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Analysis of Yoke-Skin Interaction

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INTRODUCTION

The skin serves a particularly important structural purpose in the vertically split yoke design of the SSC collider dipole. The azimuthal skin stress must be sufficient at the operating temperature to keep the yoke mid-plane gap closed up to the operating field with an adequate mechanical reserve. It is also highly desirable, although less essential, that it be sufficient to keep the gap closed at room temperature. The opposing force in the latter case comes from the horizontal yoke-collar interference. In a recent note[1] on the collar design I showed that to ensure a closed mid-plane gap at room temperature a skin tension >23 kpsi is required[2], and at 4 K and 6.7 T, including the stiffness of the collars, a skin tension >26 kpsi is required. In this note I will discuss how the skin tension is generated, what the effects of friction are, how the skin tension is effected by interaction with the yoking press, and how the skin stress changes with thermal cycling.

The skin tension is applied by the shrinkage of the mid-plane weld. Strain gage measurements made on F3[3] and DSS012[4] indicate that the skin yields substantially near the weld, limiting the skin tension to somewhat less than the yield stress of the shell material in its annealed state. (See the appendix.) With type 304 stainless steel, which has a yield strength of 35 kpsi, the measured[3,4,5] stress at the mid-plane weld is about 30 kpsi. (We now intend to use type 316LN, which has a yield strength of 50 kpsi[6].) Because of frictional effects the skin tension decreases away from the mid-plane. However, it is the value of the skin tension at the yoke parting plane that determines the yoke-yoke clamping force and the mid-plane weld is at the parting plane. Discussion of the effects of friction and of possible redistribution of the skin stress during various assembly and operation steps is the major topic of this note.

YOKING/SKINNING PRESS

If the magnet is not in the yoking press when the skin is welded, then the situation is equivalent to the classic "rope around a capstan" problem. The skin tension decreases exponentially away from the weld:

$$\sigma = \sigma_o \, e^{-\mu\theta}$$

where σ is the azimuthal skin stress,
μ is the coefficient of friction between the yoke and the skin, and

θ is the angular distance from the weld.

However, the yoke and skin are clamped in the yoking press, which serves to guarantee that the yoke-yoke gap is closed and the skin conforms to the yoke, when the weld is made. This increases the frictional force between the yoke and skin and adds a frictional force between the skin and the tooling. In the calculation below the press is modelled as applying a uniform radial pressure to the outside of the skin with the integral of the vertical component of this pressure equal to the press load. Consider a small segment of skin extending between θ and $\theta + d\theta$ and extending over an axial length ℓ. other edge. The difference between the two forces is balanced by the friction:

$$\sigma \, \ell t = (\sigma + d\sigma) \, \ell t + \left[\mu \left(\sigma \frac{t}{r} + P \right) + \mu_p \, P \right] \ell r d\sigma$$

or

$$d\sigma = - \left[\mu \left(\sigma + P \, \frac{r}{t} \right) + \mu_p \, P \, \frac{r}{t} \right] d\theta$$

where t is the skin thickness

r is the yoke radius

P is the radial pressure applied by the yoking tooling, and

μ_p is the coefficient of friction between the skin and the tooling.

This has the solution:

$$\sigma = \begin{cases} \left[\sigma_o + \tilde{\sigma}_p \right] e^{-\mu\theta} - \tilde{\sigma}_p & \text{for} \quad \theta \leq \frac{1}{\mu} \ln \left[\dfrac{\sigma_o + \tilde{\sigma}_p}{\tilde{\sigma}_p} \right] \equiv \theta_o \\ 0 & \text{for} \quad \theta > \theta_o \end{cases}$$

$$\text{where} \quad \tilde{\sigma}_p = \left(\frac{\mu + \mu_p}{\mu} \right) P \, \frac{r}{t} \, .$$

The stress at the weld and the exponential "length constant" are the same as in the "no press" case, but the stress exponentially approaches $-\tilde{\sigma}_p$ rather than 0. Once the stress reaches zero, there is no further stretching of the skin and the stress remains zero. The angle θ_o at which this occurs is indicated above.

When the magnet is removed from the press the stress gradient is larger than can be supported by the reduced frictional force. The stress will redistribute itself until the stress gradient is the maximum allowed by the friction, resulting in the stress distribution in equation (1). In this redistribution portions of the skin may move, but always in the same direction as when the tension was originally applied, so the frictional forces are always in the same direction. Because of the symmetry of the problem, the stress redistribution can cause no net motion at $\theta = 0$ and $\theta = \pi/2$. Thus:

$$\int_0^{\pi/2} \epsilon \, d\theta = \int_0^{\pi/2} \epsilon_f \, d\theta$$

and therefore

$$\int_0^{\pi/2} \sigma \, d\theta = \int_0^{\pi/2} \sigma_f \, d\theta .$$

where ϵ (ϵ_f) is the strain before (after) and

σ (σ_f) is the stress before (after) the stress redistribution.

The final value of the skin stress at the weld can be determined by equating the integrals of σ in equations (1) and (2).

As an example, Figure 1 shows the stress as a function of azimuth assuming σ_o = 40 kpsi, $\mu = \mu_p$ = 0.5 and P = 690 psi. The latter corresponds to a press load of 9000 lbs./in. and applies a clamping force equal to that of a skin tension of 23 kpsi. It is therefore the load required to ensure that the mid-plane gap is closed before welding. The curve labelled "No Press" is the skin tension that would result if the skin were welded without a press. "In Press" gives the skin tension after welding while the press is still closed and "Out of Press" gives the final skin tension. About half the skin tension at the mid-plane is when the magnet is removed from the press.

The large loss of skin tension come from the considerable radial pressure the press must apply to guarantee closure of the yoke gap. In fact, the yoking/skinning press serves two purposes: 1) close the yoke mid-plane gap and 2) make the skin conform to the yoke. The first requires a considerable vertical force which can be applied most efficiently far from the weld. The second requires a considerably lower pressure which is uniformly applied. I have not worked out in detail what pressure is required but I guess that a pressure of 100 psi should be sufficient to force the skin everywhere to be within a few mils of the yoke. The yoking tooling currently under design is intended to apply full load between 60° and 90° from the weld and a much reduced pressure, on the order of 100 psi, between 0° and 60°.

The skin stress as a function of azimuth in and out of the press is plotted for several assumed values of the friction coefficients (see the appendix) and for different distributions of press load. In all cases the weld shrinkage is assumed to generate 40 kpsi at the weld and the total vertical press load is 4500 lb./in. The results are also summarized in Table I. By redistributing the press load the skin tension at the weld can be increased from 21 kpsi (uniform pressure, Fig. 1) to 31 kpsi (200 psi "side" pressure, Fig. 2) to 33 kpsi (100 psi "side" pressure, Fig. 6). If the friction coefficient is 1.0 (Fig. 3) rather than 0.5 (Fig. 2) the parting plane skin stress decreases by 14% and the average stress decreases by 37%. If the yoke-skin friction coefficient is 1.0, but a low friction coating is placed on the tooling to reduce the friction coefficient to 0.2 (Fig. 4), the final skin stress is 13% larger than if the skin-tooling friction is also high. (The difference is relatively small because the yoke-skin pressure is considerably larger than the tooling-skin pressure.) The most favorable condition, of course, is to have a low friction coefficient on both sides of the skin; with $\mu = \mu_p = 0.2$, the skin stress at the weld is over 36 kpsi and the average stress is 31 kpsi.

Table I

P (<60°) (kpsi)	P (>60°) (kpsi)	μ	μ_p	σ_{of} (kpsi)	$<\sigma_f>$ (kpsi)
0.0	0.0	0.5	-	40.0	27.7
0.69	0.69	0.5	0.5	20.6	14.3
0.20	1.18	0.5	0.5	30.5	21.1
0.20	1.18	1.0	1.0	26.3	13.3
0.20	1.18	1.0	0.2	29.7	15.0
0.20	1.18	0.2	0.2	36.5	31.3
0.10	1.28	0.5	0.5	32.6	22.6

Since it is the skin stress at the yoke parting plane that sets the yoke-yoke clamping force, all the cases shown except the uniform radial pressure case have adequate skin tension. Because, however, there is a stress gradient, there is a possibility of further stress redistributions that will decrease the parting plane skin tension. The most extreme (and extremely unlikely) redistribution would result in a uniform skin stress at the average value displayed in Table I. Only the cases with $\mu = \mu_p = 0.5$ and 100 psi "side" the pressure and with $\mu = \mu_p = 0.2$ have average skin tension adequate to close the yoke gap at room temperature under this (very pessimistic) assumption. However, even in the worst case (Fig. 3) if the skin tension became azimuthally uniform, the yoke gap would stay closed to almost 9 T.

COOLDOWN

With cooldown, the skin stress increases because of the larger thermal contraction of the skin than the yoke. The integrated thermal contraction from room temperature to 4 K is 2.9×10^{-3} for stainless steel and 2.1×10^{-3} for yoke steel[7] stainless steel to be 30 Mpsi, the skin stress increases by 24 kpsi under cooldown. The frictional force sets the maximum stress gradient that can be supported. With cooldown, the radial yoke-skin pressure increases; therefore if the friction coefficient does not decrease, the maximum allowed stress gradient will increase and there will be no tendency for the stress to redistribute.

As the skin cools, both the stress and the yield strength increase. If the skin is close to the room temperature yield point and the stress increases faster than the yield, the skin could yield further. However, even under the most optimistic assumptions, the peak skin stress after the magnet is removed from the press is at least 3 kpsi less than in the press and the peak stress in the press is at least 5 kpsi below the yield strength. Thus the stress increase with cooldown must exceed the yield strength increase by at least 5-10 kpsi for further yielding to take place. NBS data[6] on thermal contraction and yield strength of 316LN suggest that the stress increases no faster than the yield strength. The expected stress increase, assuming a difference in integrated thermal contraction between the skin and yoke of 1.0×10^{-3} and a modulus of 30 Mpsi, and the yield strength increase are displayed in Table II and Figure 7. At no point does the stress increase exceed the yield strength increase. Even if the yield strength changes are reduced by 50%, the stress change exceeds the yield change by a maximum of only 5 kpsi. Therefore it seems quite unlikely that any yielding will occur during cooldown.

Table II

stress(T) - stress(293) (kpsi)

T(K)	stress	yield
293	0.0	0.0
280	2.0	2.0
260	5.1	5.5
240	8.1	9.5
220	11.1	14.0
200	14.1	18.9
180	16.6	24.3
160	19.2	30.2
140	21.7	36.6
120	23.9	43.4
100	26.2	50.7
80	27.8	58.5
60	29.0	66.8
40	29.7	75.5
20	30.0	84.8
4	30.0	92.5

CONCLUSIONS

If the yoking tooling is properly designed, so that only the pressure needed to make the skin conform to the yoke is applied over most of the circumference, the weld shrinkage is sufficient to generate skin stress near the yoke parting plane that exceeds the minimum required to guarantee closure of the yoke gap under all circumstances. With cooldown the skin stress increases by >20 kpsi; it is unlikely that there will be any yielding or stress redistribution. Even under improbably pessimistic assumptions, the azimuthal stress at 4 K is sufficient to keep the mid-plane gap closed to fields well in excess of 8 T. The use of a low friction coating between the yoke and skin may be useful to add additional margin to the system, but does not appear to be essential.

References

[1] J. Strait, Design of a Vertically Split Yoke and Associated Collar for the 50 mm SSC Collider Dipole: Yoke-Collar Interface, TS-SSC 90-033, 6/26/90.

[2] The required skin tensions quoted in Ref. 1 assumes a 0.188" thick skin. The current design uses a 0.195" thick skin.

[3] J. Strait, FNAL Short Magnet Program, Minutes of the MSIM, 11/9-10/88

[4] J. Strait, Status of FNAL Short Magnet Program, Minutes of the MSIM, 4/13-14/89.

[5] C. Taylor, LBL Quadrupole Program, Minutes of the MSIM, 6/12/90.

[6] NBS Handbook on LNG Materials and Fluids Data and NBS Handbook on Structural Materials for Superconducting Magnets.

[7] C. Goodzeit, Structural Response of DSX201 Yoke and Shell (and Vertically Split Version) to Thermal and Lorentz Loads, 4/23/90 (Presented to the 5 cm Task Force, 5/9/90).

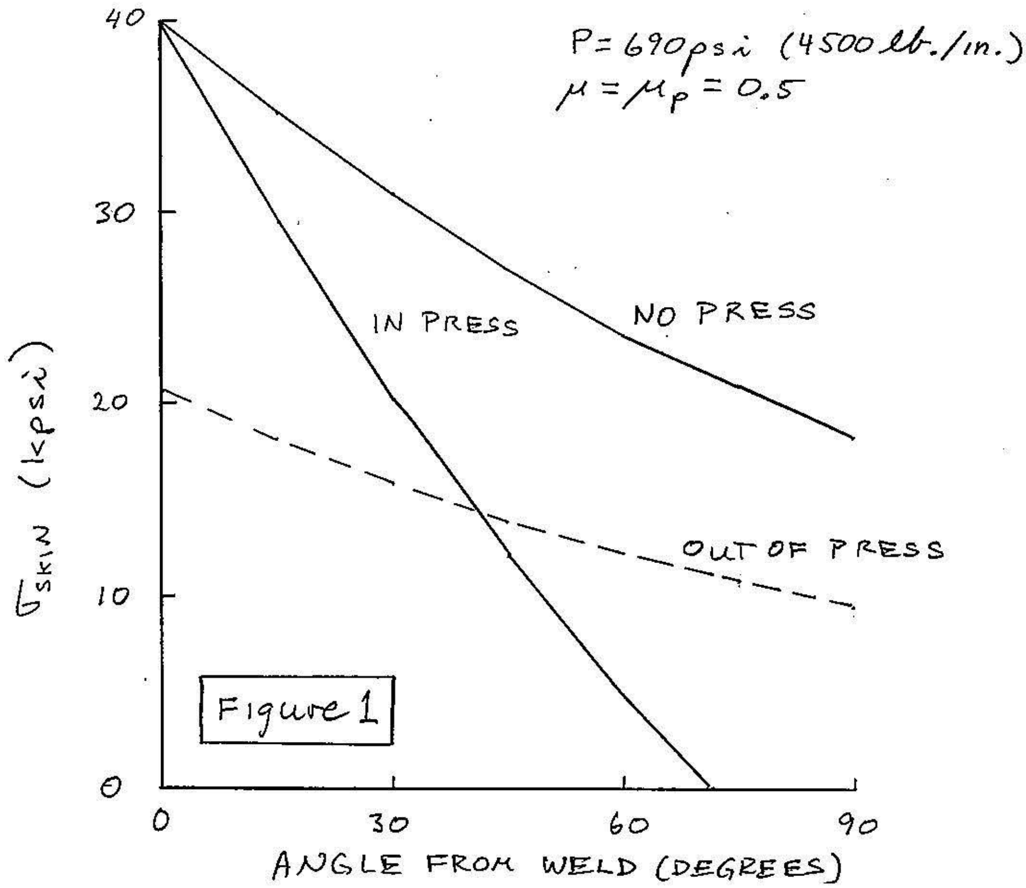


Figure 1

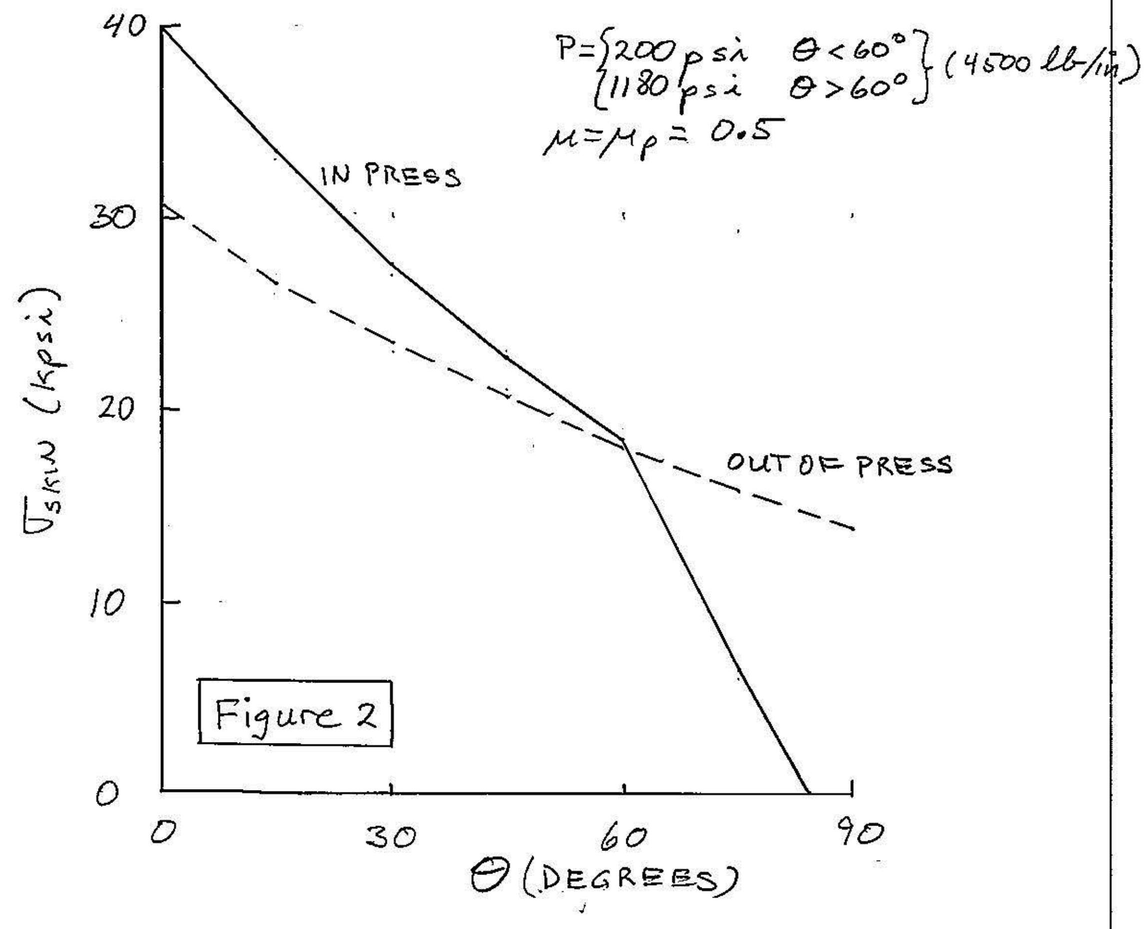


Figure 2

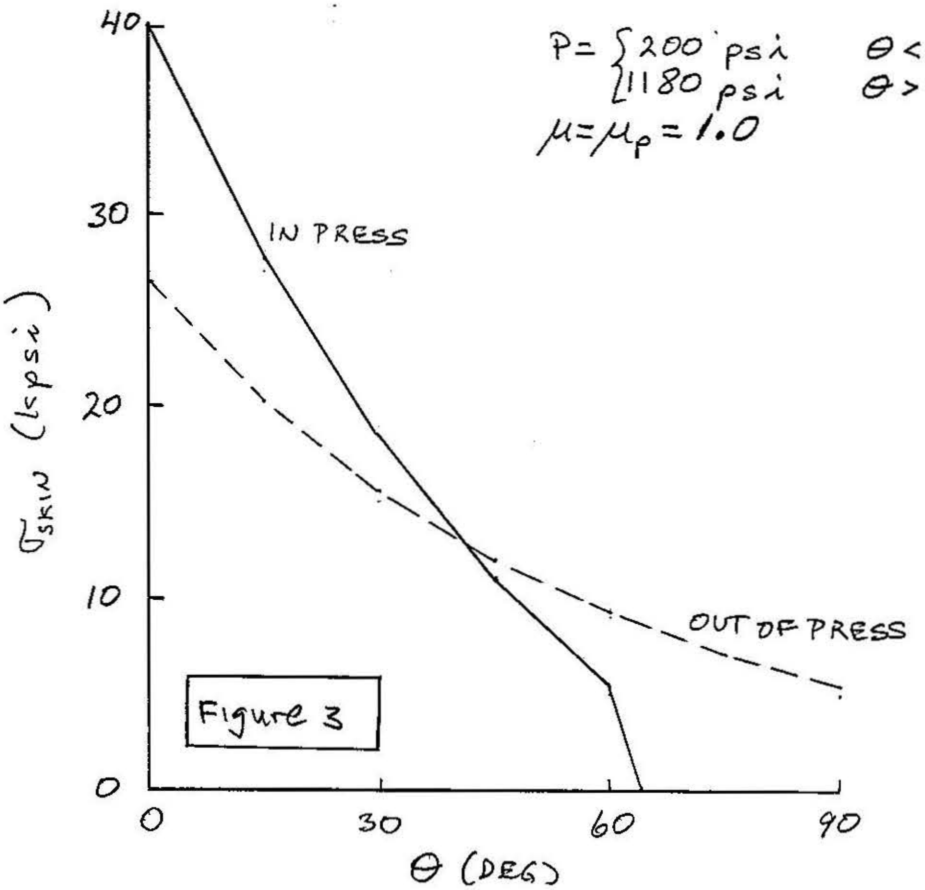


Figure 3

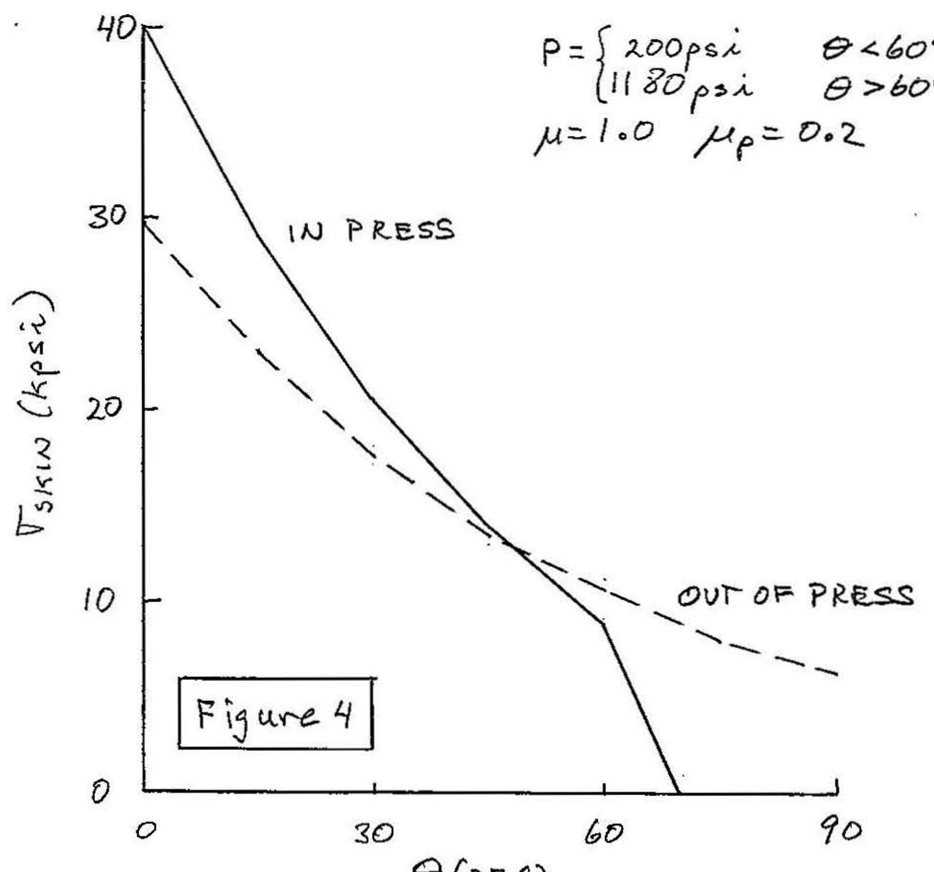


Figure 4

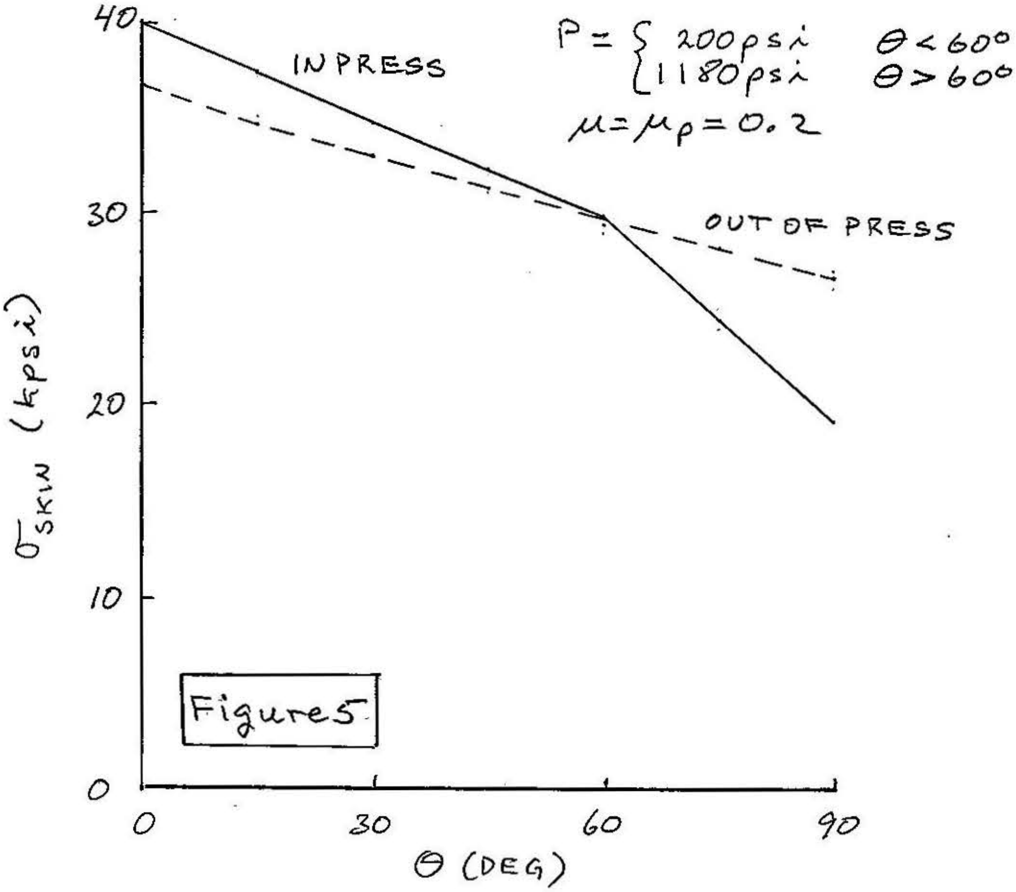


Figure 5

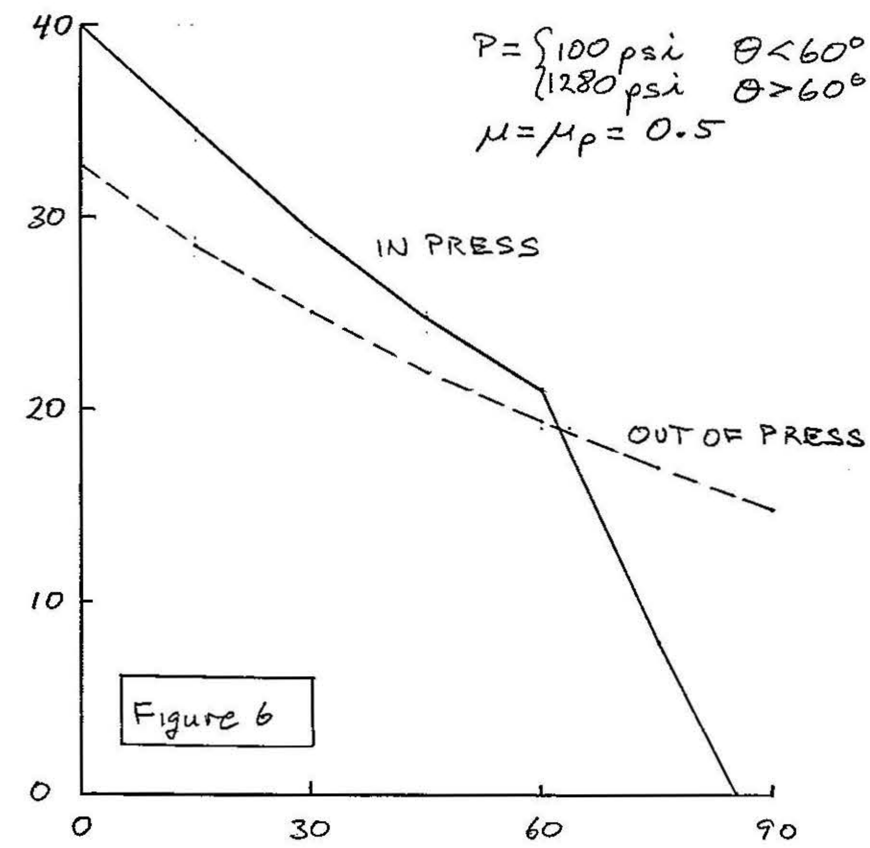
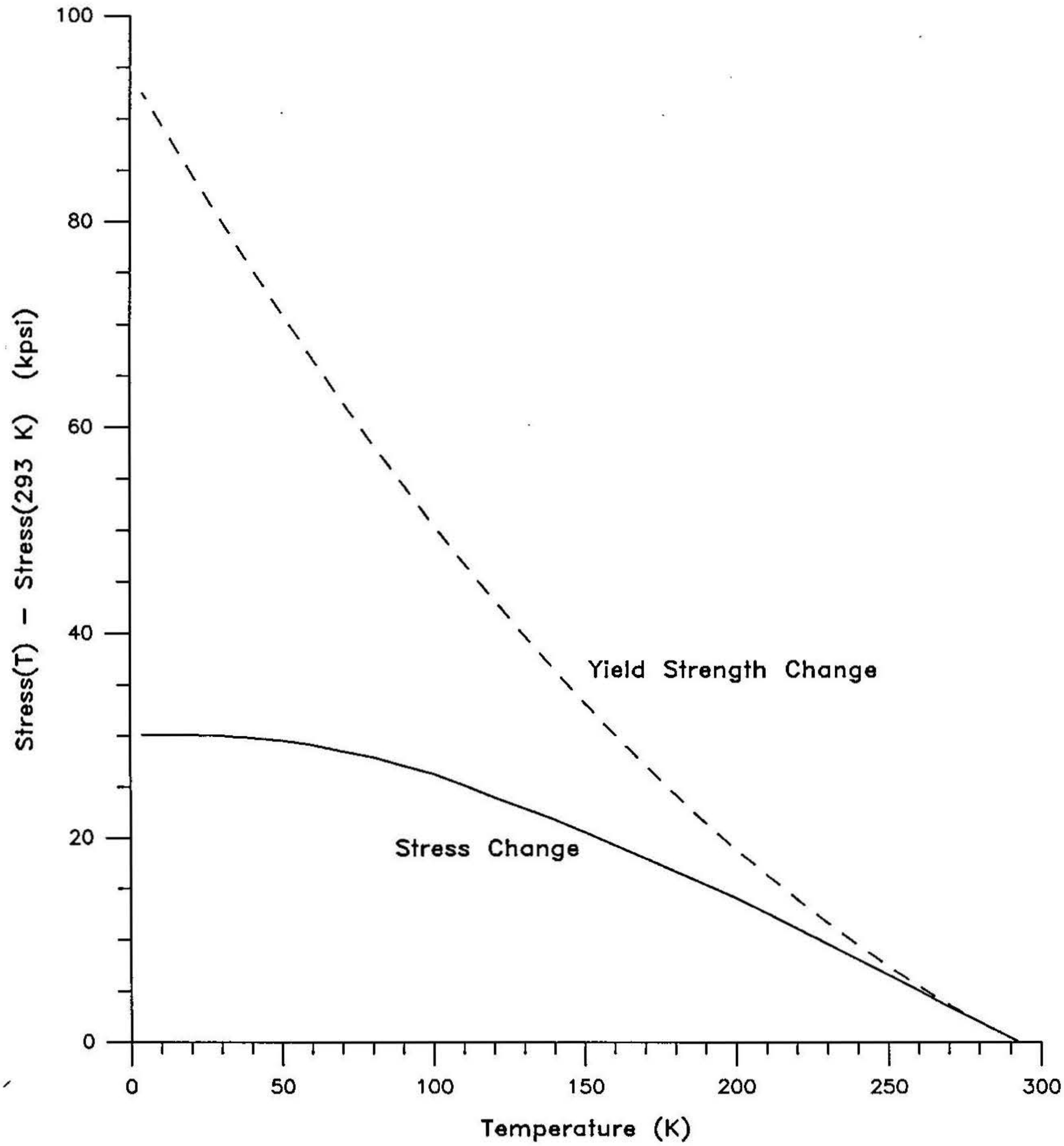


Figure 6



100
80
60
40
20
0
0
50
100
150
200
250
300
Stress(T) - Stress(293 K) (kpsi)
Temperature (K)
Yield Strength Change
Stress Change

Figure 7

APPENDIX

Analysis of Skin Stress Data

In this appendix I briefly evaluate skin stress data from three sources: two experiments done at FNAL with magnets F3[3] and DSS012[4] and one experiment done at LBL with magnet QC-1[5]. In these experiments strain gages were mounted on the skin and their resistance changes to 4 K were measured before the skin was welded allowing the measurement of absolute skin stresses. In the two FNAL experiments strain gages were mounted to the outside of the skin at 4 azimuthal locations. In the LBL measurement strain gages were mounted both outside and inside the skin at two 45° and 90° locations. To accommodate the inside gages small "wells" were cut in the skin at 45°. (The bus slots provide clearance at 90°.) The FNAL data are sensitive to small local bending of the skin as the weld shrinkage pulls the skin tight around the yoke. The LBL data suffer from the smaller number of azimuthal measurements and the lack of measurements near the weld.

In the measurements of F3 and DSS012 the strain gages were mounted on the skin before the skin was welded to the magnet. The free standing skin was cooled to 4 K to measure the strain gage offsets, allowing an accurate measurement of the skin strain change with magnet cooldown. It was not recognized at the time, however, that strain gages "train" with thermal cycling, so there may be uncertainties on the order of 50 $\mu\epsilon$ (1.5 kpsi) due to shifts in the thermal offset between the first (calibration) and second (measurement) times the gages were cooled. The skin was welded in a prototype yoking/skinning "press" which had the same cross section as the production press tooling, but covered only about one-quarter of the axial length of the magnet with a series of clamps compressed by large bolts. This device was capable of causing the skin to conform globally to the yoke but could not seriously compress the yoke. Strain measurements were normalized to the values with the skin clamped around the yoke before welding.

The skin on F3 was welded, then cut off (for reasons that I do not recall) and welded again. Strain gage data were taken on both assemblies and are displayed in Figures A-1 and A-2 respectively. At each angle from the mid-plane there were two strain gages about 2" apart. On the first assembly the strain gage nearest the weld show considerable yielding but the other 6 are below the yield stress. Equation (1) was fit to the data for $\theta > 20°$, yielding a friction coefficient $\mu = 0.45$ and $\sigma_o = 42$ kpsi. (The modulus is assumed to be 28 Mpsi for this analysis.) This is shown as the solid line in Fig. A-1. The dashed lines show the expected slopes for $\mu = 0.75$ and 0.15. The data in Fig. A-2 show no significant yielding, so all data are used in the fit: $\mu = 0.31$ and $\sigma_o = 34$ kpsi. Again the fit is the solid line and the dashed lines represent the $\mu = 0.75$ and 0.15. The scatter in the data about a smooth curve presumably results from a combination of local skin bending and stick-slip motion of the skin over the yoke.

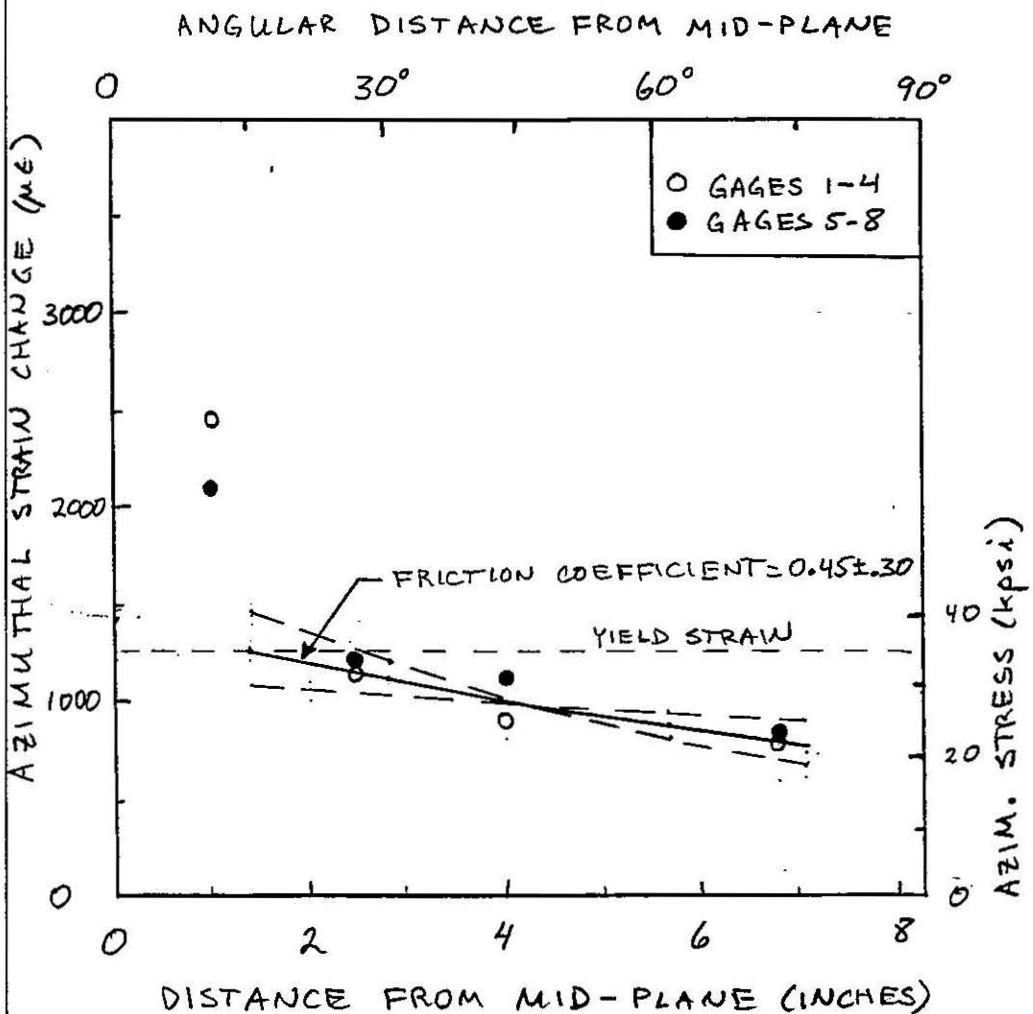
The strain difference with cooldown and the net strain change following warmup are shown in Fig. A-3. Since the skin tension increases, "high spots" where the skin does not locally contact the yoke will be pulled "down". This will cause local bending which will introduce some scatter into the data. The bending will be in the same direction as when the skin was welded. Indeed, the point at 23° which is "low" following welding is also low following cooldown. The average stress increase with cooldown is 20±2 kpsi and the net change with thermal cycling is -1.5±0.7 kpsi. The net change is near zero and the difference is in the range that might be expected for strain gage "training". Therefore the small apparent change should be treated as an upper limit.

Data from DSS012 are displayed in Figs. A-4 and A-5. The scatter in the welding data is considerably larger than for F3 and is well correlated between the two sets of gages. Presumably this skin had greater local variations in the radius of curvature. As on the first assembly of F3, the skin yields considerably near the weld. Because of the large bending effects, no fit was made to the data. With cooldown, the scatter is again larger than for F3 and the "low" point at 42° appears in both the welding and cooldown data. The average stress increase with cooldown is 18±3 kpsi. The net change with the full thermal cycle is -0.3±1.0 kpsi.

Data from QC-1 were presented by Clyde Taylor at the MSIM on 6/12/90. His one transparency is shown as Fig. A-6. Putting a curve of the form in equation (1) through the average stresses at 45° and 90° gives $\mu = 0.41$ and $\sigma_o = 27$ kpsi. Using all possible pairs of 45° and 90° data gives μ in the range from 0.1 to 0.7 and σ_o in the range from 18 to 40 kpsi. The average stress increase with cooldown is 37±3 kpsi and is, within the scatter of the data, the same at 45° and 90°.

The three sets of data from which a friction coefficient can be extracted are remarkably consistent and indicate a value in the neighborhood of 0.4. There is considerable scatter in the data, so values as high as 0.6-0.7 or as low as 0.2 cannot be ruled out altogether. However, a friction coefficient as large as 1.0, as assumed in some examples in the main text, is inconsistent with the data. The data are consistent with the expectation that the stress near the weld is close to the yield strength of 35 kpsi. The cold-warm difference is considerably larger in the LBL measurement than in the two FNAL measurements, but the usual assumption of a $\gtrsim$20 kpsi increase is supported. There is no evidence for stress redistribution with thermal cycling.

F3 SKIN STRAIN FROM WELDING



(SET 9) - (SET 5)

(Strain after welding) - (strain in press before welding)

Figure A-1

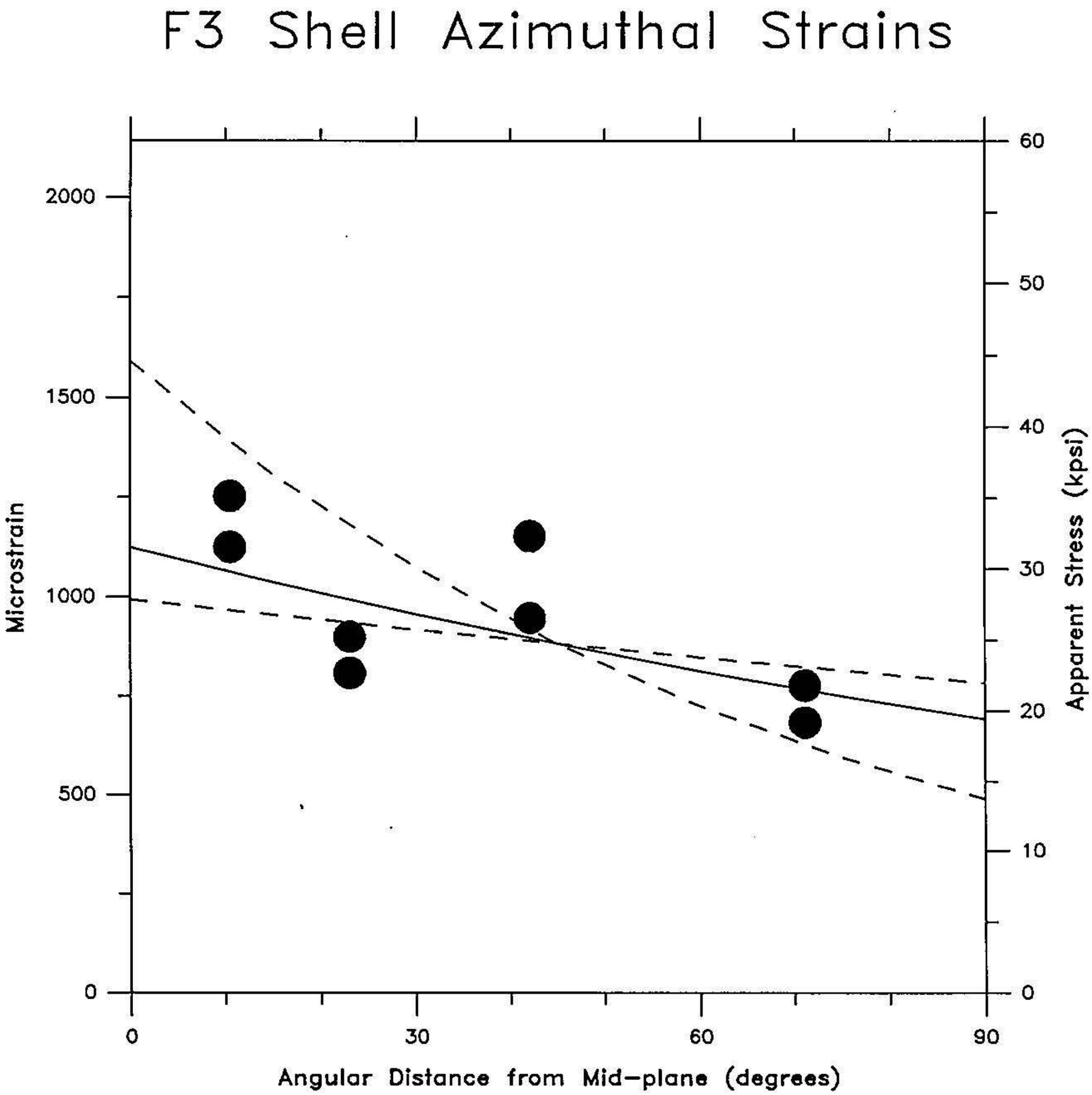

F3 Shell Azimuthal Strains
Microstrain
Apparent Stress (kpsi)
Angular Distance from Mid-plane (degrees)
0
500
1000
1500
2000
10
20
30
40
50
60
0
30
60
90

Figure A-2

F3 Shell Strains

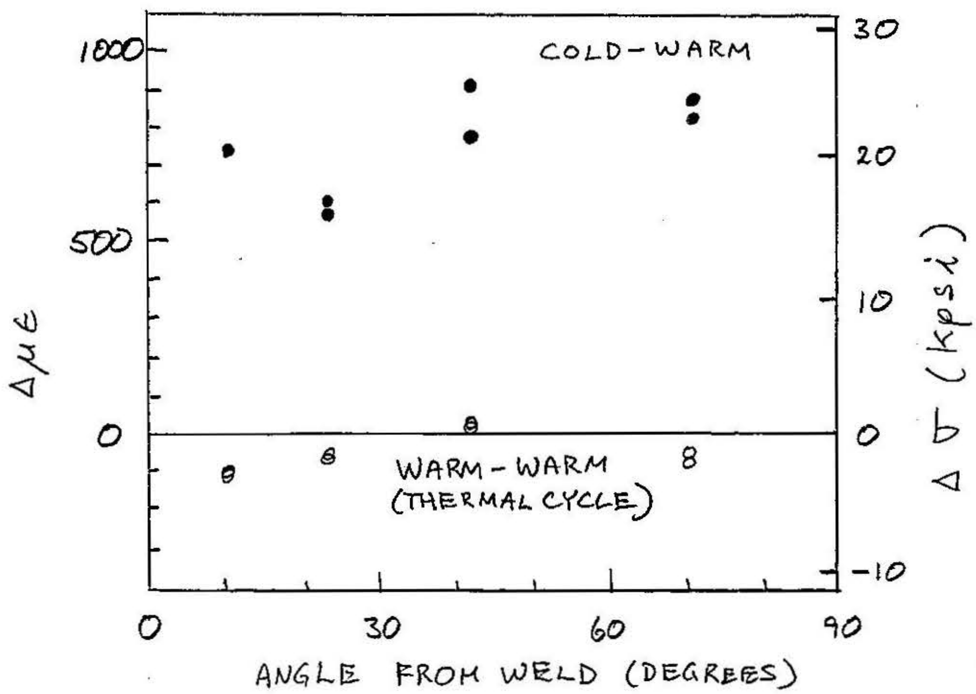
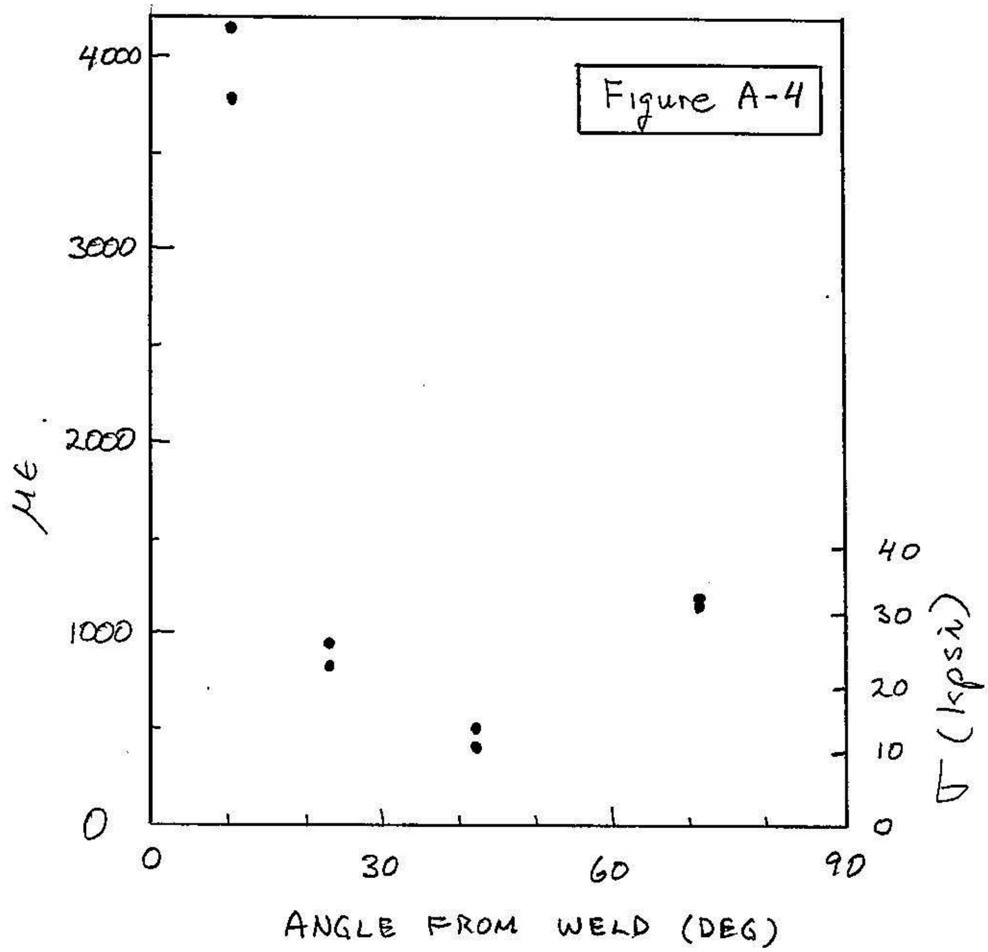
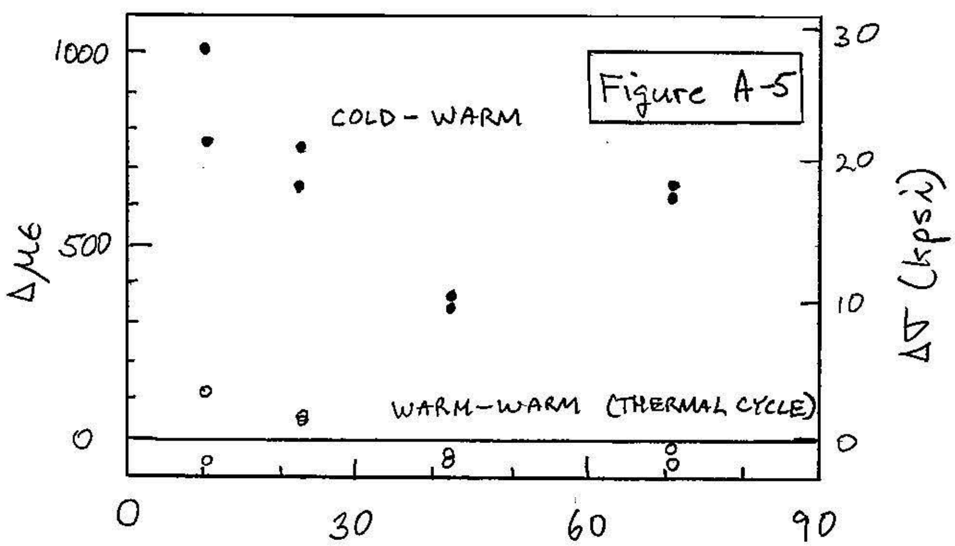
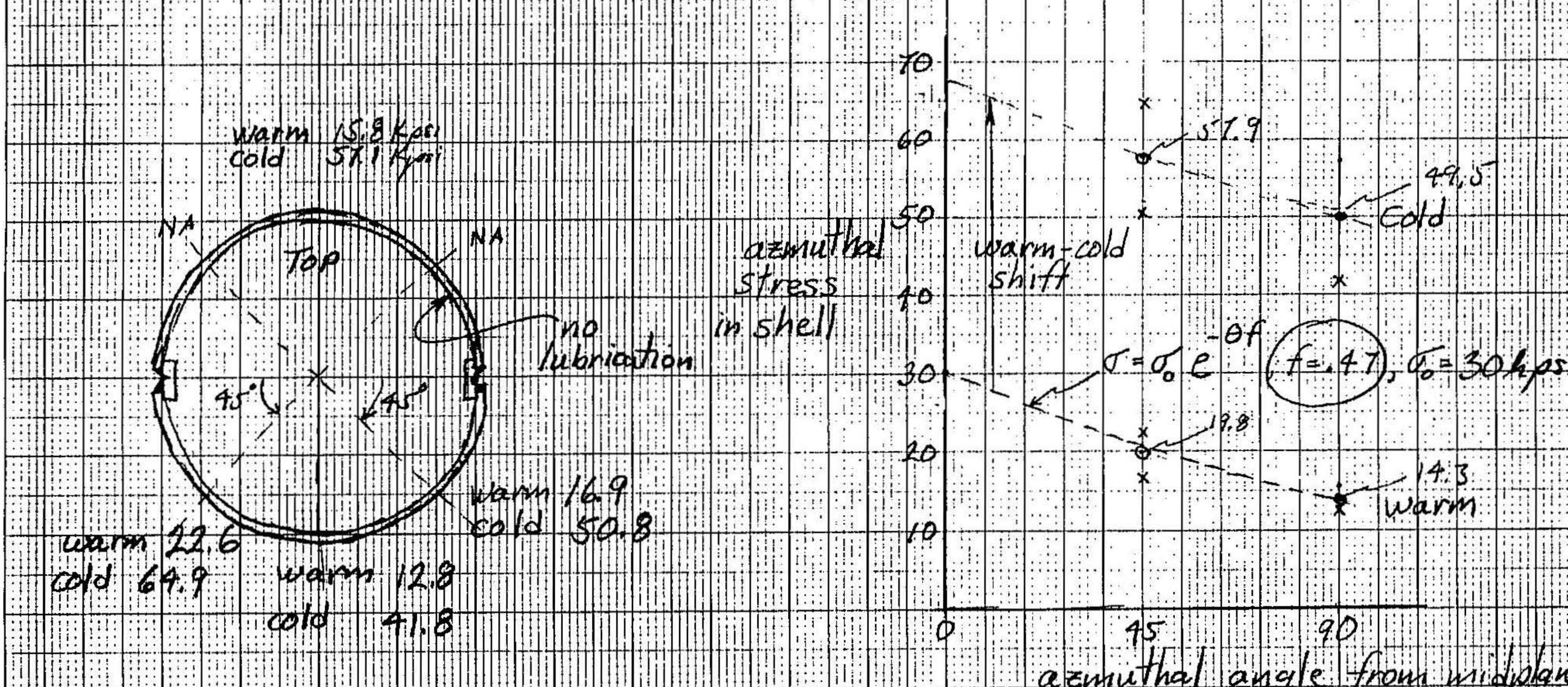


Figure A-3

DSS O12 SHELL STRAINS







warm → after welding
cold → LN_2 (77K)

Figure A-6

Azmuthal stress distribution in welded shell on QC-1
a) after welding (rm. temp)
b) LN_2 temp

CST LBL
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Distribution:

FNAL
- R. Bossert
- J. Carson
- J. Haggard
- J. Kerby
- W. Koska
- P. Mantsch
- G. Pewitt

SSCL
- T. Bush
- R. Coombes
- C. Goodzeit
- N. Hassan (at FNAL)
- J. Jayakumar
- R. Palmer
- P. Sanger
- G. Spigo
- J. Turner

LBL
- D. Dell'Orco
- C. Taylor
- R. Schermer