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**STRUCTURAL ANALYSIS INTERPRETATION TASK
FOR THE MAGNET SYSTEM FOR MIRROR FUSION
TEST FACILITY (MFTF)**

GENERAL DYNAMICS

Convair Division

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SUMMARY

The primary objective of this study was to develop recommendations to improve and substantiate the structural integrity of the highly stressed small radius region of the MFTF magnet. The specific approach is outlined below:

- o Extract detail stress/strain data from General Dynamics Convair Finite-Element Refinement Analysis
- o Diagram local plate stress distribution and its relationship to the adjacent weldment
- o Update the parametric fracture mechanics analysis using most recent MFTF related data developed by National Bureau of Standards
- o Review sequence and assembly as modified by Chicago Bridge & Iron for adaptability to refinements
- o Investigate the need for fillet radii weldments to reduce stress concentrations at critical corners
- o Review quality assurance plan for adequacy to insure structural quality in the small radius region
- o Review instrumentation plan for adequacy of structural diagnostics in small radius region
- o Participate in planning a small-scale fatigue test program of a typical MFTF weldment

As a result of this study, the following recommendations have been implemented into the fabrication plans for the MFTF magnet:

- o Corner fillets are to be incorporated in the small radius region to reduce stresses in critical corners and eliminate potential plastic strain cycling
- o More stringent NDE is to be provided for welds 1, 3, 4, and 8 during assembly
- o Two additional rosette strain gages on the exterior of the case in the minor radius will be added to the structural instrumentation plan
- o Crack propagation gages on the exterior of the case at the 3 in. to 5 in. plate transition will be added to the structural instrumentation plan
- o A fatigue test program of the case weldment will be conducted to experimentally substantiate the design stress level

The analysis performed for this study has shown that incorporation of the corner fillet radius in the small radius region will eliminate plastic strain cycling. The fracture mechanics update analysis showed the magnet system will safely survive the design service life even under worst case conditions, provided that the recommended critical initial flaws are found by NDE and properly reworked. The additional strain gage instrumentation will provide better diagnostic of the small radius region stress distribution. The addition of crack propagation gages will provide safe magnet operation by providing warning of an incipient critical fracture. Satisfactory completion of the weldment fatigue test will provide experimental evidence on the structural suitability of typical production weldments.

1.0 Extract Local Plate Stresses in Most Highly Stressed Areas

The MFTF finite-element structural analysis is documented in References 1 and 2. Reference 1 provides the original baseline using General Dynamics Structural Analysis Program (GDSAP) and Reference 2 provides a refinement analysis using NASTRAN. The refinement analysis verified that the peak nominal structural case stresses were slightly below the 80 ksi design goal.

Since the finite element analysis generates stress data at the mid-points of the elements, an extrapolation of stresses in critical regions is necessary to obtain a more complete picture of the stress behavior at points away from the data points. More detailed stress distributions were therefore calculated for the inner crossover plate at a location of 45 degrees from the axis of symmetry in the minor radius and also for the intermediate crossover plate at the axis of symmetry in the minor radius (Figures 1-1 and 1-2). These were the critical areas identified by the analyses discussed in References 1 and 2.

The stress extrapolation for the intermediate crossover plate is shown in Figure 1-3. The points shown on the cross section at the top of the figure are node points of the elements. Stress data from the three midpoints between these node points were plotted and are shown at the bottom of Figure 1-3. (The distance scales of the cross section and stress plot are the same.) The stresses shown are principal stresses whose directions closely correspond to the X and Y (radial and longitudinal) directions shown. Calculation of principal stresses at the inner edge based on extrapolation of midpoint bending moments and forces verified this method of stress determination. The stresses were extrapolated to the point of tangency of the fillet radius of the inner surface at the intersection of the inner radius case and intermediate crossover plates. The peak principal stress, the longitudinal (hoop) stress, at this point was 80 ksi as shown in Figure 1-4.

- INTERMEDIATE CROSSOVER PLATE AT THE INSIDE OF THE MINOR RADIUS
- INNER CROSSOVER PLATE AT THE INSIDE OF THE MINOR RADIUS

Figure 1-1. Detailed Stress Distributions Have Been Obtained for the Critical Locations

1-1

Figure 1-2. The Refined Element Analysis Determines the Critical Stresses

Figure 1-3. Stress Data Was Extracted from the GDSAP Finite Element Analysis

Figure 1-4. The Peak Stress in the Intermediate Crossover is 80 ksi at the Beginning of Fillet Radius

A similar stress extrapolation was performed on the inner crossover plate of the minor radius at 45° from the axis of symmetry. The principal (longitudinal) stresses for this section extrapolate to 90 ksi at the outside surface as shown in Figure 1-5. It must be remembered that this is a complex joint. The basic analysis here only gives an indication of the stress level in this local area. The longitudinal stress distribution shown in Figure 1-5 at the joint shows a combination of bending and membrane tension. However, the case side plate will not permit such bending since curvature of the case plate about that axis is essentially zero. This strain constraint would reduce the peak stress in the actual situation. As a further verification of the design, a parametric fracture mechanics analysis, was also performed and is discussed in Section 2.0 of this report.

Figure 1-5. The Peak Stress in the Inner Crossover Plate is 90 ksi When Extrapolated to the Corner Intersection with the 3.2-in. Case Side Plate

2.0 Parametric Fracture Mechanics Analysis (Update)

Since the original fracture mechanical analysis was performed, significant achievements have been made by Lawrence Livermore Lab in the development of parent material and weldments for the MFTF magnet. The original analysis was conducted from May 1978 to October 1978 and is documented in Reference 1. Since that time, the parent material, 304LN stainless steel, has been procured and suitable weld processes using 316L filler have been developed. For both the parent material and weldments, the fracture toughness and flaw growth characteristics in liquid helium have been evaluated by the National Bureau of Standards (NBS). The results of these tests are shown in Table 2-1. The designations "Arcos" and "McKay" refer to the weld rod supplier. The designations "horizontal" and "vertical" refer to the orientation in which the weldment was produced. Both horizontal and vertical orientations are typical for fabrication of the MFTF magnet base structure. As shown in Table 2-1, an interesting result of these tests is that the 304LN parent material flaw growth characteristics is approximately an order of magnitude more severe than the weldments. This is attributed to the effects of nitrogen strengthening and martensitic transformation at the crack tip.

A linear elastic fracture mechanics computer program called FLAGRO III, which was developed by Rockwell International Corporation and described in Reference 3, was used for MFTF fracture analysis. This computer code predicts the life of a component based on flaw growth damage integration package which interrelates the following elements.

- o The initial flaw size
- o The cyclic loading
- o Constant amplitude flaw growth rate material properties
- o Crack tip stress intensity factor analyses which account for size and shape, and overall geometric effects
- o Fracture toughness of the material

Table 2-1. MFTF Fracture Mechanics Data (Weldments and Parent Material)

Test Specimen	Fracture Toughness $\text{ksi}\sqrt{\text{in}}$	Flow	Growth	Example Flow Growth	
		C	n	ΔK ($\text{ksi}\sqrt{\text{in}}$)	da/dn (in/cycle)
ARCOS (horizontal) Weldment	146	0.156×10^{-10}	3.63	10	0.669×10^{-7}
				30	0.362×10^{-5}
				80	0.128×10^{-3}
McKay (horizontal) Weldment	183	0.664×10^{-11}	3.95	10	0.580×10^{-7}
				30	0.447×10^{-5}
				80	0.216×10^{-3}
McKay (vertical) Weldment	170	0.328×10^{-10}	3.45	10	0.925×10^{-7}
				30	0.410×10^{-5}
				80	0.121×10^{-3}
304LN Parent Material	202	0.911×10^{-9}	2.93	10	0.776×10^{-6}
				30	0.194×10^{-4}
				80	0.344×10^{-3}

FLAGRO III uses the flaw growth rate equation developed by Collipriest, and shown below, which approximates the flaw growth process with an inverse hyperbolic tangent function.

$$da/dn = C_1 \text{ EXP } \left[C_2 \text{ TANH }^{-1} \left(\frac{\ln (\Delta K^2 / (1 - R) K_c \Delta K_0)}{\ln ((1 - R) K_c / \Delta K_0)} \right) \right]$$

where K_c = Critical stress intensity factor for cyclic growth

ΔK_0 = Threshold stress intensity range

C_1 = Growth rate intercept

C_2 = Dimensionless coefficient relating to midrange slope

and da/dn = Fatigue crack extension per load cycle

ΔK = Applied stress intensity range ($K_{\max} - K_{\min}$) or
 $(1 - R) K_{\max}$

R = Load ratio (minimum load/maximum load)

The constants, C_1 and C_2 , can be related to the slope, n , and to the coefficient, C , of the Paris equation (when the Paris equation is fit strictly through the linear or midrange portion of the data) by the relationships

$$C_2 = \ln (K_c / \Delta K_0)^{n/2}$$

$$C_1 = C (K_c \Delta K_0)^{n/2}$$

FLAGRO III also has the capability to predict cyclic life using the Paris growth equation:

$$da/dn = C (\Delta K)^N$$

where: C = Growth rate intercept

N = Growth rate slope

For analysis of MFTF, both the Collipriest and Paris growth equations are evaluated. In all cases, the Collipriest equation predicted the shortest cyclic

life. Therefore, the Colipriest predictions were used for analysis of MFTF since it is slightly more conservative.

A typical flaw growth plot for the 304LN parent material is shown in Figure 2-1. As shown, for an 80 ksi stress level assuming an initial flaw of 0.075 inch deep by 0.150 inch wide, nearly 16 times the service life are predicted. Although this indicated life safely exceeds the 4 life design goal, some uncertainty exists in determination of the cyclic stress levels in local areas. For example, at corner intersections stress concentrations occur. Also, residual welding stresses can locally increase the stress level. Therefore, a more conservative approach was investigated in which it was assumed that the maximum stress at discontinuities including residual stresses can be as high as the material yield strength. Since this is a worst case assumption, the required design service requirement was reduced to two lives. Working backward two lifetimes from the indicated cyclic yield strength failure point shown in Figure 2-1, the maximum tolerable initial flaw size for parent material was determined. This flaw is 0.157 inch deep with a half width of 0.183 inch. Projecting this initial flaw to 80 ksi flaw growth curve resulted in an indicated life of 8.9 which still safely exceeds the nominal stress design goal of 4 lives. Similar worst case analysis for each of the weldments is presented in Figures 2-2 through 2-4. A summary of the maximum tolerable flaw size for each material based on a two-life requirement at cyclic yield stress is provided in Table 2-2. As shown, all of the maximum tolerable flaw sizes are larger than the original design goal of 0.075 inch deep by 0.075 inch half-width. Although this data implies that some relaxation in inspection and repair is permissible, it is not encouraged. It is still recommended that all defects found by standard NDE be reworked.

Figure 2-1. Crack Growth Curves for 304LN Parent Material

Figure 2-2. Crack Growth Curves for Arcos Horizontal Weldment (316L Weld in 304LN)

Figure 2-3. Crack Growth Curves for McKay Vertical Weldments (316L Weld in 304LN)

Figure 2-4. Crack Growth Curves for McKay Horizontal Weldments (316L Weld in 304LN)

Table 2-2. Maximum Tolerable Flaw Size Based on Two Life Requirement Under Worst Case Conditions

MATERIAL	MAXIMUM TOLERABLE INITIAL FLAW SIZE* a and c (see sketch below)	CYCLIC LIFE AT 80 KSI ASSUMING MAXIMUM INITIAL FLAW SIZE
304LN PARENT MATERIAL	0.1831 IN.	8.9 MAGNET LIVES
MCKAY VERTICAL WELDMENT	0.2911 IN.	15.4 MAGNET LIVES
MCKAY HORIZONTAL WELDMENT	0.2142 IN.	14.4 MAGNET LIVES
ARCOS HORIZONTAL WELDMENT	0.2313 IN.	17.4 MAGNET LIVES

*BASED ON 2 LIVES AT YIELD STRESS (120 KSI)

3.0 Fillet Radius Weldments in Critical Corner Areas

Welded fillet radii are being incorporated in the corners of the structural case that are subjected to high tensile stresses. These radii will insure that plastic strain cycling does not occur in the critical corner regions. The two most highly tensile stressed areas are shown in Figure 3-1. For both of these locations, a 1.00-inch fillet radius will be provided. This radii will be incorporated throughout the small radius region of the magnet structural case. The exact arrangement for each radii location is shown in Figures 3-2 and 3-3. For both locations, no modifications to the jacketed conductor bundle or bladder are required.

The 1.00-inch fillet radius was selected based on recently conducted photoelastic tests. These tests were conducted by Massachusetts Institute of Technology-Francis Bitter National Magnet Laboratory (MIT-FBNML) in support of the Stanford Superconducting Magnet (SSM) program. The geometry and loading for SSM was sufficiently similar to permit scaling to match MFTF conditions. Figure 3-4 illustrates the geometry and applied loading for the MIT test. Preliminary results indicate that the peak stress concentration factor is 2.2 in the fillet radius when expressed in terms of the nominal bending stress in the thick tooth. This stress concentration value in the critical corner regions will safely insure that no plastic strain cycling will occur.

Figure 3-1. Two Fillet Radii are Recommended for Small Radius Region

ALL DIMENSIONS IN INCHES

Figure 3-2. Clearance is Available for Fillet Radius in the Region of Joint 1

Figure 3-3. Jacket and Bladder are Already Chamfered in the Region of Joint 4

MIT SSM PHOTOELASTIC TEST

$$\begin{aligned} a &= .806 \\ b &= 1.148 \\ R &= .219 \end{aligned}$$

$$f_{\max} = K_T \left(\frac{6M}{b^2} \right), \quad K_T = 2.2$$

$$\begin{aligned} a/b &= .702 \\ R/b &= .191 \\ R/a &= .272 \end{aligned}$$

MFTF CONFIGURATION -

$$\begin{aligned} a &= 3.2 \text{ IN} \\ b &= 5.0 \text{ IN} \\ a/b &= .702 \end{aligned} \quad \left. \vphantom{\begin{aligned} a &= 3.2 \text{ IN} \\ b &= 5.0 \text{ IN} \\ a/b &= .702 \end{aligned}} \right\}$$

$$\begin{aligned} \text{FOR } R/a &= .272, R = .870 \text{ IN} \\ \text{FOR } R/b &= .191, R = .955 \text{ IN} \end{aligned}$$

Figure 3-4. Photoelastic Tests Indicate a 1-in. Fillet Radius Will Result in Stress Concentration Factors Less Than 2.2

4.0 Quality Assurance Refinements for the Small Radius Region

During subassembly fabrication, the added fillet weldments at joints number 1, 3, and 4 can be both penetrant inspected and Gamma radiographed prior to insertion of the vacuum guard chamber and the coil bundle as shown in Figure 4-1. Prior to penetrant inspection, the surface must be properly prepared. Both root and final passes must be 100% inspected. In order to achieve the maximum benefit from the Gamma radiography, the guidelines and standards established ASTM or equivalent procedures must be followed. Prior to inspecting the final article, Gamma radiography techniques must be established that will provide a quality level in which flaws up to 2 percent of the material thickness can be located. This technique must be established for each thickness and each different joint configuration. The source to film distance is critical and must be controlled to provide optimum sensitivity and image definition. Identification and traceability must be maintained for each joint as well as individual joint techniques as part of the permanent records of the welded assembly. Due to the complexity of the completed assembly, further inspection of these joints at periodic intervals is prohibited.

Weld joint number 8, shown in Figure 4-2, is also a highly stressed weld. However, assembly sequence precluded adding a fillet to the back side of this joint. Since this weld is in the highly stressed area, it is recommended that the root pass or the apex of this weld be ultrasonically (U/S) inspected using the longitudinal wave method. In addition, the weld should be thoroughly cleaned and this root pass should be penetrant inspected. A test article of this same joint configuration, having only the root pass welded should be made in order to establish and refine the ultrasonic technique for the inspection of the root of this weld. U/S inspection of this joint must be correlated with mechanical thickness measurements of the inner radius plate. Using this technique should provide sufficient detail whereby any lack of penetration in excess of 0.10" at the root of the weldment should be detectable.

- FILLET RADII CAN BE RADIOGRAPHED & PENETRANT INSPECTED DURING FABRICATION
- RT (COBALT 60) — 100% (FLAW SIZE 2% OF THICKNESS)
- PT (ROOT & FINAL PASS) — 100%

Figure 4-1. MFTF Subassembly NDE Inspection of the Small Radius Region Fillet Weldments

- UT — JOINT 8 — ROOT & FINAL — 100% INSPECTION (FLAW SIZE <0.100 INCH)
- PT — " — ROOT & FINAL PASS — 100% INSPECTION

Figure 4-2. MFTF Completed Assembly NDE Inspection of Small Radius Region
Close-out Welds

5.0 Structural Instrumentation for Small Radius Region

The MFTF fault analysis, analysis refinement, and stress evaluation studies have indicated a desirability for additional strain instrumentation in critical high stress regions of the magnet case. The added instrumentation will provide additional operational data.

Figure 5-1 depicts locations for the addition of more metal foil gages (MM type WK-15-250BG-350) to detect peak stresses in the small radius region of the case. As noted, two additional gages are required to provide additional directions of measurement (radial and longitudinal) to the existing single axis gage. Also, three single axis gages are added to form a rosette near the case corner on the intercoil structure side of the case.

GDC fault analysis (Reference 4) fault condition number 1 and number 5 results indicate the desirability of additional instrumentation. Fault condition number 1, depicted in Figure 5-2, is a relatively high stress region that marginally should be monitored; however, the probability of gage and wiring installation survivability after bladder installation is very low. Therefore, no instrumentation is added to this region.

Figure 5-3 illustrates fault condition number 5 which is the major to minor radius transition butt weld joint. For monitoring this high stress weld joint crack propagation gages are to be installed near the inner edge of each of these joints. The crack propagation gages are made from high endurance 'K' alloy foil with a thin glass-fiber reinforced backing that is installed by conventional strain gage techniques using a cryogenic rated adhesive. These crack propagation gages are manufactured by Micro-Measurements.

Figure 5-1. Two Additional Rosette Strain Gages to Detect Peak Stresses in the Case Small Radius Region are Being Added to the Structural Instrumentation Plan

JOINT GEOMETRY

Figure 5-2. Additional Instrumentation is Not Recommended in Fault Location #1 Due to Low Probability of Gage Survival

Figure 5-3. Crack Propagation Gages Are Being Added to the Structural Instrumentation Plan

6.0 Structure Case Weldment Experimental Fatigue Test

Purpose and Scope

The purpose of the test program described herein is to provide practical structural case weldments capable of sustaining the anticipated design service life of the magnet system. Due to the prohibitive cost and technical complexities of full-scale component testing, a small-scale test program is being planned. The use of small-scale specimens require many technical compromises. The rationale for technical scaling and selection of test parameters is based primarily on engineering judgement as outlined herein. This test plan was reviewed with John Horvath (LLL) and Harry McHenry (National Bureau of Standards, Boulder) and their recommendations have been incorporated.

Cyclic Stress Level (Phase I)

The constant-amplitude cyclic stress level is 80 ksi at $R=0.0$. This stress level is based on two major consideration:

- 1) Researchers have shown a direct correlation between combined membrane cyclic stress failures and uniaxial stress failure (Reference 5). Therefore, a uniaxial test at peak operating stress is planned.

This approach is slightly conservative for the MFTF magnet. The combined stresses in MFTF consist of bending as well as membrane stresses. When bending is considered, it is found that the tensile stresses peak at the outer surface fibers of the plate material and diminish approaching the neutral axis. The stress intensity at the crack tip of a propagating flaw will likewise diminish as the flaw grows toward the neutral axis due to three-dimensional constraint imposed by the adjacent material.

- 2) Finite element analysis of the MFTF magnet system has verified the nominal 80 ksi peak stress level (Reference 2). This stress represents the maximum nominal stress within the magnet structure. At discontinuity

locations (such as access holes, corner radii, nicks, gouges, etc.) the local peak stress could be much higher. In ductile materials, like 304LN, the peak stress at these small localized zones is limited to the yield strength. If a flaw exists in any of these locations, it could propagate rapidly under cyclic loading. However, these flaws would soon grow out of the localized highly stressed areas into the nominally stressed regions. Subsequent propagation would occur corresponding to the nominal stress intensity. Consequently, it would be excessively severe to conduct the cyclic test at levels greater than the nominal design stress.

Each specimen shall be tested to a scatter factor of four times the design life of 500 cycles (i.e., 2000 cycles total).

Cyclic Stress Level (Phase II)

Assuming that each specimen sustains Phase I loading, Phase II testing will immediately be initiated. For this phase, the cyclic stress is 120 ksi and $R=0.0$. At this level, the test specimen will be cycled to failure or terminated after a reasonable number of cycles have been accumulated (i.e., between 2,000 and 10,000). Long cyclic life from Phase II testing would provide additional assurance of the structural integrity of the weldments.

Cyclic Rate

Cyclic rate shall be less than 1.0 Hz to minimize internal heat generation.

Test Specimen Configuration

A preliminary test specimen configuration is shown in Figure 6-1. The throat diameter "D" was made as large as possible to minimize the effects of local micro-fissure accumulation. However, its size was limited by the cyclic load capacity of the selected testing vendor. Present planning indicates that these tests will be performed by Martin-Marrietta Corporation using a test machine

with 70,000 pound rated cyclic load capacity. Within this load range, a 0.750-inch throat diameter will readily permit 120 ksi cyclic stress.

The straight portion length "L" of the test specimen is between 1.00 to 3.00 inches long. This length was selected to maximize the probability that a typical accumulation of micro-fissures will be represented within the test section.

Test Specimen Orientation

The prime orientation with respect to weldments is transverse. The transverse weld is of most interest since it encompasses the fusion bond line and heat affected zone maximizing the value of the test results.

Test Specimen Weld Quality

The weldment includes typical micro-fissures. The micro-fissures within the selected weldment represent the maximum size which are considered to be acceptable.

Test Environment

Immersed in liquid helium at atmospheric pressure.

Number of Specimens

A minimum of six specimens of each orientation are to be tested. The adequacy of this number of specimens is substantiated in Reference 6.

In addition to the test specimens, a dummy specimen will be fabricated to aid in initial test machine setup and calibration.

Post-test Evaluation

All failed specimens will be evaluated for the presence of micro-fissures. Any specimen which did not fail during cyclic loading will be statically pull tested to failure prior to performing post-test evaluation.

7.0 REFERENCES

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