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**CONDUCTOR STRESS ANALYSIS FOR THE
MIRROR FUSION TEST FACILITY
(MFTF) MAGNET SYSTEM**

MASTER

GENERAL DYNAMICS
Convair Division

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(MFTF) MAGNET SYSTEM**

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TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
1 INTRODUCTION	1
2 STRUCTURAL REQUIREMENTS	3
2.1 MATERIAL PROPERTIES	3
2.2 FACTORS OF SAFETY	3
3 ANALYSIS	6
3.1 INTRODUCTION	6
3.2 BASELINE	6
3.3 0.005" GAP HOMOGENIZATION	15
3.4 0.010" GAP HOMOGENIZATION	25
4 RESULTS	27
4.1 GENERAL	27
4.2 BASELINE NO. 6	27
4.3 0.005" GAP HOMOGENIZATION	32
4.4 0.010" GAP HOMOGENIZATION	32
4.5 PARAMETRIC COMPARISON	32
5 CONCLUSIONS	39
6 RECOMMENDATIONS	40
7 REFERENCES	41
APPENDIX A: MFTF CONDUCTOR PACK ANALYSIS: BASELINE MODEL GDSAP COMPUTER ANALYSIS RESULTS	A-1
APPENDIX B: MFTF CONDUCTOR PACK ANALYSIS: 0.005" WINDING GAP GDSAP COMPUTER ANALYSIS RESULTS	B-1
APPENDIX C: MFTF CONDUCTOR PACK ANALYSIS: 0.010" WINDING GAP GDSAP COMPUTER ANALYSIS RESULTS	C-1

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
1.1 GDSAP MFTF Finite Element Model	2
3.1 MFTF Conductor/Insulation Cross-Section	7
3.2 MFTF Insulation Buttons	8
3.3 MFTF Slotted Insulation	9
3.4 MFTF Superconductor Copper Wrap	10
3.5 Orientation Diagram for Connectivity Schematics	11
3.6 MFTF Conductor Pack Connectivity Scheme No. 1	13
3.7 MFTF Conductor Pack Connectivity Scheme No. 1 F.E. Model Hoop Stresses	14
3.8 MFTF Conductor Pack Connectivity Scheme No. 2	16
3.9 MFTF Conductor Pack Connectivity Scheme No. 1 and No. 2 F.E. Model Hoop Stress Comparison	17
3.10 MFTF Conductor Pack Connectivity Scheme No. 3	18
3.11 MFTF Conductor Pack Connectivity Scheme No. 4	19
3.12 MFTF Conductor Pack Connectivity Scheme No. 5	20
3.13 MFTF Conductor Pack Connectivity Scheme No. 3 F.E. Model Hoop Stresses	21
3.14 MFTF Conductor Pack Connectivity Scheme No. 4 F.E. Model Hoop Stresses	22
3.15 MFTF Conductor Pack Connectivity Scheme No. 5 F.E. Model Hoop Stresses	23
3.16 MFTF Conductor Pack Connectivity Scheme No. 6	24
4.1 MFTF Conductor Pack Connectivity Scheme No. 6 F.E. Model Hoop Stresses	29
4.2 Baseline No. 6 - Conductor Hoop Stress Curve Fit Results	30
4.3 MFTF Conductor Pack Hoop Stress Extrapolation Scheme	31
4.4 MFTF Conductor Pack Connectivity Scheme No. 6 for 0.005 Inch Winding Gap Homogenization	33

LIST OF FIGURES (Continued)

<u>Figure</u>	<u>Page</u>
4.5 MFTF Conductor Pack Connectivity Scheme No. 6 F.E. Model Hoop Stresses for 0.005 Inch Winding Gap Homogenization	34
4.6 MFTF Conductor Pack Connectivity Scheme No. 6 for 0.010 Inch Winding Gap Homogenization	35
4.7 MFTF Conductor Pack Connectivity Scheme No. 6 F.E. Model Hoop Stresses for 0.010 Inch Winding Gap Homogenization	36
4.8 MFTF Conductor Hoop Stress as a Function of Winding Gap	38

LIST OF TABLES

<u>Table</u>	<u>Page</u>
2.1 Structural Material Mechanical Properties	4
2.2 Magnet Structural Safety Factors	5
4.1 Conductor Pack Connectivity Study Results Summary	28
4.2 Conductor Pack Winding Gap Homogenization Study Results Comparison	37

SUMMARY

This report describes the analysis performed to establish the sensitivity of winding gaps on conductor hoop stress. Since this task was a follow-on to the program that confirmed the structural integrity of the MFTF magnet case, jacket, and shield system (Ref. 1), every effort was made to utilize analysis methods and tools developed during that program. Figure 1.1 illustrates the large, 5000 degree of freedom GDSAP model developed during that program which was used extensively throughout this analysis task. This model accurately represents the case and jacket structure and simulates the conductor pack stiffness with an array of interconnected rod elements. All results contained herein are based on linear-elastic, small deflection theory.

To enable us to use this analysis tool, homogenization techniques were utilized to idealize the non-linear gap problem into a linear problem compatible with our existing analysis techniques. Details of the homogenization are presented in Section 3, Analysis.

This study has shown that conductor hoop stresses are not particularly sensitive to the winding gaps analyzed (0.005 and 0.010 inch), but it is still recommended that winding gaps be kept minimal because of conductor pack movement considerations.

INTRODUCTION

This report documents the stress analysis of the MFTF magnet system conductor pack. The analysis is based on LLL criteria to establish the sensitivity of conductor hoop stress to interconductor winding gaps of 0.005 and 0.010 inch. LLL defined the conductor pack material properties which were the basis for this analysis.

The finite element analysis that forms the basis of the work contained herein is summarized in Sections 3 and 4. Details of the finite element model (Figure 1.1) may be found in Ref. 1, Appendix A, Volume I.

Detailed computer output and plate stress margin of safety summaries for the baseline, 0.005 in. winding gap and 0.010 in. winding gap analyses are presented in Appendices A through C, respectively.

- QUARTER SYMMETRIC MODEL
- PLATE ELEMENTS (SEPARATE JACKET & CASE)
- CONDUCTOR PACK MODELED
- REFLECTS CURRENT GEOMETRY AND STIFFNESS

(A) TYPICAL NODE ARRANGEMENT

(B) TYPICAL MODEL CROSS SECTION

Figure 1.1. GDSAP MFTF Finite Element Model

STRUCTURAL REQUIREMENTS

2.1 MATERIAL PROPERTIES

The mechanical properties for the MFTF structural materials are listed in Table 2.1. The properties for the magnet case, intercoil, and jacket are the same as those used in the previous MFTF structural analysis tasks (Ref. 1). The properties tabulated for conductor bundle stack were developed and obtained from LLL (Ref. 2).

2.2 FACTORS OF SAFETY

Factors of safety used in this analysis are the same as those used in previous MFTF structural analysis tasks for the case, jacket and intercoil structure (Ref. 1). At that time, LLL specified that the coil structure shall have a minimum factor of safety of 1.5 on yield strength for operating magnetic and thermal loads. Factors of safety used on the MFTF structure are shown in Table 2.2.

Table 2.1. Structural Material Mechanical Properties

Material	Usage	Temp °K	F _{TU} (ksi)	F _{TY} (ksi)	E ₁₀₆ (psi)	Source
304L	Support Struts	RT	100	40	28.5	LLL
		4.5	245	70	29.6	
304LN (0.12% N)	Magnet Case and Intercoil	4.5	244.6	111.8*	29.7	NBS
E316L ΔFe = 4.5 ΔFe = 9.2	Case Weld Metal	4.5	193	116*	31.9	NBS
		4.5	187	128*	31.9	
316L	Jacket	RT	80	40	29.5	
		4.5	200	80	31.9	
Conductor Bundle Stack Inter-Turn (Button Direction)	—	RT			2.0	LLL
Inter-Layer (Slotted G-11 Direction)	—	RT			3.0	LLL
Hoop	—	RT			21.4	LLL

*120 ksi was used for design. LLL will pursue obtaining 120 ksi minimum yield strength

Table 2.2. Magnet Structural Safety Factors

Structure or Condition	Factor of Safety		Life Factor
	Yield	Ultimate	
Case, Jacket, Intercoil	1.5	—	4.0
Support Structure	1.5	3.0*	4.0

*Based on ASME Codes Requirements

ANALYSIS

3.1 INTRODUCTION

The objective of the MFTF conductor stress analysis was to calculate a realistic upper bound for the conductor strain using the existing GDSAP model; conductor winding gaps and plasticity effects were to be reflected in the analysis (Ref. 3). Predicted conductor pack stresses and strains were to be determined within the limitations of the existing six-conductor element idealization previously modeled (see Figure 1.1). To accomplish this task, we had proposed a piecewise linear analysis of the conductor pack.

Subsequent to contract go-ahead, we were directed by LLL to rescope this task to address the sensitivity of conductor stress to winding gaps (Ref. 4). It was agreed that the analysis would be redefined to "linearly" approximate the effects of 0.005 and 0.010 inch per turn gaps in the major and minor radius radial direction. In addition, it was recognized that transverse gaps did not contribute significantly to conductor hoop tension stresses.

3.2 BASELINE

The initial task of this analysis was to establish a baseline conductor pack connectivity scheme that adequately reflected the conductor pack's response to applied electromagnetic and thermal loads. The conductor pack is a series of niobium titanium superconductors imbedded in a copper matrix, separated by insulating materials of various geometric configurations (see Figures 3.1 thru 3.4). As illustrated in Figure 1.1, the conductor pack is modeled as an array of axial load carrying rod elements. The axial (hoop) stiffness of the pack is represented by six sets of hoop rod elements. These hoop elements are connected to the case and to one another with rod elements that represent the transverse stiffness of the pack. The conductor pack, however, is capable of sustaining tensile loads only in the hoop direction and thus the modeled conductor pack transverse rod connectivity should reflect this physical requirement.

Figure 3.5 is the orientation diagram for all subsequent conductor pack connectivity schematics. Briefly, double line rod elements reflect true areas; dark (solid) rods indicating tension loads and light rods indicating compression loads. The + and - symbols indicate the sign of the residual load of rods with areas set equal to 0.01 sq. in.

Figure 3.1. MFTF Conductor/Insulation Cross-Section

Figure 3.3. MFTF Slotted Insulation

Figure 3.4. MFTF Superconductor Copper Wrap

Figure 3.5. Orientation Diagram for Connectivity Schematics

Figure 3.6 displays the conductor connectivity schematic that was initially assumed to most accurately represent the conductor pack. Under the influence of magnetic loads, it can be seen that fictitious tensile loads exist at planes 2, 3, and 5 in the radial direction of the major radius; these radial pressures are 301, 489, and 257 psi, respectively. In the minor radius in the radial direction the top layer in planes 9 thru 14 all reflect fictitious tension loads. These pressures range from 2429 psi at plane 9 to 938 psi at plane 14 (about 900 psi average pressure).

Thermal load case results reflect tension loads in almost all conductor stabilizing rods in the radial direction of the major radius, while the combined results (thermal plus magnetic) nearly duplicate the magnetic load case results. Thus, it can be seen graphically that the applied magnetic loads completely dominate the assumed connectivity scheme as was expected. Thus, it was decided to consider magnetic loads only during all subsequent conductor pack connectivity studies.

The fictitious transverse tension stresses that are illustrated schematically in Figure 3.6 for the initial connectivity scheme reflect the complex interactions between the conductor pack and the case and between the separate elements of the conductor pack itself. Some of the phenomena that contribute to the development of transverse tension in the conductor pack model are the following.

1. During the application of applied magnetic loads the conductor pack undergoes electromagnetic constriction.
2. There is an interaction between locally applied magnetic loads and overall conductor hoop stresses.
3. Conductor case deflections affect the validity of the assumed conductor pack connectivity scheme.
4. Of secondary importance are several small discrepancies that exist between the finite element model applied loads and the true electromagnetic load distribution.

The load discrepancies mentioned in item four developed during the MFTF design analysis task, when the finite element model was constantly undergoing small geometric changes. The electromagnetic loads which were based on a particular model geometric configuration were not updated when the model geometry was changed. Thus, discrepancies arose because of the location for a particular load vector may not be the same as the location used to calculate the load. However, the total applied load is correct and discrepancies of this type will not have a significant effect on the overall results. Also, as the object of this study is to report sensitivities rather than absolute numeric results, the impact of these load discrepancies is further reduced.

The resulting conductor hoop stresses for the initial assumed connectivity scheme are shown in Figure 3.7. As previously predicted (Ref. 5), idealized conductor number 2

SAP BASELINE MODEL ROD RESULTS (RUN NO. 1)

LEGEND:

SOLID ROD (—) INDICATES TENSION

LIGHT ROD (==) INDICATES COMPRESSION

+ OR - INDICATES TENSION OR COMPRESSION IN TRANSVERSE ELEMENTS WHOSE STIFFNESSES
HAVE BEEN ELIMINATED

Figure 3.6. MFTF Conductor Pack Connectivity Scheme No. 1

Figure 3.7. MFTF Conductor Pack Connectivity Scheme No. 1
F. E. Model Hoop Stresses

has the highest tension, 22,500 psi, for the combined thermal and magnetic loading condition. It can also be seen that the inside turns (2, 4, 6) have a higher hoop tension stress than their corresponding outside turns (1, 3, 5) as was expected.

After analyzing the results of connectivity scheme No. 1, it was decided to model the conductor pack as a partially free standing pack in the minor radius. Figure 3.8 presents this connectivity scheme and analysis load case results. Figure 3.9 compares the resulting conductor hoop stresses of connectivity schemes 1 and 2. As can be seen, the relationship between the magnitudes of the six idealized conductors is no longer correct (i.e., conductor No. 4 has a higher hoop tensile load than hoop conductor No. 2). At that time, this result was believed to be due to the radial tension loads at planes 2, 3, 4, and 5 of 301, 490, 191, and 257 psi, respectively. Subsequent analysis review however indicated that this was not the case, as excessive conductor deflections (in excess of 1.0") were being induced in the free standing minor radius region.

A total of three additional free standing connectivity schemes (3, 4 and 5) were analyzed before the concept was abandoned. Details of these connectivity schemes and resulting conductor hoop stresses are shown in Figures 3.10, 3.11, 3.12 and 3.13, 3.14, 3.15, respectively. Connectivity scheme No. 3 and 4 provided for some free standing conductors in both the major and minor radius. In both cases, deflections approaching 1.8" were experienced in the major radius area. Connectivity scheme No. 5 provides for free standing conductors in the minor radius area only; this scheme was also invalidated because of resulting 1.0" conductor deflections.

Connectivity scheme No. 6 is shown graphically in Figure 3.16. This scheme provides for no free standing conductors (i.e., at least one stabilizing conductor in every row or column is connected to the case). A fictitious radial pressure of approximately 600 psi is being applied to conductor No. 1 in the minor radius. At this time, it was decided that within the limitations of the existing model and analysis technique, connectivity scheme No. 6 would be adequate and serve as the baseline model for all subsequent analyses. Results of the baseline analysis are presented in Section 4.

3.3 0.005" GAP HOMOGENIZATION

To determine the sensitivity of conductor hoop stress to manufacturing interconductor winding gaps, a homogenization technique was used to develop idealized conductor pack radial and transverse stiffness data. The following steps are utilized in this process:

1. Determine the average pressure in the conductor pack in the direction under consideration (P_A).

SAP BASELINE MODEL ROD RESULTS (RUN NO. 2)

MAGNET PLANES

LEGEND:

SOLID ROD (—) INDICATES TENSION

LIGHT ROD (=) INDICATES COMPRESSION

Figure 3.8. MFTF Conductor Pack Connectivity Scheme No. 2

Figure 3.9. MFTF Conductor Pack Connectivity Scheme No. 1 and No. 2
F.E. Model Hoop Stress Comparison

MAGNET LINES

MAGNETIC
LOAD CASE
RESULTS

THERMAL
LOAD CASE
RESULTS

COMBINED
RESULTS

LEGEND:

SOLID ROD (—) INDICATES TENSION

LIGHT ROD (==) INDICATES COMPRESSION

Figure 3.10. MFTF Conductor Pack Connectivity Scheme No. 3

SAP BASELINE MODEL ROD RESULTS (RUN NO. 4)

MAGNET PLANES

Figure 3.11. MFTF Conductor Pack Connectivity Scheme No. 4

MAGNET PLANES

MAGNETIC
LOAD CASE
RESULTS THERMAL
LOAD CASE
RESULTS COMBINED
RESULTS

LEGEND:

SOLID ROD (—) INDICATES TENSION

LIGHT ROD (=) INDICATES COMPRESSION

Figure 3.12. MFTF Conductor Pack Connectivity Scheme No. 5

Figure 3.13. MFTF Conductor Pack Connectivity Scheme No. 3
F.E. Model Hoop Stresses

Figure 3.14. MFTF Conductor Pack Connectivity Scheme No. 4
F.E. Model Hoop Stresses

Figure 3.15. MFTF Conductor Pack Connectivity Scheme No. 5
F.E. Model Hoop Stresses

SAP BASELINE MODEL ROD RESULTS (RUN NO. 6)

MAGNET PLANES

Figure 3.16. MFTF Conductor Pack Connectivity Scheme No. 6

2. Convert the winding gap (G) into an equivalent gap strain per unit conductor width (C_W).

$$\text{i.e., } E_G = G/C_W$$

3. Assume that this strain corresponds to the previously calculated average stress, P_A , and calculate an equivalent modulus (E_G).

$$\text{i.e., } E_G = P_A C_W / G$$

4. Compute a homogenized modulus that reflects the reduced conductor pack stiffness.

$$E_T = \frac{1}{\frac{1}{E_G} + \frac{1}{E}}$$

Based on the results of baseline No. 6, the average compressive stress in the conductor pack in the major radius in the radial direction was determined to be 2807 psi (actual stresses ranged from 3900 psi at plane 7 to 2013 psi at plane 2). Likewise, the average compressive stress in the minor radius in the radial direction was computed to be 1380 psi (stresses ranging from 403 psi at plane 14 to 3214 psi at plane 9). Using these average stresses, the 0.005 in gap per turn was homogenized into the following effective conductor pack stiffnesses:

$$\text{Layer-to-Layer Direction: } E_{\text{eff}} = 2.8300 \times 10^5 \text{ psi}$$

$$\text{Button-to-Button Direction: } E_{\text{eff}} = 1.3922 \times 10^5 \text{ psi}$$

These calculated conductor pack stiffnesses were then input into the baseline No. 6 connectivity scheme finite element model and analyzed. Results of this analysis are presented in Section 4, Results.

3.4 0.010" GAP HOMOGENIZATION

The 0.010" winding gap conductor stress analysis was conducted using the same homogenization techniques as those described for the 0.005" gap study. Using the same average stresses presented previously, the 0.010" gap per turn was homogenized the following effective conductor pack stiffnesses:

$$\text{Layer-to-Layer Direction: } E_{\text{eff}} = 1.4851 \times 10^5 \text{ psi}$$

$$\text{Button-to-Button Direction: } E_{\text{eff}} = 7.2142 \times 10^4 \text{ psi}$$

An analysis using these reduced conductor pack stiffnesses was then conducted using the baseline No. 6 connectivity scheme. Results of this analysis are presented in Section 4.

RESULTS

4.1 GENERAL

Table 4.1 summarizes the typical conductor pack stress results of the various connectivity schemes analyzed. Comparison of computer runs 1 and 6 (both models contain no free standing conductors) appear similar, but the connectivity scheme used in run No. 6 reduced the fictitious radial pressure of 900 psi to 600 psi or approximately 30%. Therefore, baseline No. 6 was selected for comparison purposes.

4.2 BASELINE NO. 6

A conductor hoop stress plot for the assumed baseline model configuration is shown in Figure 4.1. Of the six idealized hoop conductors, conductor No. 2 has the highest hoop stress (~17090 psi). A two-step extrapolation process was used to estimate the highest real conductor stress based on these results. In Figure 4.2, 2nd order polynomials were curve fit to the idealized conductor hoop stress results of baseline No. 6. Polynomials for conductor stack columns 1-3-5 and 2, 4, 6 were derived as follows (see Figure 4.3):

$$(\sigma)_{1-3-5} = 18009.889 + 423.707X + 0.532X^2$$

$$(\sigma)_{2-4-6} = 21454.375 + 426.491X - 0.302X^2$$

These two polynomials were then used to extrapolate analysis results to the first row of conductors at $X = -3.75$,

$$(\sigma)_{1-3-5} \Big|_{X = -3.75} = 16,428.47 \text{ psi}$$

$$(\sigma)_{2-4-6} \Big|_{X = -3.75} = 19,850.79 \text{ psi}$$

A first order polynomial was then fit to these two data points and their corresponding Y coordinate for row interpolation

$$\text{i. e., } \sigma = -402.63 Y + 30423.85$$

This expression is evaluated at $Y = 22.28$ in. to derive the peak conductor hoop stress of 21,453.25 psi.

RESULTS

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$$\text{i. e., } \sigma = -402.63 Y + 30423.85$$

This expression is evaluated at $Y = 22.28$ in. to derive the peak conductor hoop stress of 21,453.25 psi.

TABLE 4.1
CONDUCTOR PACK CONNECTIVITY STUDY RESULTS SUMMARY

Rod ID#	Run #1 Results psi	Run #2 Results psi	Run #3 Results psi	Run #4 Results psi	Run #5 Results psi	Run #6 Results psi
10 - Cond #1	14710	10640	14710	14710	11230	13760
23 - Cond #2	18930	15030	10960	10960	14440	17090
36 - Cond #3	10910	11320	12750	12720	11780	9608
49 - Cond #4	14910	15470	14040	13800	14740	12650
62 - Cond #5	3943	4444	3682	3709	5189	5254
75 - Cond #6	7287	7830	8203	8233	7736	7791

NOTES:

- Run #1 provides for no "free standing" conductors and has a fictitious radial pressure of approx. 900 psi applied to Conductor #1 in the minor radius because of assumed conductivity scheme.
- Run #2 provides for some "free standing" conductors in the minor radius. Conductor pack deflections are 1.0" or more there.
- Run #3 provides for some "free standing" conductors in both the major and minor radii. Conductor pack deflections are approaching 1.8" in the major radius.
- Run #4 provides for some "free standing" conductors in both the major and minor radii. Conductor pack deflections are approaching 1.8" in the major radius.
- Run #5 provides for "free standing" conductors in the minor radius only. Conductor pack deflections are 1.0" in the minor radius.
- Run #6 provides for no "free standing" conductors. A fictitious radial pressure of approx. 600 psi is being applied to Conductor #1 in the minor radius because of assumed connectivity scheme.

Figure 4. 1. MFTF Conductor Pack Connectivity Scheme No. 6
F. E. Model Hoop Stresses

FIGURE 4.2. BASELINE NO. 6 - CONDUCTOR HOOP STRESS CURVE
FIT RESULTS

Figure 4.3. MFTF Conductor Pack Hoop Stress Extrapolation Scheme

Appendix A contains the complete SAP finite element model output and selected conductor pack stress and strain data for this analysis.

4.3 0.005" GAP HOMOGENIZATION

Figures 4.4 and 4.5 present the conductor pack results for the 0.005" gap per turn homogenization study. Comparison of these results with those previously presented for the baseline model indicate that

1. Conductor elements on the inside of the major radius (i.e., conductors 2, 4, and 6) tend to carry more of the electromagnetic load in hoop tension as the effective stiffness in the radial and transverse directions is decreased.
2. Conductor elements on the outside of the major radius (i.e., conductors 1, 3, and 5) tend to carry less of the electromagnetic load in hoop tension as the effective stiffness in the radial and transverse directions is decreased.

Appendix B contains the complete GDSAP finite element model output for this analysis.

4.4 0.010" GAP HOMOGENIZATION

The results for the 0.010" gap homogenization study are presented in Figures 4.6 and 4.7. The same trends in conductor hoop stress that were reported in paragraph C (0.005" Gap Homogenization Results) are also apparent here, i.e., decreasing conductor pack transverse and radial stiffness causes model conductors 2, 4, and 6 to carry more electromagnetic load in hoop tension while model conductors 1, 3, and 5 carry less electromagnetic load in hoop tension.

The complete GDSAP finite element model output for the analysis is contained in Appendix C.

4.5 PARAMETRIC COMPARISON

Table 4.2 and Figure 4.8 present conductor hoop tension results as a function of analysis winding gap size. The data in Table 4.2 was used to derive peak conductor pack hoop stresses for each analysis case. The predicted results for the 0.005" and 0.010" gap analyses are almost identical being 19,311 and 19,206 psi, respectively. As previously presented, the predicted peak hoop stress for the baseline analysis case was 21,453 psi. The decrease in predicted conductor hoop stress with increased winding gap size is contrary to anticipated results and believed to be a consequence of the fictitious radial tension load applied throughout the minor radius (see Figure 3.16).

SAP 0.005" GAP HOMOGENIZATION MODEL ROD RESULTS

Figure 4.4. MFTF Conductor Pack Connectivity Scheme No. 6 for 0.005 inch Winding Gap Homogenization

Figure 4.5. MFTF Conductor Pack Connectivity Scheme No. 6
F.E. Model Hoop Stresses for 0.005 Inch Winding
Gap Homogenization

**SAP 0.010" GAP HOMOGENIZATION MODEL ROD RESULTS
(BASED ON BASELINE MODEL NO. 6)**

Figure 4.6. MFTF Conductor Pack Connectivity Scheme No. 6
for 0.010 Inch Winding Gap Homogenization

Figure 4.7. MFTF Conductor Pack Connectivity Scheme No. 6
F.E. Model Hoop Stresses for 0.010 Inch Winding
Gap Homogenization

Table 4.2. Conductor Pack Winding Gap Homogenization
Study Results Comparison

Rod ID No.	Baseline #6 Results (psi)	0.005" Gap Results (psi)	0.010" Gap Results (psi)
10 - Cond. #1	13760	12414	12144
23 - Cond. #2	17090	16943	17008
36 - Cond. #3	9608	8860	8653
49 - Cond. #4	12650	13971	14248
62 - Cond. #5	5254	3390	2904
75 - Cond. #6	7791	8082	8255

Figure 4.8. MFTF Conductor Hoop Stress as a Function of Winding Gap

CONCLUSIONS

The analysis reported herein is based on linear elastic small deflection theory. For reasons of convenience and cost, non-linear gaps were idealized as reduced conductor pack stiffnesses in this analysis to determine the sensitivity of the conductor hoop stress to these winding gaps. Observing the limitations of this idealization, the following can be reported with confidence.

1. Interwinding gaps analyzed (0.005" and 0.010") did not significantly effect conductor pack hoop stress.
2. Increasing gap size tends to increase the amount of electromagnetic load carried in hoop tension by conductors on the inside of the major radius (i.e., conductors 2, 4, and 6 of Figure 4.3) and decrease the amount of electromagnetic load carried by conductors on the outside of the major radius (i.e., conductors 1, 3, and 5 of Figure 4.3).

RECOMMENDATIONS

Although this study has shown that conductor hoop stresses are not particularly sensitive to the analysis case winding gaps (0.005 and 0.010"), it is recommended that these gaps be kept minimal during the winding process. This recommendation is based upon an understanding of the limitations of this analysis and upon an appreciation of the consequences of conductor pack movement.

It is also recommended that for future analysis of this type consideration be given to existing finite element computer codes that can more accurately analyze this type of problem. For example, the General Dynamics Energy Systems group recently completed a similar analysis for the toroidal field coils using the ANSYS Finite Element Computer Code (see Ref. 6). In that analysis, ANSYS standard library gap elements were used with success. However, this type of analysis is relatively expensive as compared to typical linear elastic analyses and the need for this type of analysis should reflect this increased cost factor.

REFERENCES

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