs of current density for their mathematical model and excellent agreement has been obtained. As part of the MAGIC development, a post-processor called POSTMAGIC was also created. POSTMAGIC efficiently produces magnetic field distribution for typical operating conditions and automatically generates iso-field contour plots for convenient display of the magnetic field results. A sample iso-field plot is shown in Figure 5. Superimposed on the iso-field lines are the associated electromagnetic force vectors which have been distributed to nine regions. The force vectors were distributed in this fashion for compatibility with the GDSAP (General Dynamics Structural Analysis Program) finite-element model for the LCP also. POSTMAGIC also links MAGIC to GDSAP by automatically generating force input data required for the GDSAP program. Integrating these computer programs allowed ready analysis of several different conditions anticipated for tokamak operation.

Thermal gradient-induced stresses incurred during cooldown and warmup phases of magnet operation can also impose significant design conditions. At General Dynamics, we used our THERMAL ANALYZER computer program to accurately compute the temperature gradients which the magnet components will experience during these conditions. The THERMAL ANALYZER computer program is a general-purpose procedure for the solution of multi-node, finite-difference numerical models of heat transfer problems [6]. Typical time-phased data developed for the LCP coil using this program are shown in Figure 6.

The CONVERT program, effectively linking our THERMAL ANALYZER program to GDSAP by automatically generating compatible temperature data, was initiated in 1977. The CONVERT program allowed prediction of thermal stresses at several different time phases during the computer-simulated cooldown and warmup cycle. This feature aided determination of most crucial time phases and adjustment of recommended operating procedures to minimize risk.

The essential design conditions for the LCP coil are shown in Table I. More importantly, compatible combinations of these individual effects must be developed to properly represent anticipated operating conditions. For example, during normal operation, the following individual effects must be combined:

- Electromagnetic forces for the normal condition plus pulsed field forces.
- Residual thermal strain gradients (induced by differences in the thermal contraction of coil components).
- LHe boiloff internal pressure.
- Seismic effects (if required at the selected operating site).

Also as shown in Table I, combined conditions must be scaled by appropriate safety factors. The ability to combine and scale the anticipated conditions is a valuable benefit of integrated and coordinated procedures. This capability minimizes the risk of overlooking a worst-case condition.

The GDSAP finite-element model of the LCP coil uses plate elements to represent the magnet case structure and rod elements to represent the conductor pack (Figure 7). Nine hoop rod elements represent the conductor pack at a given section. Each rod is assigned axial properties that represent approximately one-ninth of the cross-section. Radial connectors represent the stiffness of the pack in the radial direction. They are activated so as to act only in compression. The electromagnetic forces for all the node points of the simulated conductor pack were generated using a MAGIC program model constructed with matching nodal coordinates. Likewise, the THERMAL ANALYZER model was constructed with its nodal arrangement matching the GDSAP finite elements, thus minimizing problems associated with data transfer to the GDSAP program.

During the initial phase of the LCP coil design, stainless steel straps (tension bands) were uniformly distributed throughout the conductor pack by co-winding them over the conductor layers. These bands helped to restrain the huge radial forces and associated hoop stresses within the conductor pack. The bands were eliminated when GDSAP finite-element analysis revealed that the equivalent amount of material placed in the coil outer ring as added thickness was significantly more efficient. Based on this analysis, the outer ring was designed to be 8.9 cm (3.50 inches) thick. The principal operating stresses for the outer ring are presented in Figure 8. The peak stresses shown are well below the material yield strength of 450 MPa (65 ksi), since the case structure is designed to keep the combined stresses reacted by the conductor within the elastic range.

The out-of-plane forces for the alternative or fault condition in which one magnet in the tokamak has zero current while the others are fully charged pose a very challenging design problem. Figure 8 depicts the structural severity of this condition. For the LCP coil design, side plates 7.3 cm (2.86 inches) thick were required to react the huge bending moments caused by the side forces shown in Figure 4. The resulting principal stresses for the worst-case conditions are shown in Figure 9. Designers of future tokamak should give consideration to either preventing fault conditions or providing coil-to-coil structure to more efficiently react these out-of-plane forces.

3. MIRROR FUSION TEST FACLITY (MFTF) MAGNET SYSTEM

In October 1978, a confirmatory analysis and the detailed design of the MFTF magnet system was completed for Lawrence Livermore Laboratory (LLL). The intense 5½ month effort emphasized producibility and structural integrity. LLL is presently winding the superconducting coils and procuring magnet components. Operation of MFTF in 1981 will establish technical feasibility of the mirror fusion concept. An assembly view of the Yin-Yang magnet pair is shown in Figure 10.

MFTF Coil Characteristics

- **Weight** — 311,100 Kg (343 tons)
- **Size** — 8 meter (spherical)
- **Operating Current** — 5,775 amps
- **Stored Energy** — 500 MJ
- **Cooling** — Liquid Helium pool boiling
- **Conductor** — Copper stabilized NbTi
- **Peak Field Strength** — 7.68 Tesla

The GDSAP finite-element model developed for structural analysis of the MFTF magnet system is shown in Figure 11. In this model, six hoop-rod elements are used to simulate the axial stiffness of conductor pack. Similar to the LCP model, radial connections simulate the transverse stiffness of the pack. The electromagnetic operating forces for the MFTF magnet system were computed by Lawrence Livermore Laboratory staff using their in-house developed computer program called EFFI (Electromagnetic Field, Force, and Inductance)[7]. The complex force distribution within the MFTF magnet system during normal operation is depicted in Figure 12. As shown, the induced spreading force tending to open the lobes of each magnet is 52.62×10^6 Newtons (11×10^6 pounds) per quarter magnet section. This huge force establishes the primary structural design condition for the MFTF magnet systems. To link the EFFI program to GDSAP, a special-purpose linking program was developed.

Thermal gradients were derived from cooldown and warmup analysis simulations using our THERMAL ANALYZER program. Details of this activity are described in depth in another General Dynamics paper presented at this conference.

Structural analysis performed on the MFTF magnet system resulted in several structural design refinements. The most significant changes include the addition of the side stiffeners shown in Figure 10 to react the 20.68 MPa (3000 psi) pressure exerted by the conductor pack. Also, local thickening of structural case plate material up to 12.7 cm (5 inches) thick in the intercoil member attachment areas was required to react the interactive forces between the two coils.

The resulting principal stresses predicted for the case structure for the normal operating condition are shown in Figure 13 (electromagnetic loads only). Peak stresses in the critical minor radius region for the complete normal operating condition approach 550 MPa (80 ksi). To sustain these high stresses, a special chemistry of nitrogen-strengthened, stainless steel designated 304LN with a yield strength of 825 MPa (120 ksi) has been developed for the structural components.

4. CONCLUSIONS

The analysis experience that we gained on the LCP and MFTF programs has reinforced our opinion that detail computer analysis of large superconducting magnets is essential to ensure structural integrity. Linking our computer analysis program into an integrated procedure has minimized the error-prone drudgery associated with manual data transfer. This capability enables us to accurately assemble compatible operating conditions, efficiently identify and evaluate critical design conditions, and optimize the magnet structure to meet specification requirements.

References

1. M.J. Cronk, *Solid Sap: User's Manual P5679,* Report NO. CASD-CIH-74-008, General Dynamics Convair, October 1977.
2. K.R. Johnson, et al, *Instruction Manual for Crack Propagation Predictive Analysis Computer Program, FLAGRO (Release 2)* Rockwell International Corp. Space Division April 1975.
3. D.S. Hackley, et al, *Large Coil Program Phase II Final Report,* Report No. 91Z0080-1, General Dynamics Convair, February 1979.
4. J.W. Wohlwend, et al, *Structural Analysis of the Magnet System for the Mirror Fusion Test Facility (MFTF),* Report No. CASD-LLL-78-003, General Dynamics Convair Division, October 1978.
5. R.W. Baldi and D.W. Lieurance, *Magnetic Integration Calculations Computer Program, CASD-ERR-77-051, General Dynamics Convair Division, December 1977.*
6. *R.F. O'Neill and E.R. Neuharth, Convair Thermal Analyzer, Computer Program No. P4560,* Report. No. GDC-BTD69-005A, General Dynamics Convair, 29 May 1969.
7. S.J. Sackett, *EFFI — A Code for Calculating the Electromagnetic Field, Force, and Inductance in Coil Systems of Arbitrary Geometry.* Report No. UCID-17621, Lawrence Livermore Lab, 5 May 1977.

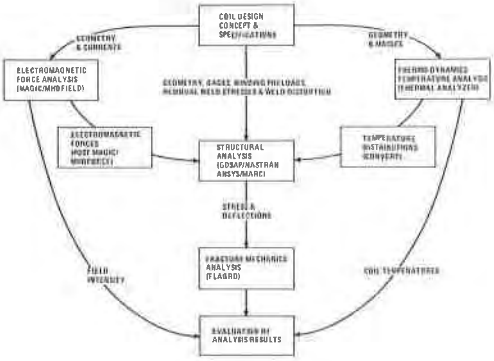


Figure 1. General Dynamics' integrated analysis procedure for superconducting magnets.

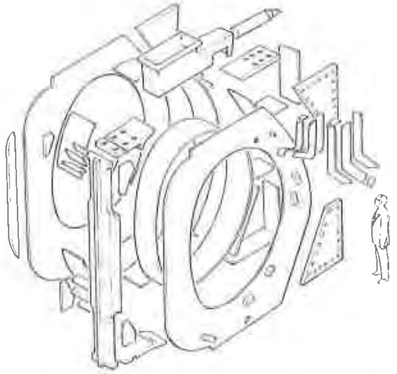
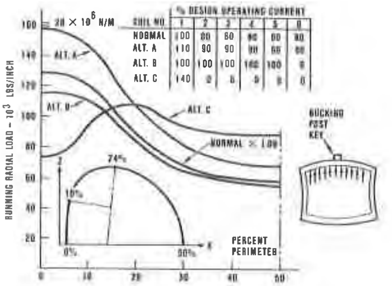


Figure 2. *Exploded view of General Dynamics magnet structure for the Large Coil Program.*



COIL NO.	1	2	3	4	5	6
	% DESIGN OPERATING CURRENT					
NORMAL	100	80	80	[illegible]	80	80
ALT. A	110	90	90	[illegible]	[illegible]	[illegible]
ALT. B	100	100	100	100	100	0
ALT. C	140	0	0	0	0	0

Figure 3. *LCP in-plane electromagnetic running forces (MAGIC based data).*

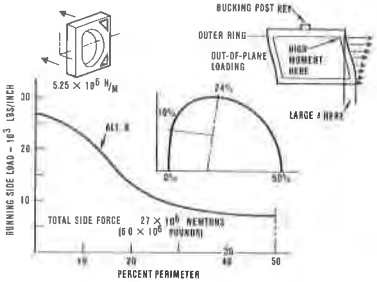


Figure 4. *LCP out-of-plane electromagnetic running forces (MAGIC based data).*

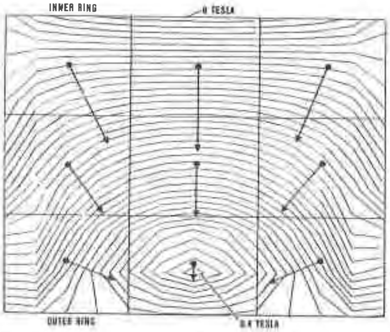


Figure 5. *LCP iso-field plots with associated lumped electromagnetic force vectors for normal operating conditions.*

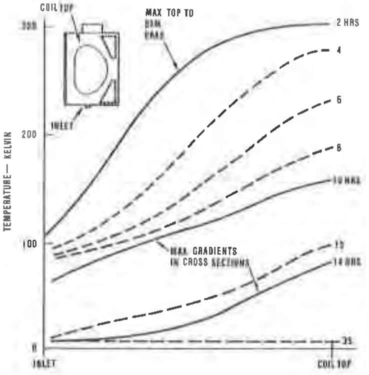
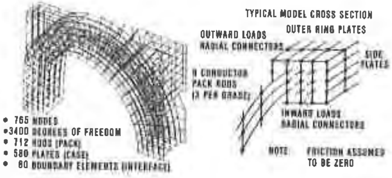


Figure 6. *LCP perimeter temperature gradients at various times during magnet cooldown.*



- 765 NODES
- 3400 DEGREES OF FREEDOM
- 712 RODS (PACK)
- 580 PLATES (CASE)
- 80 BOUNDARY ELEMENTS (INTERFACE)

Figure 7. *LCP finite element model for structural analysis.*

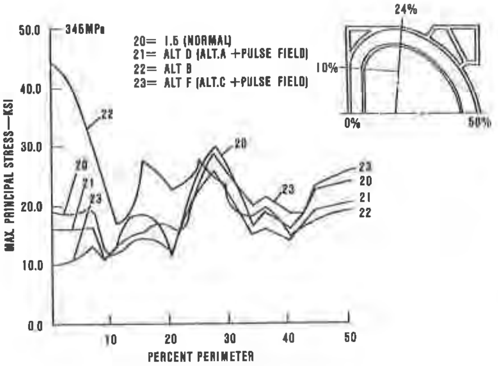


Figure 8. LCP principal stresses in the structural case outer ring for the most severe design conditions.

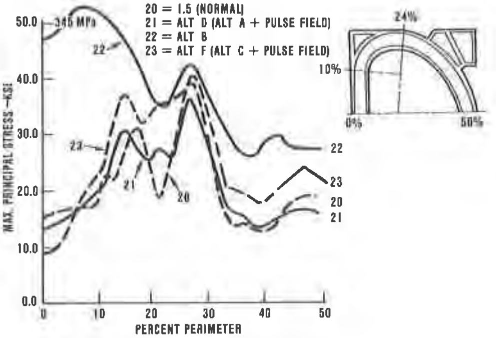


Figure 9. LCP principal stresses in the structural case side plate for the most severe design conditions.

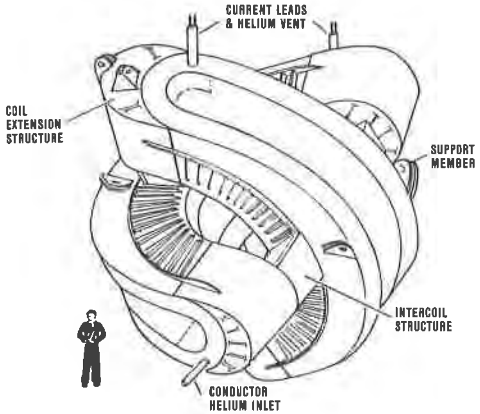


Figure 10. MFTF superconducting magnet.

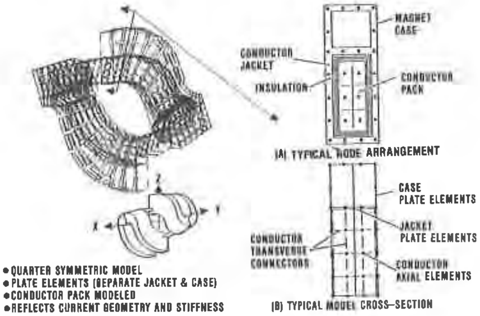


Figure 11. MFTF finite element model for structural analysis.

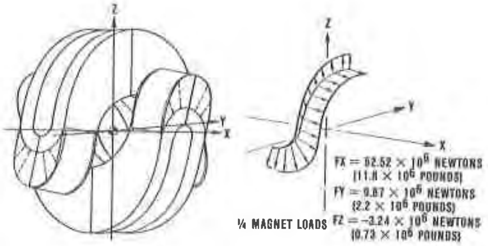


Figure 12. MFTF magnet electgromagnetic forces for the normal operating condition.

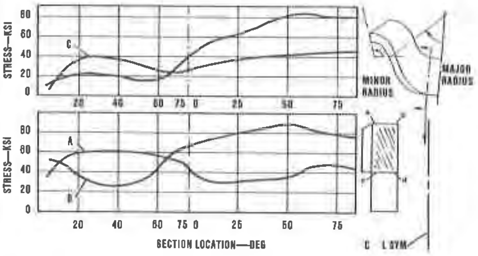


Figure 13. MFTF magnet principal stresses in the structural case for normal operating condition.

Table 1. Large coil program structural design conditions.

Category	Ref No.	Condition	Midplane Bdy Cond	Note
Electromagnetic	1	Normal	Sym	
	2	Alternate A	Sym	
	3	Alternate B Coil No. 1	Sym	
	4	Alternate C	Sym	Torque Beam Free In X, Z
	5	Reg. Pulse Fields	Sym ±A/S	
Thermal	6	Residual Thermal	Sym	Steady State
	7	Pack At 80°K Quench	Sym	Steady State
	8	Pack At 100°K Quench	Sym	Steady State
	9	Cooldown – 2 Hrs	Sym ±A/S	Transient Time Slice
	10	Cooldown – 10 Hrs	Sym ±A/S	Transient Time Slice
	11	Cooldown – 14 Hrs	Sym ±A/S	Transient Time Slice
	12	Warmup – 2 Hrs	Sym ±A/S	Transient Time Slice
Other	13	100 Psia Int. Pressure	Sym	He Boiloff
	14	1G Gravity	Sym	For Weight Calculations
	15	Handling, Shipping Loads	Sym	Manufacturing Support
Design Conditions	• 1.50 × [1+5+6+13]			Normal Operating Condition
	• 1.00 × [2+(2.0×1.10) 5+6+13]			2.0 Factor Converts Reg. To Ext.
	• 1.00 × [3+6+13]			Other Factor Is Current
	• 1.00 × [4+(2.0×1.40) 5+6+13]			Multiplier
	• 1.00 × [7+13]			Quench Conditions
	• 1.00 × [8+13]			
	• 1.50 × [13] @ RT			RT Proof Test