Fermilab

Magnetic Loads on the Tohoku Bubble Chamber Magnet's Support System after Magnet Reconfiguration

by

J. Patrick Kelley

December 2, 1987

Contents

List of Tables

List of Figures

Nomenclature

Capital Letters

A - area

E - modulus of elasticity

$\overline{E}$ - average modulus of elasticity

F - force

F_C - total axial magnetic force applied to the cryostat resulting in cryostat roll

F_H^C - preload on a horizontal post after cooldown

F_I^C - total force on a pair of inconel rods after cooldown, due to preloading

F_I^P - force on an inconel rod due to preloading prior to cooldown

F_p - magnitude of initial preloading

F_P - total axial magnetic force seen by all the axial post assemblies

F_R^C - total preload on a randolite/aluminum post after cooldown due to preloading

F_R^P - force on a randolite/aluminum post of an axial post

F_T - total axial magnetic force on a coil

F_V - total axial magnetic force applied to the vacuum vessel wall

K - spring constant axial

K_C - spring constant for the cryostat of a coil

K_H - spring constant for a single horizontal post

K_i - spring constant

K_I - spring constant for a single inconel rod after cooldown

Capital Letters (Continued)

K_I^T - spring constant for the 16 inconel rods in a coil after cooldown

K_P - spring constant for all the axial post assemblies of a coil

K_R - spring constant for the randolite/aluminum post of an axial post assembly

K_R^T - total spring constant for all the randolite/aluminum posts in a coil

K_T - total spring constant of the coil

K_V - spring constant for the vacuum vessel wall of a coil

L - length

M - factor used to obtain the vertical loads on a cryostat from raw strain gauge readings

T - temperature

Greek Letters

ΔL	-	change in length
ΔL_S	-	total thermal contraction in the stainless steel mounting of a horizontal post
ΔL_C^A	-	total contraction of all the aluminum in a post due to cooldown effects
ΔL_C^I	-	total contraction in an inconel rod due to cooldown effects
ΔL_C^R	-	total contraction of all the randolite in a post due to cooldown effects
ΔL_H^C	-	total thermal contraction due to cooldown in a horizontal post
ΔL_I^T	-	difference in net contraction between the randolite/aluminum post and the inconel rods
ΔL_P^I	-	total contraction in an inconel rod due to preloading
Δx_P	-	total contraction of a horizontal post due to room temperature preloading
$\Sigma\Delta L_A$	-	total thermal contraction in the aluminum pieces of a horizontal post
$\Sigma\Delta L_R$	-	total thermal contraction in the randolite segments of a horizontal post

Introduction

After the 1985 Engineering and Physics Runs of the Tohoku Bubble Chamber, a decision was made to increase the overall volume of the chamber [1]. A consequence of this decision was that the relative position of the Chamber's split solenoidal coils, with respect to one another, was altered. The reconfiguration placed the coils 12.6 inches further apart than they were during the 1985 Run [2]. Increasing the distance between the coils results in a diminishing of the attractive forces between the coils. Since a coil's axial support loads are the resultant of the magnetic attraction between the iron to which it is mounted and to the opposite coil, increasing the distance between the coils results in a larger coil to iron attraction and, subsequently, larger loads on the axial support system. Worse case predictions of the axial loads for the new configuration [2], obtained by using TRIM, a 2D magnetostatics program, were more than twice as high as those predicted by Craddock [3] for the 1985 Configuration; 480,000 lb. *vs.* 224,000 lb.

During the 1985 Magnet commissioning run, measurements were made to determine axial, horizontal, and vertical loads on the magnet's cryostat [3]. Since axial loads were of the greatest concern (due to iron saturation, peak forces were predicted to occur before design currents were reached), both strain gauges and dial indicators (deflection probes) were used to measure the axial loads. Strain gauges alone were used to measure horizontal and vertical loads. The results obtained from the axial load measurements were, at best, confusing. The dial indicator measurements indicate a peak load of 335,000 lb, roughly 50% greater than the predicted value. On the other hand, the strain gauge measurements indicate a peak load of 179,000 lb, approximately 20% less than predicted [3]. No reasonable explanation was offered for this discrepancy. Consequently, since much higher loads were expected for the reconfigured magnet, and since no agreement (except for general behavior) existed between the two measuring techniques or the TRIM predicted behavior, a decision was made to reevaluate the work presented by Craddock in Reference [3] (placed in Appendix B for convenience). Additionally, an analysis of the data recorded during the 1986 Recommissioning Run, obtained using the functioning instrumentation from the 1985 Run and dial indicators added by Craddock after the 1985 Run, is presented.

Dial Indicator Placement

The West Coil of the Tohoku Bubble Chamber Magnet was instrumented with six nonmagnetic Starrett dial indicators. Three of the dial indicators were used during the 1985 Run. These three dial indicators penetrate the coil's vacuum vessel from the east and rest on the cryostat. The three indicators are on a 29-1/2 inch radius, positioned horizontally, and each is radially in line with an axial post assembly, located on a 38-3/8 inch radius. What we designate as the top cryostat indicator can be located by rotating 27° to the north of the coil's vertical centerline. The other two indicators are each located by rotating 27° below the horizontal centerline, one on the north side of the coil, the other on the south side of the coil. These are respectively referred to as the north and south cryostat indicators. Referring to FNAL Dwg. #2771-MD-56365 (Appendix C), if the conductor, and hence the cryostat, experiences a force in the direction of the iron, the movement measured by the indicators must be the sum of the deflection of the cryostat (cryostat roll), the compression of the axial post assemblies, and the deflection resulting from the flattening of the vacuum vessel against the iron (see next paragraph).

The dial indicators added by Craddock after the 1985 Run penetrate the iron from the west side of the magnet and rest on the West Coil's vacuum vessel. These vacuum vessel dial indicators are positioned horizontally in line with the same axial post assemblies discussed above (*i.e.*, those assemblies associated with the cryostat indicators). Hence, the vacuum vessel indicators are located on a radius of 38-3/8 inches and at the previously described angular positions. As before, we shall designate the indicators as the top, north, and south vacuum vessel indicators. Reference FNAL Dwg. #9213.400 MD 202692 in Appendix C. The purpose of the added dial indicators is to measure vacuum vessel roll. Prior to energizing the coil, the wall of the evacuated vacuum vessel is deflected inward and away from the iron surface. As the coil is energized to higher currents, the axial loads on the support assemblies gradually force the vacuum vessel wall back in contact with the iron.

Figure 1: Spring system representing axial post assembly compression and vacuum vessel roll.

Analysis of the Dial Indicator Data—1985 Run

Consider the axial post assembly depicted on FNAL Dwg. #2771-MD-56365. Ideally, we would like to represent this support system under load as a pair of springs in series with one another, as in Figure 1. The first spring with spring constant K_P is associated with the actual post assembly. (reference FNAL Dwg #2771-ME-156057 in Appendix C). The second spring with constant K_V would be attributed to the deflecting vacuum vessel. The governing equations for this system are

$$\begin{aligned} F_T &= F_P = F_V \\ \Delta x_T &= \Delta x_P + \Delta x_V \end{aligned}$$

$$K_T = \frac{1}{\frac{1}{K_P} + \frac{1}{K_V}}$$

$$F_T = K_T \Delta x_T$$

$$F_P = K_P \Delta x_P$$

$$F_V = K_V \Delta x_V$$

In order to solve this system of six equations with nine variables or constants, we must be able to measure or calculate, from known mechanical properties, three of the unknown. (Note that the expression for K_T is found from the other equations, and hence is not an independent equation.) This would leave us with six equations in six unknowns. Unfortunately, we only have two known variables; Δx_V measured with the vacuum vessel dial indicators and K_P, which we can calculate using Mruzek's measurements of the mechanical properties of the randolite/post assembly [4] and the known properties of inconel [16,17] (this calculation is presented in Appendix D). Hence, we don't have sufficient information about the system to find the total force on the axial assemblies. What is needed to solve the system of equations is the variable Δx_T. This could be obtained by placing the cryostat indicators directly on the axial post assemblies along their longitudinal axis. From this perspective one must ask why, if he specifically wished to measure axial loads, Craddock placed the cryostat dial indicators where he did, radially in line with the posts, but at a different radius. He offers no explanation in his paper [3].

Since the cryostat dial indicators are not placed in line with the longitudinal axis of the axial posts, Craddock's approach [3] was somewhat different from that presented above. The cryostat dial indicators see both, in addition to the deflection of the vacuum shell, a deflection from cryostat roll and from compression of the axial posts. It is not possible to resolve the total detected movement into its constitute parts, using the dial indicators available during the 1985 Run. Craddock therefore modeled the system by adding a third spring in series with the spring network previously described. This is shown schematically in Figure 2.

The governing equations for the system are

Figure 2: Spring system representing cryostat roll, axial post assembly compression, and vacuum vessel roll.

$$F_T = F_C = F_P = F_V \quad (1)$$

$$\Delta x_T = \Delta x_C + \Delta x_P + \Delta x_V \quad (2)$$

$$F_C = K_C \Delta x_C \quad (3)$$

$$F_P = K_P \Delta x_P \quad (4)$$

$$F_V = K_V \Delta x_V \quad (5)$$

$$F_T = K_T \Delta x_T \quad (6)$$

$$K_T = \frac{1}{\left(\frac{1}{K_C} + \frac{1}{K_P} + \frac{1}{K_V}\right)} \quad (7)$$

This is a system of eight independent equations in 12 variables or constants. (Note again that K_T is not an independent equation.) At the time of Craddock's writing, and hence for the 1985 Run, no measurements for Δx_V were available. For the 1986 Run, Δx_V was measured. A value for K_P is known (Appendix D), and Δx_T is measured. We now have eight equations in nine unknowns, a system which can't be solved uniquely. Craddock therefore used ANSYS, a finite element structures code, to theoretically supply him with values for unknown quantities, producing a solvable system of equations. Specifically, he used a 2D ANSYS model to determine the maximum deflection of an evacuated vacuum vessel at the location of an axial post assembly. He then determined the total axial load required to return the vessel to complete contact with the iron [3,5]. From these two values, K_V can be found. The values he found in this fashion were .012 inch for maximum deflection, 55,000 lb for the total axial load required to "bottom out" the vacuum shell against the iron, and hence a value of 4.58E6 lb/in for K_V. Note that, since total axial loads of 224,000 lb were predicted, it was expected that the vacuum vessel would "bottom out" well before maximum loads were reached.

Craddock also used a 2D ANSYS model to find a value for K_C [6] (See Appendix E). To perform this analysis, he ignored the post assembly and constrained the cryostat at a single point on the top of the cryostat to post coupling structure. This point is located on or near what would be the longitudinal axis of the post assembly. Axial deflections, due to radial and axial loads, were determined. The axial deflections, due to radial loads, were ignored when calculating K_V (although, at the operating currents, these deflections were predicted to be about 1/3 of the deflection due to axial load). With an axial load of 462000 lb, the axial deflection was predicted to be .0128 inches, and hence K_C was taken to be 36.1E6 lb/in. Note that there is some purely axial movement at the model's anchored node. This movement should have been subtracted from the net axial deflection to obtain the deflection due to cryostat roll alone. This can be seen by studying Figure 23 of [6].

Knowing K_C, K_P, and K_V, we can calculate K_T from Eq. (7). Since Δx_T is measured, the total axial load can be found from Eq. (6).

Summarizing briefly, Craddock was able to calculate K_P using known mechanical properties for inconel and Mruzek's measured data, predict values for K_C and K_V, using ANSYS, and measured Δx_T. With these quantities, he only needed equations (6) and (7) to find the total axial load on the post assemblies. However, as noted previously, he found no reasonable agreement between dial indicator measurements, TRIM predicted values or strain gauge measurements.

Logic dictates, if there is confidence in the measurement techniques, that the 2D ANSYS models use to predict properties of three-dimensional vessels may be at fault. Craddock therefore installed the dial indicators to measure the vacuum shell deflection. This might imply his lack of confidence in his vacuum vessel calculations. However, results obtained during the 1986 Run indicate that the vacuum shell "bottoms out" at approximately .014 inches (Appendix F). Although this value is roughly 17% greater than the value Craddock predicted, and we don't known the amount of force that was required to cause this magnitude of deflection, it does give some measure of confidence to Craddock's calculations. Indeed, FNAL Dwg. #2771-ME-56411 indicates a machined flatness tolerance of .030 inches on the vacuum vessel wall, which might imply the discrepancy is due to machining imperfections.

After making the above observations, we are led to the conclusion that our discrepancies between predicted and measured values of axial load may be caused by incorrect predictions made by the 2D model of the cryostat. As noted above, Craddock ignored axial deflections due to radial loads. He also did not account for the linear displacement of the vessel along the post's longitudinal axis, when determining his deflection, attributing the entire deflection to cryostat roll. Due to time constraints, the author has not investigated the impact of these observations upon the final results. However, another approach was carried out to determine the sensitivity of the results to an error in using a predicted value for K_C. Wands' [7] (Appendix G) performed a 3D ANSYS analysis of the cryostat and its support system, to determine the system's critical component (which component would fail first as axial loading is increased). As a byproduct of his analysis, the deflection of the cryostat at a radius of 29.7 inches was calculated. At an axial load of 600,000 lb, this deflection was .118 inches. Assuming linear behavior would imply a deflection of .121 inches at a radius of 29.5 inches. This value, when corrected for the difference in applied load, is almost 7-1/2 times greater than the value Craddock predicted with his 2D ANSYS model. Additionally, Wands' model was constrained so that the deflection was due only to cryostat roll. Note that his model only considered axial loads and ignored radial loads which do cause some axial deflection. Using Wands' results leads to a K_C of 4.96E6 lb/in. What follows is a comparison of results obtained using Craddock's and Wands' values of K_C to evaluate the dial indicator data from the 1985 Run.

Using equations (6) and (7), we shall derive expressions to be used with the dial indicator data from the 1985 Run. The following constants are used in the derivation.

Craddock	Wands
$K_C = 36.1E6\ lb/in$	$K_C = 4.96E6\ lb/in$

$$K_P = \begin{cases} 11.4E6\ lb/in & F_T \leq 143900\ lb \\ 8.51E6\ lb/in & F_T > 143900\ lb \end{cases}$$

(Point where preloading is relieved ≃ 143900 lb) (Appendix C-D and Cryostat Axial Loads)

$$K_V = \begin{cases} 4.58E6\ lb/in & F_T \leq 55000\ lb \\ \infty & F_T > 55000\ lb \end{cases}$$

Point where vacuum vessel "bottoms out" ≃ 55000 lb)

Equation (2) gives

Craddock	Wands

$F_T \leq 55000\ lb$

$$K_T = \frac{10^6}{\frac{1}{36.1}+\frac{1}{11.4}+\frac{1}{4.58}} \qquad K_T = \frac{10^6}{\frac{1}{4.96}+\frac{1}{11.4}+\frac{1}{4.58}}$$

$$K_T = 3.00E6\ lb/in \qquad K_T = 1.97E6\ lb/in$$

$55000\ lb < F_T \leq 143900\ lb$

$$K_T = \frac{10^6}{\frac{1}{36.1}+\frac{1}{11.4}} \qquad K_T = \frac{10^6}{\frac{1}{4.96}+\frac{1}{11.4}}$$

$$K_T = 8.66E6\ lb/in \qquad K_T = 3.46E6\ lb/in$$

$F_T > 143900\ lb$

$$K_T = \frac{10^6}{\frac{1}{36.1}+\frac{1}{8.51}} \qquad K_T = \frac{10^6}{\frac{1}{4.96}+\frac{1}{8.51}}$$

$$K_T = 6.89E6\ lb/in \qquad K_T = 3.13E6\ lb/in$$

Using Equation (6), our equations for evaluating the dial indicator data from the 1985 Run are

Craddock	Wands

$F_T \leq 55000\ lb$

$$(8)\quad F_T = 3.00E6\Delta x_T \qquad (@55000\ lb,\quad \Delta x_T = .0183'')$$

$$F_T = 1.97E6\Delta x_T \quad (11) \qquad (@55000\ lb,\quad \Delta x_T = .0279'')$$

$$55000 < F_T \leq 143900\ lb$$

(Vacuum shell "bottomed out")

$$(9)\quad F_T = 8.66E6(\Delta x_T - .0183) + +55000 \qquad (@143900\ lb,\quad \Delta x_T = .0286'')$$

$$F_T = 3.46E6(\Delta x_T - .0279) + +55000 \quad (12) \qquad (@143900\ lb,\quad \Delta x_T = .0536'')$$

$$F_T > 143900\ lb$$

(Vacuum shell "bottomed out", preload relieved)

$$(10)\quad F_T = 6.89E6(\Delta x_T - .0286) + +143900$$

$$F_T = 3.13E6(\Delta x_T - .0536) + +143900 \quad (13)$$

Table 1 presents the loads predicted by each of these methods where Δx_T is taken to be the average of the three cryostat dial indicator readings from the 1985 Run. Note that the zero offset value for these readings were subtracted prior to averaging.

Figure 3 graphically presents the results given in Table 1, along with the loads Craddock predicted using TRIM [8]. Note that the muon notch was filled during the 1985 Run [9]. As we should expect, there is a large difference in the values obtained using Craddock's 2D ANSYS results and Wands' 3D ANSYS results. It should be noted that, using Wands' results, we obtain much better agreement with the strain gauge results for total axial loads presented by Craddock [3]. Since the values for deflection presented by Wands and Craddock differ almost by a factor of 7-1/2, it is conceivable that Craddock misrecorded his computer results in [6]. At this time, the author has no way of verifying this theory.

I Amps	Δx_T inches	Craddock F_T Kilopounds	Wands F_T Kilopounds
50	.0025	7.50	4.93
100	.007	21.0	13.8
150	.0145	43.5	28.6
200	.0245	109	48.3
250	.0335	178	74.4
300	.0395	219	95.1
400	.0495	288	130
500	.0555	329	150
550	.0565	336	153
600	.0560	333	151
650	.0559	332	151
700	.0525	309	140

Table 1: Calculated values of total axial force obtained using dial indicator data from the 1985 Run and using two sets of equations; the first with properties predicted by Craddock's 2D ANSYS model of the cryostat, the second with properties predicted by Wands' 3D ANSYS model of the cryostat.

Figure 3: Tohoku Bubble Chamber Magnet results from dial indicator readings made on the West Coil during the 1985 commissioning run.

Summarizing, Craddock, using a 2D ANSYS model of the cryostat, predicted a spring constant for cryostat roll that, when used with measured dial indicator values, led to calculated forces that were 50% higher than magnetic axial loads predicted by TRIM. He calculated, but did not apply, axial deflections caused by radial loads. The calculated axial deflection caused by radial loads at 700A was .0022 inches [6], and hence the deflection caused by axial loading would be 4.2% less than the measured deflection at 700A. This would reduce the predicted force at 700A by 4.8%. Additionally, Craddock, by fixing a cryostat support fixture node in his model on the side of force application, allowed a pure axial translation to be superimposed upon his roll deflection. This would lead to an overestimation of the cryostat's roll deflection and an underestimation of its stiffness. The author has no method of estimating this error.

Wands, using a 3D ANSYS model of the cryostat, predicted a spring constant that led to calculated forces that were 32% less than those predicted by TRIM. However, these forces were reasonably close to the values obtained by strain gauges and presented by Craddock [3]. The results obtained, using Wands' predicted spring constant, did not take into consideration axial deflections caused by radial loads. Wands did constrain his system so that no pure axial translations could be superimposed upon his cryostat roll deflections.

Finally, Craddock's spring constant was based on calculated deflections for an applied load of 462,000 lb. Wands' calculated deflection resulted from an applied load of 600,000 lb. Assuming linear behavior, Craddock's calculated deflection at 600,000 lb would have been .0166 inches or .0038 inches greater than his value at 462,000 lb. If the axial translation permitted in Craddock's model, which was superimposed upon his roll deflection, is of the order of magnitude as this change (.0038″), then the difference between Craddock's and Wands' results would be roughly a factor of 10. This would lend some credence to the theory that Craddock misrecorded his data from his ANSYS calculations.

In conclusion, it is felt that the equations obtained using Wands' data are the more reliable of the two sets. We shall use the spring constant obtained from Wands' data in all future calculations. Additionally, no correction will be made for axial deflections due to radial loads since the 2D cryostat model from which we would obtain this information, is already subjected to question and is not independently verifiable at this time.

Analysis of the Dial Indicator Data—1986 Run

As mentioned previously, dial indicators measuring the displacement of the vacuum shell were added to the West Coil's instrumentation between the 1985 and 1986 Run. This allows us to directly measure Δx_V. Our measured or reliably calculated values are Δx_V, Δx_T, and K_P. We shall assume K_C as known, where Wands' numerical data is used. Using our system of equations, (1) – (7), we shall derive an expression for F_T in terms of these four values.

Substituting equation (1) into (5) gives

$$F_T = K_V \Delta x_V \ . \tag{14}$$

Substituting (6) we have

$$K_T \Delta x_T = K_V \Delta x_V \ .$$

Substituting (7) and solve for K_V gives

$$K_V = \frac{\Delta x_T}{\Delta x_V}\left[\frac{1}{\frac{1}{K_C}+\frac{1}{K_P}+\frac{1}{K_V}}\right]$$

$$K_V = \frac{\frac{\Delta x_T}{\Delta x_V}-1}{\frac{1}{K_C}+\frac{1}{K_P}} \ .$$

Substituting this result into (14) leads to

$$F_T = \left[\frac{K_C K_P}{K_C + K_P}\right](\Delta x_T - \Delta x_V) \ . \tag{15}$$

Recalling that the preload on the inconel rods is relieved at 143900 lb, our general equation for axial loads becomes

$$F_T \leq 143900 \ lb$$

$$F_T = \left[\frac{(4.96E6)(11.4E6)}{(4.96E6) + (11.4E6)}\right](\Delta x_T - \Delta x_V)$$

$$F_T = 3.46E6(\Delta x_T - \Delta x_V) \ , \tag{16}$$

and for

$F_T > 143900\ lb$

$$F_T = \left[\frac{(4.96E6)(8.51E6)}{(4.96E6) + (8.51E6)}\right](\Delta x_T - \Delta x_V)$$

$$F_T = 3.13E6(\Delta x_T - \Delta x_V) \ . \tag{17}$$

After a brief discussion, we shall evaluate our dial indicator data using these two equations.

Figure 4 is a graph of the deflections measured by the three vacuum shell dial indicators. While the data obtained from the north and south indicators agree with one another, the top indicator indicates a large variation from the other two. This, most likely, can be attributed to the difficulty in torquing the vacuum vessel bolts into the iron in the general vicinity of the top indicator. The upper north area of the coil is where the transfer line between the helium dewar and coil is connected. The obstruction created by the transfer line makes it exceedingly difficult to sufficiently tighten the vacuum vessel bolts. Hence, a slight gap could exist between the vacuum vessel and the aluminum shim, between the shim pair, or between the shim and iron. Hence, the movement seen by the top vacuum vessel dial indicator, as the axial load increased, would reflect both a linear movement as the attractive forces between the coil and iron closed the gap and a movement due to the vacuum vessel roll. Note that the top cryostat dial indicator would not see this linear movement, because it is mounted to the vacuum vessel, and hence translates with the vessel. We shall therefore ignore the data for the top vacuum shell indicator and define Δx_V in equations (16) and (17) to be the average of the north and south dial indicator readings.

Figure 5 is a graph of the cryostat dial indicator readings from both the 1985 and the 1986 Runs. We notice that, at low currents, most of the deflections from

Figure 4: Tohoku Bubble Chamber Magnet vacuum shell dial indicator measured deflections (West Coil, Raw Data).

Figure 5: Cryostat's dial indicator measured deflections West Coil—Raw Data)

the 1985 Run are greater than those for the 1986 Run. It is only at the higher currents that the 1986 deflections start to exceed the 1985 values. This general behavior agrees with Sander's predictions [2], presented in his Figure 11, for TRIM run 75, if the following two assumptions are valid. The first is that the predicted behavior may be extrapolated linearly to low currents, and second, the behavior is parabolic at low currents. Note that TRIM run 75 corresponds to the case of a 6″ gap between the coil vacuum vessel and the iron and corresponds to the actual geometry of the magnet during the 1986 Run.

It should be noted that the behavior of the coil, as indicated by the north cryostat dial indicator during the 1986 Run, is similar to the behavior exhibited by the south cryostat dial indicator during the 1985 Run. It can be argued that the coil was jarred slightly between the two runs, and hence the relative positioning of the cryostat could have been altered. Recall that all axial posts are mounted using ball and socket type joints. The inconel preloading members could not keep the coil from "floating" to another position. However, the modification procedures for the magnet were designed to avoid jarring, and the group leader responsible for the actual work felt that this did not occur [10]. The author feels that the difference in the observed behavior between the two runs may be due to an error in recording the data. The data entries made for the 1986 Run were made by Gene Smith, who, at the time of the run, had been working with the magnet for 2-3/4 years. Mr. Smith is unlikely to confuse north from south in an environment with which he is intimately familiar. The data for the 1985 Run was recorded by M. Mruzek. Mr. Mruzek is an engineer who was associated with the design and fabrication of the magnet, but who left FNAL before magnet construction was started in Lab F. Indeed, he left FNAL before construction of Lab F was completed. Hence, Mr. Mruzek was unfamiliar with the local environment. This fact is verified when Mruzek's notes concerning the strain gauge to Strainsert connections are examined. Mruzek's notes refer to a north coil and a south coil, when discussing the strain gauges that measured decentering forces and that were connected to the Strainsert he designated Unit 1. There is no north or south coil, only an east and West Coil. Additionally, all data recorded by Mruzek was entered on a figure which represented a view of the coil from west to east. Since all indicators on the coil during the 1985 Run were on the east face, they were viewed from east to west. This is inherently confusing, and presents an ideal situation for allowing the data for the north and south indicators to be reversed.

Results obtained by applying equations (16) and (17) with the data obtained from the two sets of dial indicator readings are presented in Figure 6 and Table 2. A few comments need to be made concerning the application of the data with the equations. First is that Δx_T is taken to be the average of the three cryostat dial indicator readings obtained at a given current. Second is that Δx_V is the average of the north and south vacuum vessel dial indicator readings, as noted above. Finally, when examining the raw dial indicator data that is presented in Appendix F, we see that the majority of the cryostat dial indicator data is negative, whereas all the vacuum vessel dial indicator data is positive. However, both sets of data imply movement towards the iron. The sign of the data is just a function of the individual indicator's frame of reference. Therefore, since both sets of data imply movement towards the iron, the values for Δx_T and Δx_V, with few exceptions, are entered into equations (16) and (17) with the same sign.

Presented also in Table 2 are the results obtained by applying the equations used to evaluate the 1985 Run data, Equations (11), (12), and (13), to the 1986 Run. We see that the loads calculated using this method agree reasonably well with the values obtained using Equations (16) and (17). This lends a degree of confidence to the calculations performed in the evaluation of the 1985 dial indicator data.

Figure 6 also presents the results obtained using Wands' value for K_C for the 1985 Run. A comparison of the results for the two runs indicates that larger forces were obtained during the 1985 Run, an unexpected result. This conclusion, however, is strengthened by the fact that no effects of coil training were observed during the 1986 Run. Specifically, the author assisted Craddock during the 1985 Commissioning Run. At this time, as current was increased in the magnet, occasional large amplitude voltage spikes were observed in the quench detection circuits, which were directly related to audible pings being emitted by the coils. However, after the magnet was discharged, upon recharging neither the spikes nor the pings were observed. These observed symptoms were attributed to the conductor seating itself under the

Figure 6: Tohoku Bubble Chamber Magnet results from dial indicator readings made on the West Coil during both the 1985 and the 1986 Run.

I Amps	Δx_T inches	Δx_V inches	F_T Kilopounds Eq.(16&17)	F_T Kilopounds Eq.(11,12,13)
0	0	0	0	0
50	-.006	.001	-24.2	-11.8
100	-.006	.0015	-26.0	-11.8
150	-.003	.0035	-22.5	-5.91
200	.0053	.005	1.04	10.4
250	.0097	.0065	11.1	19.1
300	.0153	.0085	23.5	30.1
350	.0190	.010	31.1	37.4
400	.023	.011	41.5	45.3
450	.029	.011	62.3	58.8
500	.032	.0115	70.9	69.2
550	.035	.0125	77.9	79.6
600	.039	.0125	91.7	93.4
650	.045	.013	111	114
700	.048	.0135	119	125
725	.050	.0135	127	131
750	.052	.014	131	138

Table 2: Results obtained from dial indicator measurements made on the West Coil during the 1986 Run of the Tohoku Bubble Chamber Magnet.

increasing magnetic forces. However, once seated under a given load condition, the conductor remained seated unless a greater load was applied. Indeed, for currents greater than 550A, during the 1985 Run, these symptoms, for the most part, were no longer observed. This gave credibility to the prediction that the peak force occurred at about 550A. Returning to our discussion of the 1986 Run results, since no coil training was observed, it does seem possible that the peak axial forces during this run were less than, or roughly equal to, those observed during the 1985 Run.

Summary of the Dial Indicator Analysis

We shall now summarize the main points observed in the analysis of the dial indicator readings.

We have modeled the cryostat's axial support system as a system of three springs with spring constants K_C, K_P and K_V. Craddock

- used Mruzek's experimentally determined value of K for the randolite/ aluminum post and calculated a value for K_P, the spring constant for the axial support assembly,
- calculated values for K_C and K_V, the spring constants for the cryostat roll and vacuum vessel roll respectively, using 2D ANSYS models of the respective vessels,
- measured Δx_T, the net deflection of the cryostat at a radius of 29.5 inches caused by vacuum vessel and cryostat roll and by compression of the axial supports.

Craddock's results for axial loads found using this three-spring model and data were 50% higher than TRIM predictions for the 1985 Run.

The author has, for the 1985 Run

- briefly considered Craddock's 2D ANSYS calculations used to obtain K_C, the spring constant for cryostat roll. We observed that his calculations predict the axial deflection at the point of dial indicator measurement caused by radial loads at the operating current are about 1/3 of the magnitude of the predicted axial deflection caused by an axial load. Craddock neglected this effect in determining K_C. This, when compared with measured values of Δx_T, would result in a reduction in the calculated load (equation (16)) by 4.8%.
- observed that Craddock's 2D ANSYS model for the cryostat allowed a pure axial translation to be superimposed upon his predicted axial deflections. The impact of this fact was not investigated.

- obtained another value for K_C based on Wands' 3D ANSYS calculations. Wands' model did not consider axial deflections, caused by radial loads, but it did produce a value for deflection without having an axial translation superimposed. The deflection obtained from Wands' model and used to predict K_C was roughly 7-1/4 times the value reported by Craddock. It is conceivable, but not verifiable, that Craddock misrecorded his data. The results obtained using the new value for K_C were 32% less than TRIM predicted values, but disagreed with Craddock's strain gauge results by approximately 14%.

For the 1986 Run, Craddock added dial indicators to measure the amount of vacuum vessel roll. Using the value of K_C found from Wands' calculations, we

- obtained a value for Δx_T by averaging the three readings obtained from the cryostat dial indicators.
- obtained a value for Δx_V by averaging the north and south vacuum vessel dial indicator readings. The readings from the top indicator were much larger than those for the other two. The reason for the large variation was attributed to the inaccessibility of the vacuum vessel mounting bolts leading to inadequate torquing during installation.
- calculated the net axial force using equation (16). We found that these calculations predicted forces that were less than those found for the 1985 Run. A small degree of confidence in this result is obtained by observing that no coil training effects were observed during the 1986 Run.
- calculated the net axial force using equations (11), (12), and (13) and the data from the 1986 Run. These results agreed reasonably well with the results obtained using equation (16). Since fewer unknowns were associated with equation (16), the reasonable agreement between the results of the two methods of calculations lends confidence to our 1985 data evaluation.

Strain Gauge Placement

Both the East and West Coils of the magnet were, to a degree, instrumented with strain gauges. A pair of Model TN8C Strainsert 8 Channel Strain Indicators were used to read the gauges. The general location of the strain gauges are shown in Figure 7 (FNAL Dwg #2771-MC-193624). This figure is a reproduction of a crude sketch made by M. Mruzek and presented by Craddock [3]. Using Figure 7 as a guide, we shall briefly discuss the placement of the strain gauges.

Axial loads are determined from measurements made with strain gauges that are mounted on the randolite posts of three axial support assemblies. Specifically, two strain gauges are mounted on a plane perpendicular to the post's axis, midway between the post's room temperature and LN_2 intercept [11]. See FNAL Dwg. #2771-MD-56417 and #2771-ME-156057 in Appendix C. The strain gauges are positioned opposite one another on the perimeter of the post. Hence, the magnitude of compression due to bending seen by one gauge, is matched by the magnitude of tension seen by the second. Averaging the two readings will lead to the net axial compression seen by the post. A single strain gauge is mounted on a fourth axial support assembly. It is used only to verify the similarity of load behavior between runs.

According to Mruzek's figure, Figure 7, the top two axial support assemblies on each coil were instrumented with strain gauges. The author, however, has not discovered any information which indicates which gauges are associated with the north assemblies and which gauges are associated with the south assemblies.

During the 1985 Run, data was recorded from all strain gauges on the axial posts. However, during the 1986 Run, one of a pair of strain gauges on a West Coil axial post was found to be open. We, therefore, only obtained a complete data set from two axial support assemblies, one on each coil. Due to the limited number of channels available to read the strain gauges, the data from the remaining functional strain gauge on a West Coil axial support assembly was recorded, but the singly mounted gauge on the East Coil was not.

The horizontal post assemblies, FNAL Dwg #2771-MC-56476 and the unnum-

Figure 7: Tohoku Bubble Chamber coil instrumentation schematic.

bered drawing in Appendix C, were instrumented in two ways. The first manner of instrumentation is identical to the method used with the axial support assemblies [12]. The second method is with strain gauge bolts. The top pair of horizontal post assemblies were instrumented in this fashion. Again, the author can't locate information which would indicate which gauges are on the north assemblies and which are on the south assemblies. Craddock [3], indicates that the strain gauge bolts were unreliable. The author did not try to verify Craddock's statement emperically, nor did he use the horizontal strain gauge bolts during the 1986 Run.

During the 1985 Run, one pair of strain gauges from the East Coil's horizontal assemblies was monitored. Additionally, a single strain gauge from each of the remaining pair of gauges on the horizontal assemblies was read. During the 1986 Run, both pairs of strain gauges on the East Coil's horizontal assemblies were read. On the West Coil, the data from one pair of gauges was recorded.

Vertical loads were determined by making measurements with strain gauges (four wire) mounted in the bolts at the top of the vertical support arms (FNAL Dwg # 2771-MD-156000 in Appendix C). These bolts were made by Fermilab and then the strain gauges were installed in the bolts and calibrated by Strainsert [3]. Calibration data for each bolt exists, but the author has not been able to locate any information which states which bolt is associated with which column. It appears that Craddock [3] also had this problem, because he used an average of the calibration data to obtain his loads. He did not use a specific calibration set for each bolt. However, we do know the location of each strain gauge (despite not knowing their individual characteristics), and each was recorded during both the 1985 and 1986 Run.

The raw strain gauge data from both the 1985 and 1986 runs for the vertical, axial, and horizontal loads, is included in Appendix H. Note that all strain gauges were zeroes prior to energizing the magnet; so that only strains caused by magnetic loads were recorded.

Figure 8: Schematic of a single axial post assembly after cooldown but prior to energizing the coil.

Cryostat Axial Loads

In order to evaluate the raw data acquired from the strain gauges on the cryostat's axial post, we must do two things. The first is to derive the relevant equation for the total magnetic load on a single axial assembly, and the second is to determine at what point the preloading by the inconel rods on the axial posts is relieved. When preloading is relieved, the post assembly acts as a single spring with constant K_R instead of a set of parallel springs.

Figure 8 reflects the initial conditions of a single post assembly prior to energizing the coil. The magnitude of the force seen by the randolite/aluminum post is equal to the magnitude of the force seen by the two inconel rods. Hence,

$$F_R^C = F_I^C = F_i \ . \qquad (18)$$

Figure 9 reflects the condition that exists after the coil is energized. Defining P to be the magnetic load on the assembly, P_R to be the portion of P that causes compression in the post, and P_I to be that portion of P that relieves preloading in

Figure 9: Schematic of a single axial post assembly after energizing the coil.

the inconel rods, we may write

$$P = P_R + P_I \ , \tag{19}$$

and

$$F_R = F_i + P_R \qquad\qquad F_I = F_i - P_I \ . \tag{20}$$

F_R and F_i are the total load seen by the randolite/aluminum post and the inconel rods, respectively. Note, that since the strain gauges are zeroed prior to energizing the magnet, the strain seen by the strain gauges is caused by the force P_R. Since the components in our system are in parallel, we may write

$$\triangle x_R = \triangle x_I \ . \tag{21}$$

Recall that, for a spring

$$F = K \triangle x \ .$$

We may therefore write in place of (21)

$$\frac{P_R}{K_R} = \frac{P_I}{2K_I} \ .$$

Hence

$$P_I = \frac{2P_R K_I}{K_R} . \tag{22}$$

Substituting into (19), we have

$$P = P_R \left[\frac{K_R + 2K_I}{K_R} \right] . \tag{23}$$

Since P_R is the force found directly from the strain gauge readings, we may write

$$P_R = \epsilon \overline{E} A . \tag{24}$$

Note that since the gauges mounted on the randolite post are midway between the room temperature and the LN_2 intercept, $\overline{E}$ is the average value of the modules for randolite at the two respective temperatures. Craddock [3]* cites these values to be

$$\begin{aligned} E &= 4.48E6psi \text{ @ room temperature} \\ E &= 4.89E6psi \text{ @ 77 K.} \end{aligned}$$

Hence

$$\overline{E} = 4.69E6psi .$$

Substituting (24) into (23), we have

$$P = \epsilon \overline{E} A \left[\frac{K_R + 2K_I}{K_R} \right] . \tag{25}$$

This is our general expression for the magnetic load on a single post assembly in terms of the strain, ϵ. Since our strain gauge readouts give us readings in $\mu\epsilon$, we rewrite (25) to allow for the direct substitution of the average of the two strain gauge readings from a single assembly. Hence,

$$P = \overline{E} A \left[\frac{K_R + 2K_I}{K_R} \right] \mu\epsilon * 10^{-6} . \tag{26}$$

*From Craddock's notation, the author believes Craddock implies that M. Mruzek measured the modulus for randolite at 77 K and that Craddock measured the modulus for randolite at room temperature. Craddock cites no reference for the work however, and the author has not discovered any documentation which describes the measurements or results. A more thorough examination of Craddock's personal notes should be performed.

Substituting for our constants, we have

$$\begin{aligned} P &= 4.69 * 3.976 \left[\frac{1.064 + 2(.182)}{1.064}\right] \mu\epsilon \\ P &= 25.03\mu\epsilon \, . \end{aligned} \tag{27}$$

We now wish to determine the point at which the magnetic loading per post assembly entirely relieves the preloading of the inconel rods. This is important since the behavior of the assembly changes when the preloading is relieved and the equation (27) is no longer valid.

At the point when all preloading is relieved, the following is true (from Eq. (18))

$$P_I = F_I = F_I^C \, .$$

Substituting this into (22) gives

$$P_R = \frac{F_I^C K_R}{2K_I} \, .$$

Substituting into (23) we have

$$P = F_I^C \left[\frac{K_R + 2K_I}{2K_I}\right] \, .$$

Using the values obtained in Appendix D, we obtain

$$\begin{aligned} P &= 4586 \; lb \left[\frac{1.064 + 2(.182)}{2(.182)}\right] \\ P &= 17990 \; lb \, . \end{aligned} \tag{28}$$

This corresponds to the magnetic load on a single post assembly when all preloading is relieved. Since there are eight axial post assemblies per coil, the magnitude of the total magnetic load existing when all axial preloading is relieved is

$$P_T = 8P = 143,900 \; lb \, .$$

Note that in this analysis, the use of $K_R = 1.064E6\ lb/in$ is a tacit assumption that the preloading is relieved before any randolite/aluminum post load exceeds 5E4 lb (see Appendix D).

Substituting (28) into (27), we obtain the amount of strain that corresponds to the point where all preloading is relieved. Hence

$$\begin{aligned} \mu\epsilon &= \frac{17990\ lb}{25.03\ lb/\mu\epsilon} \\ \mu\epsilon &= 719\ . \end{aligned}$$

For loads greater than 17990 lb, our model for the post assembly is just a simple spring. At this point, the change in the strain seen by the gauges reflects the entire change in P, the magnetic load. Hence, our expression for P becomes

$$\begin{aligned} P &= \left[\overline{E}A(\mu\epsilon - 719) + 17990\right] lb \\ P &= [18.65(\mu\epsilon) + 17990]\, lb \qquad P > 17990\ lb \qquad (29) \\ & \qquad\qquad\qquad\qquad\qquad\quad \mu\epsilon = 719\ . \end{aligned}$$

We shall now use Equations (27) and (29) to reevaluate the strain gauge data from the 1985 Run. The data used was recorded on 4/27/85 by Craddock and the author (Kelley). The results are presented in Tables 3, 4, and 5. These results are respectively for the two strain gauge pairs attached to axial supports on the West Coil and the single pair attached to a support on the East Coil. Recall that the value for $\mu\epsilon$ used in Equations (27) and (29), for a single post assembly, is the average of the readings obtained from the two gauges mounted on a post. The results for the three posts are also presented graphically in Figure 10. Note that, although the strain gauge values are negative, which implies compression, and hence the sign of the magnetic loads are negative, the author has chosen to graph the data with a positive sign. The reason for this is for ease of comparison with Craddock's TRIM results, which are plotted with a positive sign in [3], as are the results of Craddock's data reduction.

Comparing the readings for the three assemblies with one another, we see that the results from the two supports on the West Coil agree quite well with one another,

Current Amps	Reading #1 $\mu\epsilon$	Reading #2 $\mu\epsilon$	Average $\mu\epsilon$	P Kilopounds
100	-25	6	-9.5	-.237
200	-352	-210	-281	-7.02
300	-709	-583	-646	-16.1
300	-788	-672	-730	-18.2
404	-960	-818	-889	-21.2
498	-1070	-908	-989	-23.0
598	-1098	-895	-997	-23.2
700	-1022	-792	-907	-21.5

Table 3: Data and reduction results for the magnetic load on an axial support assembly on the West Coil - 1985 Run. Reading #1 is the data obtained from the strain gauge with wire numbers 1, 2, 3. Reading #2 is the data obtained from the strain gauge with wire numbers 4, 5, 6.

Current Amps	Reading #1 $\mu\epsilon$	Reading #2 $\mu\epsilon$	Average $\mu\epsilon$	P Kilopounds
100	-16	-94	-55	-1.37
200	-294	-408	-351	-8.77
300	-564	-762	-663	-16.6
300	-585	-772	-679	-17.0
404	-800	-980	-890	-21.2
498	-890	-1070	-980	-22.9
598	-900	-1068	-984	-22.9
700	-830	-972	-901	-21.4

Table 4: Data and reduction results for the magnetic load on an axial support assembly on the West Coil - 1985 Run. Reading #1 is the data obtained from the strain gauge with wire numbers 7, 8, 9. Reading #2 is the data obtained from the strain gauge with wire numbers 10, 11, 12.

Current Amps	Reading #1 $\mu\epsilon$	Reading #2 $\mu\epsilon$	Average $\mu\epsilon$	P Kilopounds
50	-16	-23	-19.5	-.487
100	-84	-104	-94	-2.35
200	-342	-430	-386	-9.65
300	-660	-850	-755	-18.7
300	-634	-852	-743	-18.4
404	-879	-1175	-1027	-23.7
498	-988	-1290	-1139	-25.8
598	-1000	-1286	-1143	-25.9
700	-920	-1170	-1045	-24.1

Table 5: Data and reduction results for the magnetic load on an axial support assembly on the East Coil - 1985 Run. Reading #1 is the data obtained from the strain gauge with wire numbers 1, 2, 6. Reading #2 is the data obtained from the strain gauge with wire numbers 3, 4, 5.

Figure 10: Tohoku Bubble Chamber Magnet forces on axial supports obtained from strain gauge readings taken during the 1985 Commissioning Run.

Current Amps	P East Coil Kilopounds	P West Coil Kilopounds	P West Coil Kilopounds	$\overline{P}$ Kilopounds	P_T Kilopounds
100	-2.35	-.237	-1.37	-1.32	-10.6
200	-9.65	-7.02	-8.77	-8.48	-67.8
300	-18.7	-16.1	-16.6	-17.1	-137
300	-18.4	-18.2	-17.0	-17.9	-143
404	-23.7	-21.2	-21.2	-22.0	-176
498	-25.8	-23.0	-22.9	-23.9	-191
598	-25.9	-23.2	-22.9	-24.0	-192
700	-24.1	-21.5	-21.4	-22.3	-179

Table 6: Total axial magnetic loads for the 1985 Run, based on an average of the individual axial post readings.

whereas the results from the assembly on the East Coil is significantly higher than the other two readings. Craddock notes this fact, but does not comment on it. We shall see that this behavior was also observed during the 1986 Run, suggesting that it was not the result of initial seating. It is conceivable that other posts exhibit similar behavior, but this can't be verified. Searching for an anomaly that would explain it for a single post assembly is, quite frankly, beyond the author's time limitations.

We now wish to compare the results from the three individual assemblies with the TRIM results for the total axial magnetic load. We use Craddock's assumption [3] that these three post assemblies are representative of all assemblies in a coil. We therefore average the loads on the three assemblies to obtain the average load, $\overline{P}$, on an assembly. This average load versus current is presented in Table 6. Since there are eight axial assemblies per coil, what we shall refer to as the total axial load per coil, P_T, is eight times the average load on an assembly. The results of this calculation are also presented in Table 6 and in Figure 11. Figure 11 additionally

Figure 11: Tohoku Bubble Chamber Magnet total axial magnetic loads for the 1985 Run, based on an average of the individual axial post readings obtained from an analysis of the strain gauge data.

presents the results of Craddock's TRIM run 47 [3,8] for the magnet where the muon notch is totally filled, the configuration of the iron during the 1985 Run. We see that the strain gauge results are 14% less than the values predicted by TRIM.

It should be pointed out that the results presented here do not agree with the results Craddock presented [3]. There are two reasons for this fact. The first reason is that Craddock used the room temperature value for the modulus of randolite to determine his equations for axial load. We used an average modulus obtained from the room temperature and liquid nitrogen values of the modulus. We felt that this average value better reflected the true value of the modulus at the point of strain gauge measurement; the midpoint between the room temperature mounting and the liquid nitrogen intercept.

The second reason for a discrepancy between Craddock's reported results and ours is that Craddock made an error in the derivation of his equations. Craddock substituted the $\mu\epsilon$ of compression experienced by the randolite segment of a post with the $\mu\epsilon$ of compression seen by the entire post. Craddock writes that the force on one randolite/aluminum post is

$$F = \epsilon E A = 17.9 \mu\epsilon \ ,$$

where the room temperature value for the modulus of randolite is used. Ignoring temperature effects, this is a correct statement. The strain gauge pair sees only the $\mu\epsilon$ of compression in the randolite, but since we "know" the modulus of randolite, the force in the randolite segment of the post is known. Since this segment is in series with the other segments of the post, we therefore know the force on the post. However, the $\mu\epsilon$ seen by the strain gauge is not the $\mu\epsilon$ of the entire post. Recall that $\mu\epsilon$ may be written

$$\mu\epsilon = \frac{\Delta x}{L} \ .$$

For the randolite segment, Δx is the change in length of the randolite and L is the length of the randolite. For the post, Δx is the change in length of the post, and L is the length of the post. Hence ϵ for the randolite segment is not the same as ϵ for the entire post. However, since the post is in parallel with the inconel rods, and since the post and rods are essentially the same length, ϵ for the entire post is the same as ϵ for the inconel rods. In his expression for total force, Craddock incorrectly equated the ϵ of the randolite segment with that of the inconel rods. Hence, where Craddock meant to sum the forces on the randolite post assemblies and the inconel rods, he really summed the force on the randolite post assemblies with an underestimated value for the force on the inconel rods.

We now wish to evaluate the strain gauge data from the 1986 Run. Recall that, for the 1986 Run, we only have two functioning strain gauge pairs; one on the East Coil and one on the West Coil. Applying equations (27) and (29), we obtain the results presented in Tables 7 and 8 for the individual posts. These results are also presented graphically in Figure 12. We should immediately notice that again the force seen by the axial post assembly on the East Coil is significantly higher than that seen by the assembly on the West Coil. This would appear to indicate that the large force variation, since it has been observed twice, truly exists and is not the consequence of the initial seating of the coil. It should be noted that, although one of the strain gauges on the third instrumented axial post (located on the West Coil) was defective, the second gauge on the post produced readings that were similar to a gauge on the second instrumented post on the West Coil. This behavior also occurred during the 1985 Run.

Assuming, as before, that the behavior of the two instrumented assemblies is representative of all of the assemblies in a coil, we average the loads and multiply by eight to obtain the total magnetic load on a coil. The results of this calculation are presented in Table 9 and graphically in Figure 13. It should be noted that, since we only have two "measured" loads to use in this calculation instead of the three we had for the 1985 data, the curve is weighted differently. For the 1985 data, we had two similar loads and one significantly higher than these two. For the 1986 data, we had one high and one low reading. Hence, the 1985 curve given in Figure 11 is weighted towards a lower value than the curve for the 1986 data. We can estimate the effect of this additional weight on the 1986 data in the following manner. Note that the "low" values for loads for the 1985 Run have almost the same values. Note also that the working gauges on the West Coil for the 1986 Run almost agree with one another. Therefore, we assume that both assemblies on the West Coil would essentially see the same load. For the data at 750 amp, this would imply a total

Current Amps	Reading #1 $\mu\epsilon$	Reading #2 $\mu\epsilon$	Average $\mu\epsilon$	P Kilopounds
100	60	8	64	1.60
150	78	8	82	2.50
200	61	1	31	.775
250	20	-1	9.5	.237
300	-111	-81	-96	-2.40
350	-220	-170	-195	-4.87
400	-341	-274	-308	-7.70
450	-453	-368	-411	-10.3
500	-568	-447	-508	-12.7
550	-675	-506	-591	-14.8
600	-777	-574	-676	-16.9
650	-903	-641	-772	-19.0
700	-962	-684	-823	-19.9
725	-956	-728	-842	-20.3
750	-1121	-787	-954	-22.4

Table 7: Data and reduction results for the magnetic load on an axial post assembly on the West Coil - 1986 Run. Reading #1 is the data obtained from the strain gauge with wire numbers 1, 2, 3. Reading #2 is the data obtained from the strain gauge with wire numbers 4, 5, 6.

Current Amps	Reading #1 $\mu\epsilon$	Reading #2 $\mu\epsilon$	Average $\mu\epsilon$	P Kilopounds
50	34	-22	6	.150
100	24	-56	-16	-.400
150	-40	-97	-68.5	-1.71
200	-101	-186	-143.5	-3.59
250	-170	-293	-231.5	-5.79
300	-265	-431	-348	-8.70
350	-363	-569	-466	-11.6
400	-478	-719	-599	-15.0
450	-604	-890	-722	-18.0
500	-759	-971	-865	-20.7
550	-894	-1091	-993	-23.1
600	-1031	-1194	-1113	-25.3
650	-1186	-1308	-1247	-27.8
700	-1321	-1411	-1366	-30.1
725	-1381	-1448	-1415	-31.0
750	-1452	-1509	-1481	-32.2

Table 8: Data and reduction results for the magnetic load on an axial post assembly on the East Coil - 1986 Run. Reading #1 is the data obtained from the strain gauge with wire numbers 1,2,6. Reading #2 is the data obtained from the strain gauge with wire numbers 3,4,5.

Figure 12: Tohoku Bubble Chamber Magnet forces on axial supports obtained from strain gauge readings taken during the 1986 recommissioning run.

Current Amps	P East Coil Kilopounds	P West Coil Kilopounds	P_{avg} Kilopounds	P_T
100	-.400	1.60	.6	4.80
150	-1.71	2.50	.395	3.16
200	-3.59	.775	-1.41	-11.3
250	-5.79	.237	-2.78	-22.2
300	-8.10	-2.40	-5.55	-44.4
350	-11.6	-4.87	-8.24	-65.9
400	-15.0	-7.70	-11.4	-90.8
450	-18.0	-10.3	-14.2	-113
500	-20.7	-12.7	-16.7	-134
550	-23.1	-14.8	-19.0	-152
600	-25.3	-16.9	-21.1	-169
650	-27.8	-19.0	-23.4	-187
700	-30.1	-19.9	-25.0	-200
725	-31.0	-20.3	-25.7	-205
750	-32.2	-22.4	-27.3	-218

Table 9: Total axial magnetic loads for the 1986 Run, based on an average of the individual axial post readings.

Figure 13: Tohoku Bubble Chamber Magnet total axial magnetic loads for 1985 and 1986 Runs, based on an average of the individual axial post readings obtained from an analysis of the strain gauge data.

magnetic load of

$$P_T = 8\left[\frac{-32.2 - 2(22.4)}{3}\right] kilopounds$$
$$P_T = -205\ kilopounds\ .$$

This value is 6% less than the value given in Table 9 and in Figure 13.

Figure 13 also presents the results from TRIM Run 47, which was previously discussed, and the results of the 1985 Run. We see that the values for the total axial magnetic load for the 1986 Run are only slightly higher than those for the 1985 Run. However, the 1986 results are nowhere near as high as the value predicted prior to the run, 480 kilopounds. Indeed the behavior demonstrated by both the strain gauges and the dial indicators agree reasonably well with one another lending a small degree of confidence to our results. Conversations with Sanders [9] indicated a relative error of ±20% on the predicated magnetic loads. This corresponds to a minimum axial load of 384 kilopounds. Frankly, the author can't account for the difference between the measured and predicated loads. The following observation can be made about the behavior of the coil that cannot be quantified, but the author doubts that its effect on ??? could account for the discrepancy.

The axial supports, since they are free to rotate, should, in theory, not be influenced by loads in the radial plane, *i.e.*, the plane perpendicular to the coil's axis. Craddock [3], claims that the axial supports may tip up to .22 in from the perpendicular (from FNAL Dwgs. #2771-MD-56365 and 2771-MD-56417, this restriction is not apparent, and hence is not verifiable by the author). If the axial ball and socket joints are frictionless, and all axial posts initially are not tilted, the loads in the radial plane would not influence the recorded axial data until the coil was displaced .22 in. in any direction in the plane. However, the joints are not frictionless, and the posts are initially tilted at a variety of angles. After a full tilted position of .22 in. is reached, the axial posts may act as cantilevers and oppose the forces in the radial plane. That the axial posts could act as cantilevers is seen from the following two points. The first is that the inconel rods should keep the ball and socket joints together, keeping them from "dislocating." This point should be verified, but is not verified here, due to insufficient time. Second, since the thermal contraction of aluminum is greater than that for randolite, the aluminum couplings will mechanically clamp the randolite pieces in place, allowing a degree of bending. Considering the strain gauge data, since the readings from one gauge on a post is almost always greater than the readings from the second gauge, in some cases significantly so, it is apparent that bending is occurring. Since bending implies that the post is tilted, the compressive load on the post is reduced by the forces in the radial plane. Hence, the values presented above for the axial loads may be less than what actually exist on the coil. The author feels that, since the angle of inclination is small, approximately 1° for the .22 in. of tilt claimed by Craddock, this behavior could account for the difference between predicted and measured loads for the 1985 Run, but doesn't explain the 1986 discrepancy.

It should be pointed out that neither the author or Craddock [3] addressed the question of error. The author, quite frankly, does not have the time to address this very serious point. However, considering the number of criticisms leveled in Appendix D concerning the research and development done for the project, in addition to the assumptions made in obtaining the cooldown preload values, the error in the results reported here could be very significant. Without embarking on another episode of R&D and performing some rather difficult heat transfer calculations, it is difficult to assign a relative error to the results. The author, however, would not be surprised if the error was as great as $\pm 30\%$ or even larger. An error this large, however, still does not adequately explain the discrepancy between predicted and measured values.

Before moving on, we need to comment on the fact that the strain gauges do not return to zero when the current in the coils is discharged. Craddock [3] implied that it was preferable to have the readings return to zero under this circumstance. The author, however, feels that there is no reason to expect the strain gauge readings to return to zero when the magnet discharges. All of the support systems have a freedom of movement, and since the forces experienced by the coil during current discharge are different from what the coil experiences when it charges, the supports, in all likelihood, will not return to their initial positions. The author does not lightly dismiss some of the large differences seen between the starting and ending values of the strain gauge readings. The Strainserts used for the measurements were out of calibration and misused [19], two conditions that Fermilab's schedule did not permit us to rectify, and hence a portion of the deviation could be attributed to this fact. Indeed, the results presented here should be verified with reliable equipment as soon as possible. However, the assumption that a zeroed strain gauge should return to zero is incorrect. It would be interesting to determine if the supports exhibit a hysteresis over a number of charging and discharging cycles. If time permits, this should be investigated.

Vertical and Horizontal Loads on a Coil

In this section, we shall consider the information obtained from the vertical and horizontal support systems on the coils. Craddock [3] treats each system separately referring to a horizontal "force" and a vertical "force." Actually, these two "forces," being in the radial plane, are the components of a third force. Attempting to understand the behavior exhibited by either support system without considering the other is a futile exercise. Indeed, because Craddock did not record all of the data available to him for the horizontal supports, he could not understand the overall behavior of the coils in the radial plane.

In completing our analysis of the loads in the radial plane, we shall look first at the vertical supports and then at the horizontal supports. Finally, we shall obtain an overview of the radial forces based on the behavior of the two support systems.

For the vertical supports, the calibration data for each strain gauge bolt, as reported by Strainsert, is given in the appendix of reference [3]. For convenience, it is reproduced here. As previously mentioned, we do not know the location of

Serial #	Load Pounds	$\mu\epsilon$	Slope lb/$\mu\epsilon$
1	75K	6278	11.94
2	75K	5828	12.87
3	75K	6026	12.45
4	75K	5836	12.85

Table 10: Calibration data for the strain gauges mounted in the bolts at the top of the vertical supports.

each of the bolts. We therefore will use the average of the $\mu\epsilon$ calibration readings to obtain an "average" slope. Hence

$$M = \frac{75000lb}{6000\mu\epsilon}$$

$$M = 12.5\ lb/\mu\epsilon\ . \tag{30}$$

Note that the behavior of the strain gauge bolts over the region of interest is linear.

Since the strain gauges are used in a full bridge configuration (two active gauges) [3], the raw data for the vertical supports must be divided by two [18]. The value obtained is multiplied by (30) to obtain the load in pounds. Figures 14 and 15 present the results of this calculation *vs.* current for the East and West Coils, respectively, for both the 1985 and 1986 Runs. Negative values correspond to compressive or upward forces, while positive values correspond to tension or downward forces. We see that, during the 1985 Run, the net vertical forces on both coils were upwards at high currents. Additionally, for both coils, the downstream (north) support column saw greater net loads than the upstream (south) column. Since their vertical arms are free to pivot, this might imply that the East Coil, Figure 14, was trying to rotate clockwise (looking at the coil from west to east) as it tried to move upward. At low currents, the net vertical forces are down. The West Coil, Figure 15, exhibits similar behavior, but the magnitude of the forces for this coil are greater than those for the East Coil.

Consider now the results for the 1986 Run. The most obvious point to observe is that, for both coils, the vertical force has reversed direction. The author can't offer an explanation for this fact due to insufficient time. Similar to the 1985 results, the magnitude of the forces on the downstream (north) support column at high currents are greater than those on the upstream (south) column for both coils. However, the direction of rotation for the East Coil would be counterclockwise when viewed from the position described above. At low currents, the upstream column of the East Coil sees a greater load than the downstream column, and hence this coil appears to initially be rotating in the clockwise direction and then reverses its direction of rotation as the current is increased. We shall discuss the implications of this after obtaining the basic results for the horizontal supports.

The cryostats for the coils of the magnet are supported horizontally by pairs of horizontal posts. These posts are of a design similar to the axial randolite/aluminum posts. The designs differ in length and in diameter. There are four horizontal posts per coil. These posts are mounted in pairs, one pair at the top of the cryostat and

Figure 14: Coil A (East Coil) vertical support loads.

Figure 15: Coil B (West Coil) vertical support loads.

one pair at the bottom of the cryostat. The two posts in a pair are mounted in series with one another with the opposite ends of the pair mounted to the vacuum vessel. The cryostat is connected to the posts at the junction of the posts. See the print, in Appendix C, with the incomplete drawing number entitled "Horizontal Compression Post Layout."

The horizontal posts were preloaded during assembly (see Appendix I). When charging the magnet, the horizontal magnetic forces results in one post of a pair being compressed beyond the preload value, while the preload on the second post is relieved. The posts cannot tolerate tension, and hence the loads on the posts were monitored. The instrumentation used to monitor the loads on the horizontal posts has previously been described. As in the case of the axial support assemblies, strain gauge pairs were mounted on a randolite post midway between the room temperature and LN_2 intercept. The equation used to obtain the force from the average value of the strain gauge readings is

$$F_H = \epsilon \overline{E} A = 18.65 \mu\epsilon \; lb \; . \tag{31}$$

Here $\overline{E}$ is an average value for the modulus of randolite obtained from the room temperature and LN_2 temperature values of the modulus. We obtained this value in the previous section. Since the strain gauges are zeroed prior to energizing the coils, Equation (31) is the magnetic load seen by the post. The total load on a horizontal post is found by subtracting the preload existing after cooldown from Equation (31) (Appendix I). We subtract the preload because it is compressive in nature and the strain gauges indicate a compressive event with a negative value. Hence, the total load on a horizontal post is

$$\begin{aligned} F_H^T &= \epsilon \overline{E} A - 17100 \; lb \\ F_H^T &= [18.65 \mu\epsilon - 17100] lb \; . \end{aligned} \tag{32}$$

The results obtained from applying Equations (31) and (32) to the strain gauge data from the 1986 Run are presented in Tables 11 and 12 and Figures 16 and 17.

Current Amps	Avg $\mu\epsilon$	F_H Kilopounds	F_H^T Kilopounds	Avg $\mu\epsilon$	F_H Kilopounds	F_H^T Kilopounds
0	0	0	0	0	0	0
100	71.5	1.333	-15.76	25	.466	-16.63
150	67	1.250	-15.85	18.5	.345	-16.75
200	59	1.100	-16.00	10.5	.196	-16.90
250	61	1.138	-15.96	2	.037	-17.06
300	51.5	.960	-16.14	-6.5	-.121	-17.22
350	50	.933	-16.17	-10.5	-.196	-17.30
400	45.5	.849	-16.25	-16	-.298	-17.40
450	42	.783	-16.32	-19.5	-.364	-17.46
500	48.5	.905	-16.20	-39	-.727	-17.83
550	72	1.343	-15.76	-46	-.858	-17.96
600	101	1.884	-15.22	-34	-.634	-17.73
650	104	1.940	-15.16	-58	-1.082	-18.18
700	115	2.145	-14.96	-60.5	-1.128	-18.23
725	119	2.219	-14.88	-62.5	-1.166	-18.27
750	135	2.518	-14.58	-63	-1.175	-18.27

Right Side of Figure 7
Wire Numbers 7,8,9 and 10,11,12

Left Side of Figure 7
Wire Numbers 25, 26, 27 and 22, 23, 24

Table 11: Magnetic Loads (F_H) and total loads (F_H^T) on the instrumented horizontal posts on the East Coil for the 1986 Run.

Current Amps	Avg $\mu\epsilon$	F_H Kilopounds	F_H^T Kilopounds
0	0	0	0
100	73	1.361	-15.74
150	83	1.548	-15.55
200	91	1.697	-15.40
250	103	1.921	-15.18
300	108	2.014	-15.09
350	121.5	2.266	-14.83
400	124.5	2.322	-14.78
450	132.5	2.471	-14.63
500	147.5	2.751	-14.35
550	177.5	3.310	-13.79
600	198	3.693	-13.41
650	205	3.823	-13.28
700	221.5	4.131	-12.97
725	228	4.252	-12.85
750	236	4.401	-12.70

Table 12: Magnetic loads (F_H) and total loads (F_H^T) on a horizontal post on the West Coil for the 1986 Run. Readings were obtained from strain gauges with wire numbers 23, 24, 25 and 19, 20, 22.

Figure 16: Tohoku Bubble Chamber Magnet forces on the horizontal posts of the East Coil.

Figure 17: Tohoku Bubble Chamber Magnet forces on a horizontal post on the West Coil.

Studying Tables 11 and 12, we may note that the total loads, F_H^T, never approach the design load of 37,500 lb for any post monitored. We also note that, for the numbers experiencing a decrease in compression, the unloaded state is never approached.

Consider the behavior of the horizontal posts during the charging of the coil. Figure 16 presents the magnetic loads on the upper pair of posts on the East Coil. Initially, one might expect that, as the current was increased, the compression on one post of the pair would increase while the compression decreases on the second post. However, this behavior was not observed. Both posts initially have compression relieved, then each experiences compression and finally, at 450 amps, we see the expected behavior. This behavior is due to two factors. The first is that the horizontal posts are not fixed and are free to rotate. Hence, vertical forces will affect the behavior of the horizontal posts and vice versa. The second factor is the method of mounting the vertical support arms to the vacuum vessel and the cryostat. The vertical arms are pinned to both vessels, allowing a coil to swing in the vertical, or what we call radial, plane. A geometric study conducted with FNAL Dwg# (Appendix C) and a compass will clearly show that, for any small displacement resulting from a horizontal component of the magnetic load, the center point of the upper horizontal post pair will move upwards, in addition to moving in the direction of the load. Additionally, the magnitude of the horizontal displacement will be much larger than the vertical displacement. Since the center point of the lower horizontal post pair is on a larger radius than its counterpart, the lower point's displacements, both vertical and horizontal, are greater than the upper point. Hence the compressive loads, applied to one lower post and relieved from the second lower post, are greater in magnitude than those on the upper post pair. This is an area of concern, since it is the upper post pair that is instrumented. We have no method of emperically verifying the loads on the lower post.

The imbalance in the loads between the upper and lower horizontal post pairs causes a load to be applied to the vertical arms. The load is compressive on one arm and tensile in nature on the second arm. This causes the apparent rotation we referred to when examining the loads on the vertical supports. From the symmetry of the problem, we see that the component of the load from the horizontal imbalance

Studying Tables 11 and 12, we may note that the total loads, F_H^T, never approach the design load of 37,500 lb for any post monitored. We also note that, for the numbers experiencing a decrease in compression, the unloaded state is never approached.

Consider the behavior of the horizontal posts during the charging of the coil. Figure 16 presents the magnetic loads on the upper pair of posts on the East Coil. Initially, one might expect that, as the current was increased, the compression on one post of the pair would increase while the compression decreases on the second post. However, this behavior was not observed. Both posts initially have compression relieved, then each experiences compression and finally, at 450 amps, we see the expected behavior. This behavior is due to two factors. The first is that the horizontal posts are not fixed and are free to rotate. Hence, vertical forces will affect the behavior of the horizontal posts and vice versa. The second factor is the method of mounting the vertical support arms to the vacuum vessel and the cryostat. The vertical arms are pinned to both vessels, allowing a coil to swing in the vertical, or what we call radial, plane. A geometric study conducted with FNAL Dwg# (Appendix C) and a compass will clearly show that, for any small displacement resulting from a horizontal component of the magnetic load, the center point of the upper horizontal post pair will move upwards, in addition to moving in the direction of the load. Additionally, the magnitude of the horizontal displacement will be much larger than the vertical displacement. Since the center point of the lower horizontal post pair is on a larger radius than its counterpart, the lower point's displacements, both vertical and horizontal, are greater than the upper point. Hence the compressive loads, applied to one lower post and relieved from the second lower post, are greater in magnitude than those on the upper post pair. This is an area of concern, since it is the upper post pair that is instrumented. We have no method of emperically verifying the loads on the lower post.

The imbalance in the loads between the upper and lower horizontal post pairs causes a load to be applied to the vertical arms. The load is compressive on one arm and tensile in nature on the second arm. This causes the apparent rotation we referred to when examining the loads on the vertical supports. From the symmetry of the problem, we see that the component of the load from the horizontal imbalance on one vertical arm is approximately equal in magnitude and opposite in direction to the component on the second vertical arm. Implementing this observation, we may obtain an estimate of the vertical component of the magnetic load by averaging the loads seen by the two vertical arms and multiplying by two. The results of this procedure are presented in Tables 13, 14, 15 and 16 and Figures 18 and 19 for both the 1985 and 1986 Runs. Note that this is just an estimate of the vertical magnetic loads. Due to the effects of the axial supports described earlier, the fact that the strain gauges on the vertical arms only detect strains resulting from compression or tension, the fact that the vertical supports are not vertical and their precise position is unknown, the vertical magnetic loads cannot be obtained precisely. Indeed, since the vertical supports are not vertical, a portion of the tension or compression seen by the strain gauges could also be caused by the horizontal component of the load in the radial plane.

Before looking at specific details of the coils behavior in the radial plane, we should comment that the maximum compressive or tensile loads on any vertical arm during both the 1985 and 1986 Run was just over 3,000 lb. This is far less than the design load of 75,000 lb per arm [3]. Hence, there is no danger of the arms failing during operations.

We now wish to look at the specific details of the coil behavior in the radial plane as the magnet is charged. Due to lack of information for the 1985 Run, we shall concentrate on the 1986 Run. However, it should be noted that, for the single horizontal post from which a complete set of data was obtained for both runs, the behavior is similar (Table 17 and Figure 20). Additionally, for the 1986 Run, we only have data from one of the two upper horizontal posts on the West Coil (Table 12 and Figure 17). It appears that the behavior for the upper post pair on the West Coil is different than that for the East Coil. The single post on the West Coil appears to be decompressing over the entire range of current values. This behavior is as anticipated. The behavior of the vertical posts on the West Coil (Figure 15) is also as anticipated, with the downstream support seeing higher loads than the upstream support. These two facts imply that the instrumented horizontal post on the West Coil with the strain gauges with wires 23, 24, 25 and 19, 20, 22 is the upstream (south) horizontal post.

Current Amps	Upstream Support Pounds	Downstream Support Pounds	Average Pounds	Total Vertical Load Pounds
0	0	0	0	0
50	125	138	132	264
100	188	163	176	352
150	281	244	263	526
200	380	344	366	732
250	525	456	491	982
300	656	663	660	1320
350	781	769	775	1550
400	913	950	932	1864
450	1040	1140	1090	2180
500	1170	1340	1255	2150
550	1290	1590	1440	2880
600	1430	1830	1630	3260
650	1540	2060	1800	3600
700	1640	2320	1980	3960
725	1700	2430	2065	4130
750	1770	2550	2160	4320

Table 13: Estimate of the vertical magnetic loads on the East Coil—1986 Run.

Current Amps	Upstream Support Pounds	Downstream Support Pounds	Average Pounds	Total Vertical Load Pounds
0	0	0	0	0
50	37.5	0	19	38
100	25	37.5	31	62
200	12.5	62.5	38	76
300	0	-156.3	-78	-156
300	37.5	-56.3	-9	-18
400	0	-375	-188	-376
500	0	-750	-375	-750
600	-37.5	-1500	-769	-1538
700	-68.8	-2970	-1520	-3040

Table 14: Estimate of the vertical magnetic loads on the East Coil—1985 Run.

Current Amps	Upstream Support Pounds	Downstream Support Pounds	Average Pounds	Total Vertical Load Pounds
0	0	0	0	0
50	131	150	141	282
100	144	200	172	344
150	163	350	257	514
200	194	394	294	588
250	225	488	357	714
300	281	625	453	906
350	350	813	582	1164
400	431	1038	735	1470
450	563	1306	935	1870
500	669	1640	1155	2310
550	819	1940	1380	2760
600	994	2280	1637	3274
650	1156	2620	1888	3776
700	1331	2890	2110	4220
725	1425	3060	2243	4486
750	1538	3220	2379	4758

Table 15: Estimate of the vertical magnetic loads on the West Coil—1986 Run.

Current Amps	Upstream Support Pounds	Downstream Support Pounds	Average Pounds	Total Vertical Load Pounds
0	0	0	0	0
50	25	0	13	26
100	25	-138	-57	-114
200	0	-425	-213	-426
300	0	-719	-360	-720
300	0	-712	-356	-712
400	-69	-969	-519	-1038
500	-163	-1310	-737	-1474
600	-338	-1860	-1100	-2200
700	-813	-2970	-1892	-3784

Table 16: Estimate of the vertical magnetic loads on the West Coil—1985 Run.

Figure 18: East Coil — estimate of the vertical magnetic loads.

Figure 19: West Coil—estimate of the vertical magnetic loads.

Current	Avg. $\mu\epsilon$	F_H	F_H^T
0	0	0	0
50	3	.056	-17.04
100	-6	-.112	-17.21
200	-30	-.560	-17.66
300	-57	-1.063	-18.16
300	-76	-1.417	-18.52
400	-97	-1.809	-18.91
500	-112.5	-2.098	-19.20
600	-117	-2.182	-19.28
700	-112.5	-2.098	-19.20

Table 17: Magnetic loads (F_H) and total loads (F_H^T) on a horizontal post on the East Coil for the 1985 Run. Readings were obtained from strain gauges with wire numbers 25, 26, 27 and 22, 23, 24.

Figure 20: Tohoku Bubble Chamber Magnet forces on a horizontal post on the East Coil for both the 1985 and 1986 Runs.

The East Coil's behavior is not as anticipated. The results for the horizontal posts indicate that both posts initially experience decompression, then both are compressed at an equal "rate" and then both take on the anticipated behavior (Figure 16). The behavior between 0 and 100 amps, where both posts decompress, one slightly more than the other, implies that the centerpoint of the post pair displaces both vertically and horizontally. The vertical displacement must be much greater than the horizontal displacement. If this wasn't true, and the vertical displacement was less than the horizontal displacement, then one post would never be decompressed. As discussed previously, a horizontal displacement of the coil results in a small vertical displacement for a large horizontal displacement. Hence, what is observed is not directly correlated to what is expected. Since the vertical supports are very stiff, and their instruments indicate small loads, vertical loading can't explain the phenomena. The author suggests that there could be some play in the support systems which allow a vertical shift in the coil when loads are initially applied. However, if this were true, then once the "slop" was removed, we should observe the anticipated behavior. This we do not observe. Both posts see a compressive phase. Again, this can only be explained by the vertical displacements being greater than the horizontal displacements. The author can again offer no satisfactory, verifiable, explanation for the behavior except the possibility of too much play in the magnet supports.

Over the span of currents under discussion, 0 to 450 amps, the vertical support loads observed indicate that the horizontal component of the load in the radial plane has shifted directions (Figure 14). This is conceivable if iron on one side of the coil saturates prior to the iron on the other side. The author can't verify the validity of this theory, though he feels that the fields at these currents are not high enough to cause iron saturation. This behavior could also be the result of excessive play. If the coil "fell" and "landed" slightly cocked from the vertical, and then a horizontal displacement, due to the magnetic loads, occurred in the direction opposite the cocked position, this would explain the behavior.

Since after 450 amps we observed the expected behavior for the East Coil horizontal posts, we can determine which strain gauges are associated with a post. Since the horizontal post, under the higher compression at 750 amps, must be on the same side as the vertical arm with the higher value of tension, Figures 14 and 16 reveal that the strain gauges with wire numbers 25, 26, 27 and 22, 23, 24 are associated with the downstream (North) support. Hence, wires 7, 8, 9 and 10, 11, 12 are associated with the upstream (South) support.

It is obvious that a great deal of study still needs to be performed before the behavior of the East Coil is understood. It is interesting and necessary to calculate the load excess on the lower horizontal posts. Simple methods, such as summing the moments, are inadequate due to the lack of information concerning the direction of forces and position of supports. A model of the system should be developed to investigate the loads and behavior.

References

[1] Memorandum of Understanding—E745—Muon Neutrino Experiment Using the Tohoku High Resolution One Meter Bubble Chamber.

[2] Sanders, Robert C., "Magnetostatic Calculations for 1986-7 Tohoku Bubble Chamber Magnet," Report to the Tohoku Bubble Chamber Magnet's Safety Committee, FNAL, November 19, 1986.

[3] Craddock, W., "Measured Magnetic Forces on the Tohoku Bubble Chamber Magnet," Report to the Tohoku Bubble Chamber Magnet's Safety Committee, FNAL, October 10, 1985.

[4] Mruzek, M.T., "Randolite Compression Test, Internal Publication, RD/RS/Cryo, FNAL, July 16, 1980.

[5] Craddock, W., "Tohoku (30-Inch) Bubble Chamber Magnet Vacuum Shell Analysis," Report to the Tohoku Bubble Chamber Magnet's Safety Committee, FNAL, November 27, 1984.

[6] Craddock, W., "Tohoku Bubble Chamber Magnet Cryostat," Personal Notes, April 5, 1985.

[7] Wands, R., "3-Dimensional Finite Element Analysis of 30-Inch BCM Cryostat," Memo to Ron Fast, Fermilab, RD/Cryogenic Department, September 9, 1986.

[8] Craddock, W., "Tohoku Bubble Chamber Magnetic Field Calculations," Report to the Tohoku Bubble Chamber Magnet's Safety Committee, FNAL, January 21, 1985.

[9] Sanders, Robert C., Private Conversation.

[10] Smith, E., Private Conversation.

[11] Rogers, Clarence, and Gordon, Steven, Private Conversation.

[12] FNAL Photograph, Negative #83-216-18, March 16, 1983.

[13] Mruzek, M., "Experimental Investigation of Thermal Contraction for Fiber-Reinforced Epoxy Resins, Common Plastics, and Other Materials," Fermilab TM-974, FNAL, June 1980.

[14] Mruzek, M.T., "Summary of Selection Process for Compression Member Supports," Private Notes, March 14, 1980.

[15] "Cryogenic Materials Data Handbook," Technical Documentary Report, AFML-TDR-64-280, Air Force Materials Laboratory, Air Force Systems Command, Wright Patterson AFB, Ohio, Revised 1970.

[16] Jensen, J.E., Stewart, R.B., Tuttle, W.A., "BNL Bubble Chamber Group Selected Cryogenic Data Notebook," Brookhaven National Laboratory.

[17] "Handbook on Materials for Superconducting Machinery," MCIC-HB-04, Metals and Ceramics Information Center, Battelle, Columbus Laboratories, Columbus, Ohio, January, 1977.

[18] Mruzek, M.T., Personal Notes.

[19] Dachniwskyj, R.I., private conversation.

[20] Shigley, Joseph Edward, and Mitchell, Larry D., "Mechanical Engineering Design," 4th Ed., McGraw Hill Book Co., New York, 1983.

A Summary of Equations Used to Evaluate Magnetic Loads on the Cryostat

For the convenience of the reader, a synopsis of the relevant equations necessary to evaluate magnetic loads on the Tohoku Bubble Chamber Magnet's Cryostat is completed here.

To evaluate axial loads when the only measured quantity is Δx_T, the total deflection of the cryostat, obtained from the cryostat dial indicators, the relevant equations are

$$F_T = [1.97E6\Delta x_T]\ lb \qquad \Delta x_T \leq .0279'' \tag{A.11}$$

$$F_T = [3.46E6(\Delta x_T - .0279) + 55000]\ lb \qquad .0279'' < \Delta x_T \leq .0536'' \tag{A.12}$$

$$F_T = [3.13E6(\Delta x_T - .0536) + 143900]\ lb \qquad \Delta x_T > .0536'' \tag{A.13}$$

Here Δx_T is taken to be the average of the three cryostat dial indicator readings after the zero offset of each reading is eliminated.

If both Δx_T and Δx_V, the deflection due to vacuum vessel roll, are measured with the cryostat and vacuum vessel dial indicators, respectively, the relevant equations are

$$F_T = [3.46E6(\Delta x_T - \Delta x_V)] lb \qquad F_T \leq 143900\ lb \tag{A.16}$$

$$F_T = [3.13E6(\Delta x_T - \Delta x_V)] lb \qquad F_T > 143900\ lb \tag{A.17}$$

Here Δx_V is the average value of the north and south vacuum vessel dial indicator readings.

To evaluate the axial loads using the strain gauges mounted on the axial post assemblies, the following equations are applicable.

$$F = 25.03\mu\epsilon\ lb \qquad \mu\epsilon \leq 719 \tag{A.18}$$

$$F = [18.65(\mu\epsilon - 719) + 17990] lb \qquad \mu\epsilon > 719\ . \tag{A.19}$$

Here F is the magnetic load on the assembly to which the strain gauges are mounted. The value for $\mu\epsilon$ is obtained by averaging the readings from the two strain gauges attached to the assembly. The total axial load on the cryostat, F_T, is found by averaging all the values obtained for the load on the individual assemblies and then multiplying by 8, the number of axial assemblies per cryostat.

Vertical magnetic loads are obtained from the strain gauges mounted in the bolts at the warm end of the vertical arms by first dividing the measured value by two, and then multiplying the results by 12.5 lb/$\mu\epsilon$.

The magnetic load on a single horizontal post assembly is obtained from measured strain gauge data by using the equation

$$F = 18.65\mu\epsilon \; lb \; , \qquad \text{(A.20)}$$

where $\mu\epsilon$ is the average of the readings obtained from the pair of strain gauges on the horizontal assembly of interest.

Note that the equations used to reduce the strain gauge readings apply only if the Strainserts used to read the gauges are zeroed after cooldown, but prior to coil energization.

B "Measured Magnetic Forces on the Tohoku Bubble Chamber Magnet," W. Craddock, October 30, 1985

C Blueprints—FNAL

2771-MD-56365	2771-MC-193624
9213.400-MD-202692	2771-ME-56476
2771-ME-156057	2771-MD-156000
2771-ME-56411	2771-MD-56417
Horizontal Compression Post Layout	(not numbered)

D Calculation of K_P, the Net Spring Constant for the Axial Post Assemblies—Preloading on the Axial Post Assemblies Before and After Cooldown

Calculation of K_P

Our calculation for K_P, the net spring constant of the axial post assemblies, is performed using the data accumulated by Mruzek [4]. However, before performing the calculation, we must discuss Mruzek's work. According to Craddock, [3], Mruzek measured, at liquid nitrogen temperature, the deflection curve for a complete randolite/aluminum post in two positions: vertical and inclined 1/4″ from vertical. (Note that the behavior of a tilted post was of interest, because the ball and socket mountings allowed the post some rotational freedom.) An examination of Mruzek's paper [4] does not necessarily lead a person to Craddock's conclusion. No figure or dimensions beyond overall length and randolite rod diameter accompany the paper. Hence, it is not clear whether Mruzek evaluated a single rod of randolite with two aluminum couplings for mounting purposes, or an assembly consisting of a number of randolite rods and aluminum couplings (which is what exist in the magnet). From Mruzek's paper, it also appears that the entire assembly was immersed in liquid nitrogen (LN_2) and, though it is not specifically stated, it was removed after reaching thermal equilibrium with the bath, placed in a testing fixture, and loaded to a predetermined value. An examination of Mruzek's personal notes raises more questions than it answers. Mruzek's notes include a sketch of the randolite/aluminum post tested. The post tested indeed resembles the post that are installed in the coils, however, the figure doesn't include dimensions so that the confirmation we seek is not forthcoming. Additionally, Mruzek cross-hatched two adjacent randolite rods in his figure, stating that the cross-hatching depicted frosted areas. From this one might conclude that Mruzek did not immerse the entire assembly in LN_2, but immersed only the position of the post that, when installed in the functioning coils, would be subjected to temperatures at or below that of liquid nitrogen; the frosting occurring after the post was removed from the bath on the portions of the post that were immersed. Taking all of this into consideration, the author assumes that Mruzek tested a randolite/aluminum post identical to those that are installed in the magnet, and that this test accurately portrays the posts in their cooled-down condition. Note that Mruzek doesn't explain how he calculated the effective elastic modulus for the post. For our work, we shall only use the raw data that Mruzek reports.

Mruzek [4] reports that, for a randolite/aluminum post either mounted vertically or tilted 1/4″ from the vertical, the deflection for a load of 50,000 lb is .047″. For loads less than 50,000 lb, the deflection recorded for the tilted rod is greater than the deflection for the vertical rod. However, this trend is reversed for loads greater than 50,000 lb. The behavior of the two cases is linear for loads greater than 50,000 lb. Though the behavior is not truly linear below 50,000 lb, a consequence of the initial seating of the couplings and of minute deformations at the randolite/aluminum interface, we shall assume the behavior below 50,000 lb to be linear. Hence, the spring constant for both configurations for a single post for loads less than 50,000 lb is

$$\begin{aligned} K &= \frac{50,000\ lb}{.047 in} \\ K &= .1064E6\ lb/in/post \qquad F \leq 5E4\ lb\ . \end{aligned}$$

For the vertical geometry, Mruzek's measured deflection at 300,000 lb was .214 in. This leads to a spring constant of

$$\begin{aligned} K &= \frac{(30-5)E4\ lb}{(.214-.047)in} \qquad Vertical\ Post \\ K &= 1.497E6\ lb/in/post \quad 5E4 < F \leq 3E5\ lb. \end{aligned}$$

Finally, the deflection of a tilted post at 300,000 lb was .197 in. Hence,

$$\begin{aligned} & \qquad\qquad TiltedPost \\ K &= 1.667E6\ lb/in/post \quad 5E4 > F \leq 3E5\ lb. \end{aligned}$$

There are eight post assemblies per coil, and, since they are mounted with ball and socket joints, each could be vertical, tilted .25 in, or somewhere inbetween. We therefore shall use the average of the vertical and tilted values. Hence,

$$\begin{aligned} K_R &= 1.064\ lb/in/post \quad 0 < F \leq 5E4\ lb \\ K_R &= 1.582\ lb/in/post \quad 5E4 < F \leq 3E5\ lb. \end{aligned}$$

For N springs in parallel, it can be shown (see any basic text concerning Dynamics or Machine Design) that

$$K = \sum_{i=1}^{N} K_i \ .$$

Since our coil has eight randolite/aluminum posts in parallel, we may write

$$K_R^T = 8K_R \ .$$

Hence, for the magnet after cooldown

$$\begin{aligned} K_R^T &= 8.512E6\ lb/in \quad 0 < F \leq 4E5\ lb \\ K_R^T &= 12.66E6\ lb/in \quad 4E5 \leq F < 24E5\ lb \ . \end{aligned}$$

To find the spring constant K_p, we must now determine a spring constant for the inconel rods that, when combined with a randolite/aluminum post, make up an axial support assembly. These rods are used to axially preload the coil. The rods, after cooldown, have a temperature distribution that ranges from 4.2 K to 300 K. We shall use a simplified analysis, which assumes piecewise continuous step functions for the temperature distribution. Using FNAL Dwg. #2771-ME-156057 and 2771-MD-56417 (Appendix C) as references, we have the situation shown in Table D.1 (within a few degrees). As mentioned previously, we shall assume a step function in temperature over the sections where the temperature varies with length. This assumed distribution is presented in Table D.2. From [16] we have the following values for the modulus for Inconel

$$\begin{aligned} E &= 29.6E6\ psi@293\ K \\ E &= 30.8E6\ psi@77\ K \\ E &= 30.6E6\ psi@5\ K. \end{aligned}$$

L	ΔL(inches)	T
0 to 3″	3	Room to 77 K
3 to 4.375″	1.375	77K
4.375″ to 7.250″	2.875	77 K to 5 K
7.250″ to 8.500″	1.25	5 K
8.500″ to 12.875″	4.375	5 K

Table D.1: Tabular representation of the temperature *vs.* length in an inconel rod after cooldown.

L	ΔL	T	
0 to 1.5″	1.5″	293 K	1.5″ @ 293 K
1.5 to 3″	1.5″	77 K	
3″ to 4.375″	1.375″	77 K	4.313″ @ 77 K
4.375″ to 5.813″	1.438″	77 K	
5.813″ to 7.250″	1.438″	5 K	
7.258″ to 8.500″	1.250″	5 K	7.063″ @ 5 K
8.500″ to 12.875″	4.375″	5 K	* $L_T = 12.875''$

Table D.2: Tabular representation of the assumed temperature *vs.* length in an inconel rod after cooldown.

Weighing these values of modulus with the fractional length of the rod at a given temperature, we obtain a weighted average for the modulus of an inconel rod after cooldown. Hence,

$$\begin{aligned}
\overline{E} &= \frac{E(293\ K)\Delta L(293\ K) + E(77\ K)\Delta L(77K) + E(5\ K))\Delta L(5K)}{L_T} \\
&= \left[\frac{1.5(29.6) + 4.313(30.8) + 7.063(30.6)}{12.875}\right] E6 \\
\overline{E} &= 30.55E6\ psi.
\end{aligned}$$

Any good text on Strength of Materials will show that the spring constant for a rod may be written in terms of the modulus in the following manner,

$$K = \frac{EA}{L}\ . \tag{D.1}$$

Noting that the area of an inconel rod is $.0767in^2$, and its length is 12.875 in, our spring constant for a single inconel rod after cooldown is

$$\begin{aligned}
K_I &= \frac{(30.55E6)(.0767)}{12.875} \\
K_I &= .182E6\ lb/in/rod\ .
\end{aligned}$$

Since, in each coil, there are 16 inconel rods in parallel, the net spring constant for the rods is

$$\begin{aligned}
K_I^T &= \sum_{i=1}^{16} K_i = 16\ K_I \\
K_I^T &= 2.912E6\ lb/in\ .
\end{aligned}$$

Using this value with K_R, the spring constant for all of the randolite/aluminum posts in a coil, we may write K_P, the axial spring constant for a coil to be

$$\begin{aligned}
K_P &= K_I^T + K_R^T \\
K_p &= 11.424E6\ lb/in \quad 0 < F \leq 4E5\ lb \\
K_p &= 15.572E6\ lb/in \qquad F > 4E5\ lb.
\end{aligned}$$

It is these values for K_ρ that we use throughout this paper.

It would be interesting to derive the spring constant K_ρ using Equation D.1 and the modulus for randolite at room temperature and at 77 K, to compare with our results presented above. This exercise is performed in Appendix J for the horizontal posts. We, unfortunately, don't have the time to complete this exercise for the axial post assemblies.

Preloading on the Axial Post Assemblies Before and After Cooldown

According to Craddock [3], each of the inconel rods in an axial support assembly were preloaded to a value of 687 lb during assembly. Since there are two inconel rods associated with one randolite/aluminum post, the preloading on the post is

$$F_R^P = 2F_I^P = 2(687)$$
$$F_R^P = 1374\ lb.$$

The total contraction in an inconel rod, due to preloading, may be found using Equation (D.1), and the room temperature value for the modulus for inconel. Hence,

$$\Delta L_I^P = \frac{F_I^P L}{EA} = \frac{(687\ lb.)(12.875\ in.)}{(29.6E6\ psi)(.0767\ in^2)}$$
$$\Delta L_I^P = .00390\ in.$$

When the coils are cooled to operating temperature, the difference in thermal contraction between the post and the rods cause a change in the preloading value. We shall show that the inconel rods contract a greater amount than the posts, and hence preload values increase.

From reference [16] we have the following values for thermal expansion for inconel:

$$\frac{\Delta L}{L} = 0@293\ K$$

	L	T	$\Delta L/L$	ΔL
0 to 1.5″	1.5″	293 K	0	0
1.5″ to 5.813″	4.313″	77 K	.00218″	.00940″
5.813″ to 12.875″	7.062″	5 K	.00229″	.01617″

Table D.3: Assumed temperature distribution and thermal contraction in an inconel rod after cooldown.

$$= .00218 @ 77\ K$$
$$= .00229 @ 5K.$$

As we did in the previous section, we shall assume piecewise continuous step functions for the temperature distribution in a rod after cooldown. This assumed temperature distribution and the resulting change in length per step are presented in Table D.3. Summing the values in the last column of Table D.3 we have

$$\Delta L_C^I = \Sigma \Delta L = .0256\ in.$$

This is the total contraction in an inconel rod, due to thermal effects during cooldown.

We now need to find the thermal contraction experienced by the randolite/aluminum post. From [17] for 7075 aluminum, we have

$$\begin{aligned} \frac{\Delta L}{L} &= 0 && @293\ K \\ &= .00390 && @77\ K \\ &= .00410 && @5\ K \end{aligned}$$

For randolite, from [13], we have

$$\begin{aligned} \frac{\Delta L}{L} &= 0 && @.293\ K \\ &= .00127 && @77\ K. \end{aligned}$$

	T	L	$\Delta L/L$	ΔL
Ball and Socket	293 K	$.75''$	0	0
Coupling	77 K	$.25''$	.00390	$.000975''$
Coupling	5 K	$.25''$	.00410	$.001025''$
Ball and Socket	5 K	$.75''$	.00410	$.003075''$

Table D.4: Thermal contraction for the aluminum components of the randolite/aluminum post after cooldown.

To the author's knowledge, no data exists for the thermal contraction of randolite at LHe temperatures. Table D.4 presents the thermal contraction for the aluminum components of the post. Summing the values of the last column of Table D.4 we have

$$\Delta L_A^C = \Sigma \Delta L = .00508'' \ .$$

This is the total construction of the aluminum, due to thermal effects during cooldown.

Considering the randolite, we shall assume that the thermal contraction remains constant between 5 and 77 K. This assumption is reasonable if the thermal expansion for randolite behaves as that for G-10. We assume a step in temperature between 293 K and 77 K, occurring at the midpoint of the warmest randolite piece, and that the other randolite pieces are at 77 K. Hence, 1.437 inches of randolite are assumed to be at room temperature and experience no thermal contraction. The other 9.313 inches of randolite are at 77 K and contract

$$\Delta L_R^C = .00127 * 9.313 \ in = .01183 \ in.$$

Using this value with the total thermal contraction for the aluminum, we have

$$\Delta L_P^C = \Delta L_A^C + \Delta L_R^C = .0169 \ in.$$

This is our total change in length for the randolite/aluminum post resulting from thermal contraction during cooldown of the magnet coils.

Considering qualitatively what is occurring during cooldown, we realize that, due to the system of mounting, the inconel rods must follow the randolite/aluminum post. Therefore, the cooldown preload is proportional to the initial compression length of the inconel rods plus the difference in contraction between the posts and the rods after cooldown. Therefore,

$$\begin{aligned} \Delta L_I^T &= \Delta L_I^P + \Delta L_I^C - \Delta L_P^C \\ \Delta L_I^T &= .0126\ in. \end{aligned}$$

The total force or preload on a pair of inconel rods is therefore

$$\begin{aligned} F_I^C &= 2K\Delta L_I^T \\ &= 2(.182E6\ psi)(.0126\ in.) \\ F_I^C &= 4586\ lb. \end{aligned}$$

Therefore, the total preload on a randolite/aluminum post after cooldown is

$$F_R^C = F_I^C = 4586\ lb.$$

E "Tohoku Bubble Chamber Magnet Cryostat," W. Craddock, April 5, 1985

F Raw Dial Indicator Data—1985 and 1986 Run

G "3-Dimensional Finite Element Analysis of 30-inch BCM Cryostat," Bob Wands, September 9, 1986

H Raw Strain Gauge Data—1985 and 1986 Run

I Calculation of K_H—Before and After Cooldown—Preloading on the Horizontal Posts after Cooldown

Calculation of K_H

We shall calculate a value for K_H, the spring constant for a horizontal post, because we, quite frankly, have no idea how Craddock [4] obtained his value of $1.3 * 10^6\ lb/in$ for this spring constant. To obtain K_H, we shall use the values reported by Craddock [4] for randolite. These values are

$$E = 4.48E6\ psi \qquad \text{@Room Temperature}$$

$$E = 4.89E6\ psi \qquad @77\ K.$$

We shall make the same assumption, concerning temperature effects, that were made in Appendix D. Note that this analysis will not take into account the fact that the post could be slightly tilted.

The individual horizontal posts may be regarded as seven springs in series with one another (Appendix C, print with incomplete drawing number entitled "Horizontal Compression Post Layout"). The individual springs are the three randolite segments, two aluminum couplings, and two aluminum ball and socket joints. To obtain the various spring constants for these pieces, we shall apply the equation

$$K = \frac{EA}{L}. \tag{I.1}$$

the relationship between spring constant and the modulus that is demonstrated in any text addressing Strength of Materials.

Applying Equation (I.1) to the randolite segments, we have the results presented in Table I.1 for the pieces prior to cooldown and the results in Table I.2 for the pieces after cooldown. Note that since the large diameter randolite piece has is at room temperature at one end and at 77 K at the other end, we have based the spring constant on the average value for the modulus at these two temperatures. We also have assumed that the behavior of the randolite is the same at 4 K as it is at 77 K.

L in.	d in.	A in.^{2}	K lb/in
2.344	2.25	3.976	7.60E6
3.5	2	3.142	4.02E6
3.094	2	3.142	4.55E6

Table I.1: Spring constants for the randolite pieces in the horizontal posts at room temperature.

L in	d in	A in^2	E psi	K lb/in
2.344	2.25	3.976	4.69E6	7.95E6
3.5	2	3.142	4.89E6	4.39E6
3.094	2	3.142	4.89E6	4.97E6

Table I.2: Spring constants for the randolite pieces in the horizontal posts after cooldown.

L in	d in	A in^2	K lb/in
.75	2	π	44.4E6
.25	2	π	133E6
.25	2.125	3.547	150E6
2.906	2.25	3.976	14.5E6

Table I.3: Spring constants for the aluminum pieces in the horizontal posts at room temperature.

Applying Equation (I.1) to the aluminum pieces, we have the spring constants presented in Table I.3 for room temperature conditions and Table I.4 for cooldown conditions. The values for the modulus of aluminum used to generate these tables are [16]

$$E = 10.6E6\ psi \qquad @293\ K$$

$$E = 11.1E6\ psi \qquad @77\ K$$

$$E \sim 12E6\ psi \qquad @5\ K.$$

Note that, for the diameter of the coupling between the $2''$ and the $2.25''$ diameter randolite pieces, the average of the two diameters was assumed.

For N springs in series, the net spring constant of the set is (see any text on Strength of Materials)

$$\frac{1}{K_T} = \sum_{i=1}^{N} \frac{1}{K_i} \ . \tag{I.2}$$

Applying this equation to the values in Tables I.1 and I.3, we have for room temperature conditions

$$\frac{1}{K_H} = \left\{ \left[\frac{1}{7.60} + \frac{1}{4.02} + \frac{1}{4.55} \right] E-6 + \left[\frac{1}{44.4} + \frac{1}{133} + \frac{1}{150} + \frac{1}{14.5} \right] E-6 \right\} \frac{in}{lb}$$

L in	T K	d in	A in^2	E psi	K lb/in
.75	5	2	π	12E6	50.3E6
.25	5	2	π	12E6	151E6
.25	77	2.125	3.547	11.1E6	157E6
2.906	293	2.25	3.976	10.6E6	14.5E6

Table I.4: Spring constants for the aluminum pieces in the horizontal post after cooldown.

$$\begin{aligned} \frac{1}{K_H} &= .706E-6\frac{in}{lb} \\ K_H &= 1.42E6\frac{lb}{in} \qquad \text{@Room Temperature.} \end{aligned} \tag{I.3}$$

Applying Equation (I.2) to the values for K in Tables I.2 and I.4 we have, for cooldown conditions

$$\begin{aligned} \frac{1}{K_H} &= \left\{\left[\frac{1}{7.95}+\frac{1}{4.39}+\frac{1}{4.97}\right]E-6+\left[\frac{1}{50.3}+\frac{1}{151}+\frac{1}{157}+\frac{1}{14.5}\right]E-6\right\}\frac{in}{lb} \\ \frac{1}{K_H} &= .657E-6\frac{in}{lb} \\ K_H &= 1.52E6\frac{lb}{in} \qquad \text{@After Cooldown.} \end{aligned} \tag{I.4}$$

These values shall be used for our calculations for the magnitude of the preloading after cooldown.

Preloading on the Horizontal Post after Cooldown

According to Craddock [4], the total preload on a horizontal post assembly (a horizontal post pair, where there are two pairs to a coil) prior to cooldown was 40,000 lb. The author has roughly verified this number using Shigley and Mitchell, Equation 8–16 [20]. Since the individual posts in a pair are in series with one another, they each see 40,000 lb. What is curious is that Craddock's design load for a post was 37,000 or 37,500 lb [4]. Why the posts were preload beyond 37,500 lb is unexplained.

Using Equation (I.3), the compression of a single post, resulting from the initial preload at room temperature, can be determined. Recalling that

$$\begin{aligned} F &= K\Delta X \\ \Delta X_P &= \frac{F_P}{K_H} = \frac{40,000\ lb}{1.42E6\ lb/in} \\ \Delta X_P &= .0282''. \end{aligned} \tag{I.5}$$

In order to determine the preload after cooldown, we need to determine how much the individual post contracts upon cooling. In performing this evaluation, we shall use the same assumptions used in Appendix D concerning temperature distribution. For randolite, from [13], we have the following values for thermal contraction in randolite

$$\Delta L/L = 0 \qquad @293\ K$$

$$\Delta L/L = .00127 \qquad @77\ K.$$

To the author's knowledge, no data exist for thermal contractions to LHe temperatures. Applying these numbers, we have the results presented in Table I.5 for the randolite segments in the horizontal posts. We have assumed, for the randolite segment, with ends at room temperature and 77 K, that half of this segment is at room temperature and the other half is at 77 K. We have also assumed that further contractions occurring between 77 K and 5 K are insignificant.

Considering now the thermal contraction in the aluminum, we have from [17] for 7075 aluminum, that

$$\Delta L/L = 0 \qquad @293K$$

$$\Delta L/L = .00390 \quad @77\ K$$

L in	$\Delta L/L$ in/in	ΔL in
2.344/2	0	0
2.344/2	.00127	.00149
3.5	.00127	.00445
3.094	.00127	.00393
		$\Sigma\Delta L_R = .00986''$

Table I.5: Thermal contraction in the randolite segments of a horizontal post due to cooldown.

$$\Delta L/L = .00410 \quad @5\ K.$$

Table I.6 presents the thermal contraction for the various aluminum pieces in a horizontal post.

Consider now the thermal contraction in the stainless steel tab on the cryostat of the coil to which the horizontal posts are anchored. The thermal contraction for 304 stainless steel is

$$\Delta L/L \cong .00264 \qquad \text{Room Temperature to 5 K.}$$

Half the thickness of the tab is associated with each post, hence we are interested in the thermal contraction in $3/4''$ of stainless steel. Therefore

$$\Delta L = .75 * .00264$$
$$\Delta L_S = .00198''$$

Combining the total values of thermal contraction in the randolite, aluminum and stainless steel, we obtain

$$\Delta L_H^C = \Sigma\Delta L_R + \Sigma\Delta L_A + \Delta L_S$$

L in	T K	$\Delta L/L$ in/in	ΔL in
.75	5	.00410	.00308
.25	5	.00410	.00103
.25	77	.00390	.000975
			$\Sigma \Delta L_A = .00508''$

Table I.6: Thermal contraction in the aluminum segments of a horizontal post due to cooldown.

$$\Delta L_H^C = .0169''. \quad \text{(I.6)}$$

This is the total thermal contraction for a horizontal post, due to cooldown effects.

The thermal contraction in a horizontal post, caused by cooldown effects, will partially relieve the initial preload on a post. The preload remaining on a post, after cooldown, is proportional to the difference in the compression of the post, due to the initial loading, and the thermal contraction in the post, due to cooldown. Therefore, using equations (I.4), (I.5), and (I.6), we have

$$F_H^C = K_H(\Delta X_P - \Delta L_H^C)$$

$$F_H^C = 1.52E6(.0282 - .0169)in$$

$$F_H^C = 17,100 \; lb.$$

This is the preload on each horizontal post after cooldown of the coils. Note that our value for the cooldown preload is somewhat smaller than Craddock's [4]. This is due to our calculated value of the spring constant for a warm post. Our value for K_H at room temperature is larger than the value used by Craddock, which leads to a smaller value of ΔX_P and, consequently, a smaller value of F_H^C.