Final Thermal Analysis of the G-Zero Magnetic Spectrometer

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ABSTRACT

BWX Technologies, Inc. (BWXT) has completed the final design on a superconducting eight-coil toroidal magnetic spectrometer system for the G-Zero experiment. Conceptually designed by the University of Illinois at Urbana-Champaign, this magnet will be installed in Hall C at the Thomas Jefferson National Accelerator Facility.

This paper describes the thermal analysis performed as a part of the final design. Specific issues to be discussed include the finite element analysis of the magnet structure for evaluating cooldown rates, as well as steady state temperature distributions, and thermal siphon heat removal capabilities. The cooldown studies demonstrated that the magnet cold mass could be cooled to operating temperatures within the timeframe specified despite some limitations on the availability of coolant from the refrigeration system. The thermal siphon cooling system was analyzed with the ANSYS finite element analysis software package to assure that the thermal siphon cooling would function with the non-uniform heat-leak distribution into the cold mass structure. The finite element analysis modeling methods used to represent two phase liquid helium flow pressure drop provided very good agreement with previously published experimental data.

INTRODUCTION

The final design of the G^0 Superconducting Magnetic Spectrometer (SMS) has been completed by BWX Technologies, Inc. (BWXT) and is now in the manufacturing phase. This system is to be used for the G^0 parity experiment to be performed at the Thomas Jefferson National Accelerator Facility (TJNAF). The final design analysis included evaluation of the ability to cool the magnet with the cooling resources allocated.

This magnet consists of 8 superconducting coils that are assembled in a toroidal arrangement as shown in figure 1. Each coil is wound on a solid aluminum bobbin as two double pancakes with 36 turns per pancake. The bobbin (approximately a rectangular shape with rounded corners as shown in figure 2), is gun-drilled with three intersecting holes to form a U-shaped coolant channel. These coolant channels are connected to a liquid helium reservoir with stainless steel tubing in a fashion that promotes natural circulation cooling as shown in figure 3.

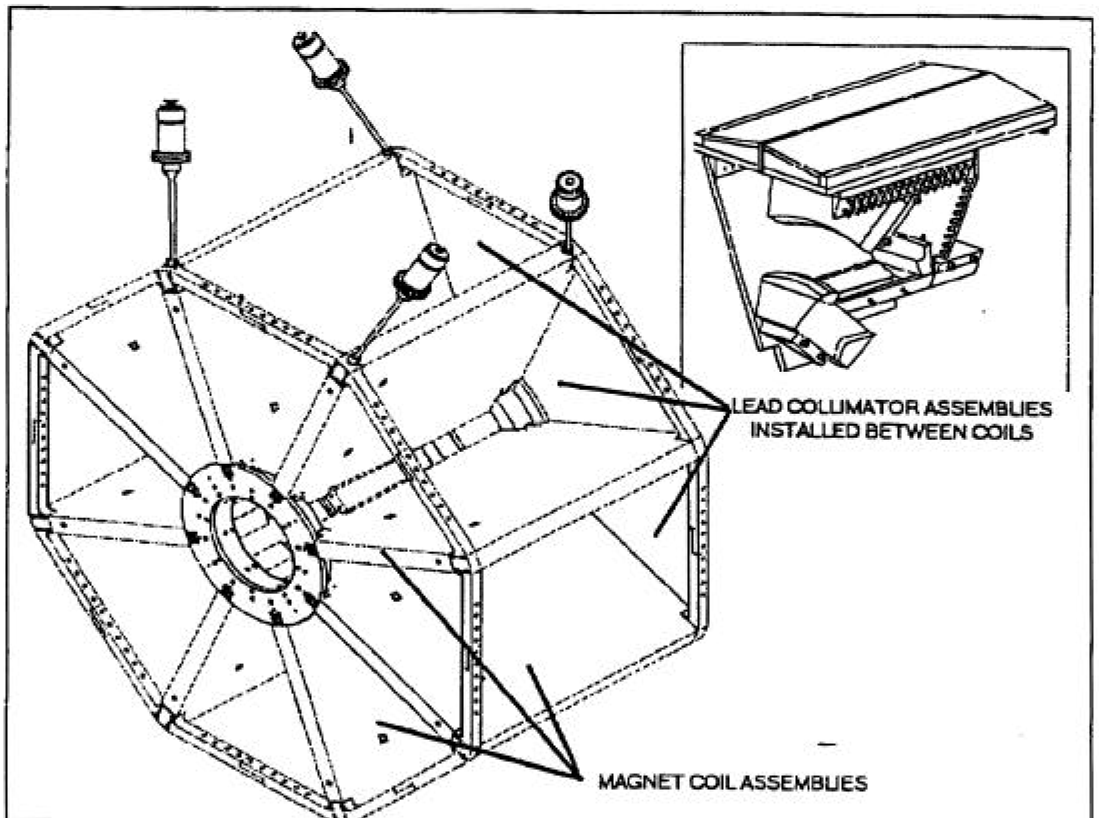

Fig.1. G^0 Superconducting Magnet Cold Mass & Support Rods

Note that the 8 coils are cooled in 4 parallel paths, and that the heat load in each of these paths will not be equal since only two coils have direct connection with the cold mass support rods. A fifth coolant channel is utilized to cool the splice joints and the lead buss. The driving force for the coolant flow is the difference in fluid density between the pipe supplying LHe to the bottom of the magnet, and the two-phase flow in the lines returning to the reservoir.

The superconductor strand is made into a Rutherford cable and soldered into a channel formed in a copper strip. Electrical insulation is provided by 0.001" thick Kapton tape wound around the conductor with 50% overlap. Further electrical insulation is provided by sheets of G-10 which are placed against the bobbin and coil case hardware. The conductor

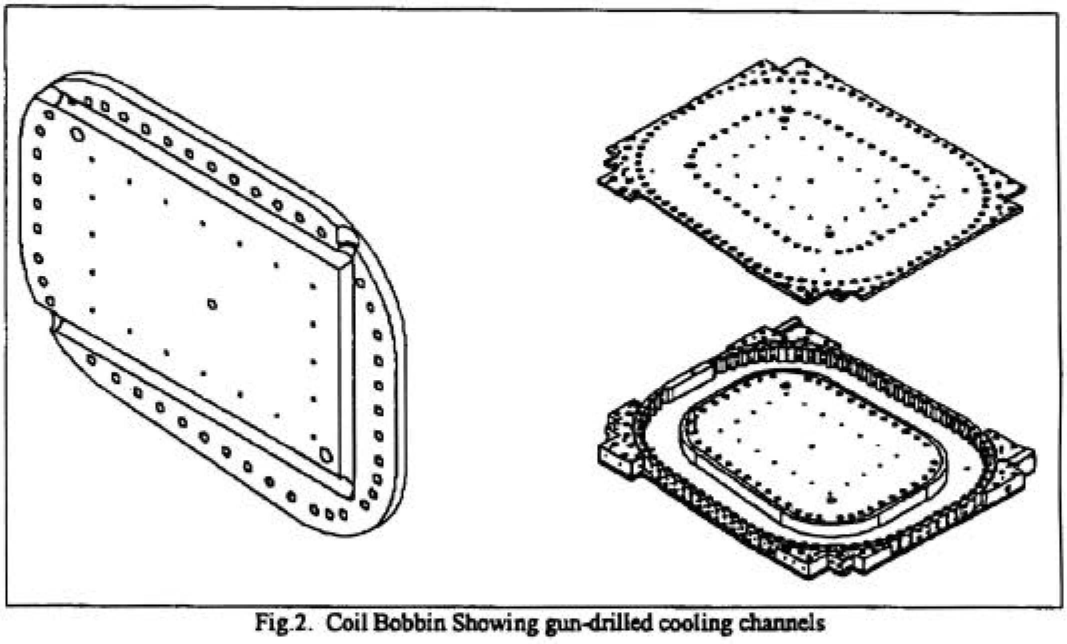

Fig.2. Coil Bobbin Showing gun-drilled cooling channels

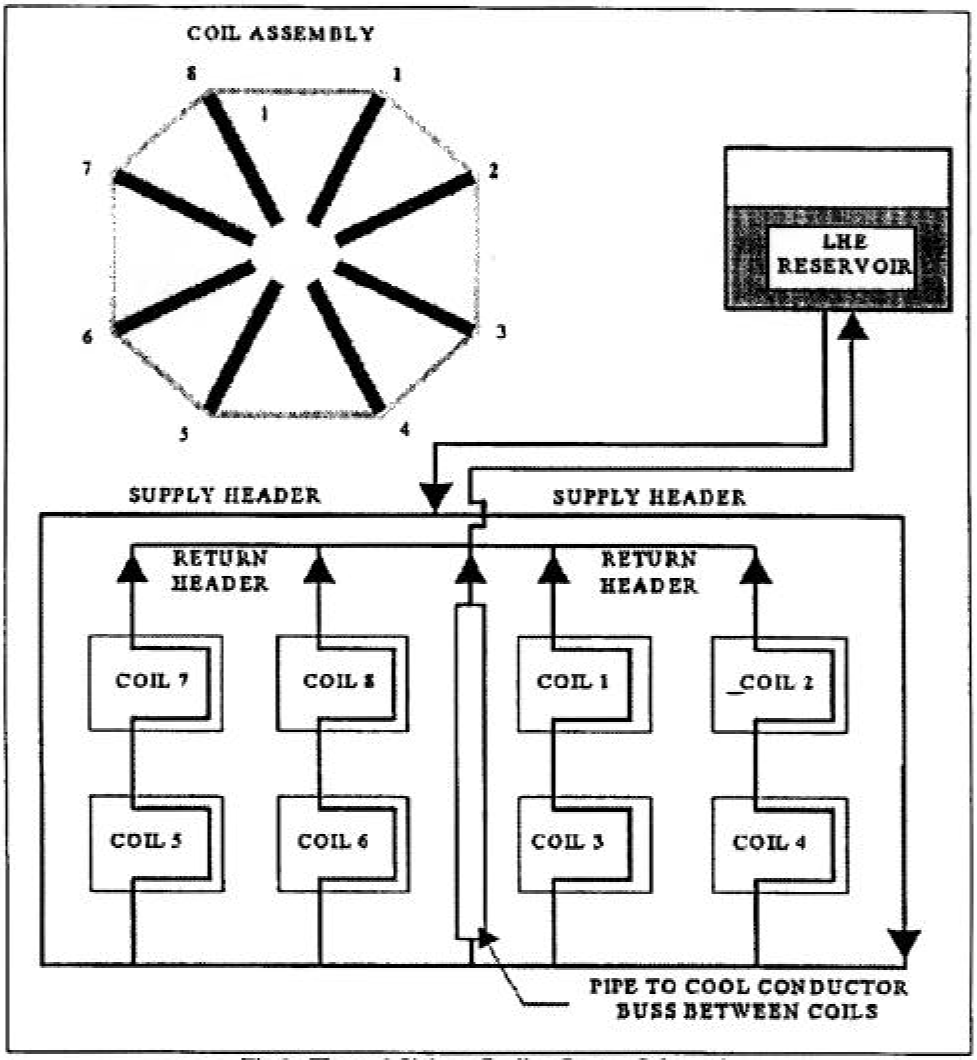

Fig.3. Thermal-Siphon Cooling System Schematic

is cooled by thermal conduction through these layers of insulation to the bobbin. Other components such as the lead collimators placed between the magnets will be cooled by conduction through their supports to the coil sideplates and then to the bobbin.

ANALYSIS OBJECTIVES

The objectives of the thermal analysis included:

- Verify heat loads to the LHe and LN2 coolant did not exceed the specified values;
- Verify the steady state conductor temperatures for superconductor stability;
- Verify steady state and transient cooling capacity;
- Verify cooling system stability with non-symmetric heat loads;
- Verify cooldown capability with available cooling resources.

ANALYSIS METHODS

The heat loads required to be removed by the LHe coolant were calculated as shown in table 1 and used as input to the thermal analysis calculations.
The G0 magnet cooling system was modeled using the FLUID66 element that is a part of the ANSYS finite element software package. This element simulates the flow of a fluid through a pipe, including the pressure drop due to fluid friction, pressure changes due to

bouyancy/elevation, and the variation in heat transfer due to the Reynolds number and physical properties of the fliud flow.

Although this element is intended for simulating single phase fluids, the two-phase behavior of the liquid helium coolant was simulated by transitioning from liquid properties to vapor properties over a very small temperature range. This was a very reasonable approximation since the pressure changes around the coolant system were small.

One key factor to keep in mind when using this element is that the fluid flowrate and specific heat must be input on a weight basis, whereas the specific heat of the solid structure is input on a mass basis. Additionally, the friction factor, f, should be based on the Moody friction factor rather than the Fanning friction factor. These two factors differ by 4:1 since they are associated with the following formulation for pressure drop:

Fanning form: $$\Delta p = \frac{2 f \rho u^2 L}{D_h} \qquad (1)$$

Moody form: $$\Delta p = \frac{f \rho u^2 L}{2 D_h} \qquad (2)$$

To verify the accuracy of the modeling of this element, two tests were performed to verify the friction pressure drop calculations, one for single phase and the other for two phase friction pressure drop calculations. Using an example found on page 245 of *Helium Cryogenics*[1], the ANSYS model calculated a single phase pressure drop of 2.478 kPa vs the textbook value of 2.5 kPa. The ANSYS input files for these test cases are listed in table 2. Using a simple 3-point transition from liquid to vapor properties over a temperature range of 0.1K, the two-phase pressure drop factor is virtually identical to that for the homogeneous model shown in figure 4 of this report.

Although the ANSYS FLUID66 element has the capability to calculate the heat transfer film coefficient from the fluid thermodynamic properties and the Reynolds number, the film coefficient was independently calculated and input as a temperature dependant material property to simplify the model solution. Additionally, the specific heat of the fluid was adjusted over 0.1 degree two-phase range to account for the latent heat of vaporization.

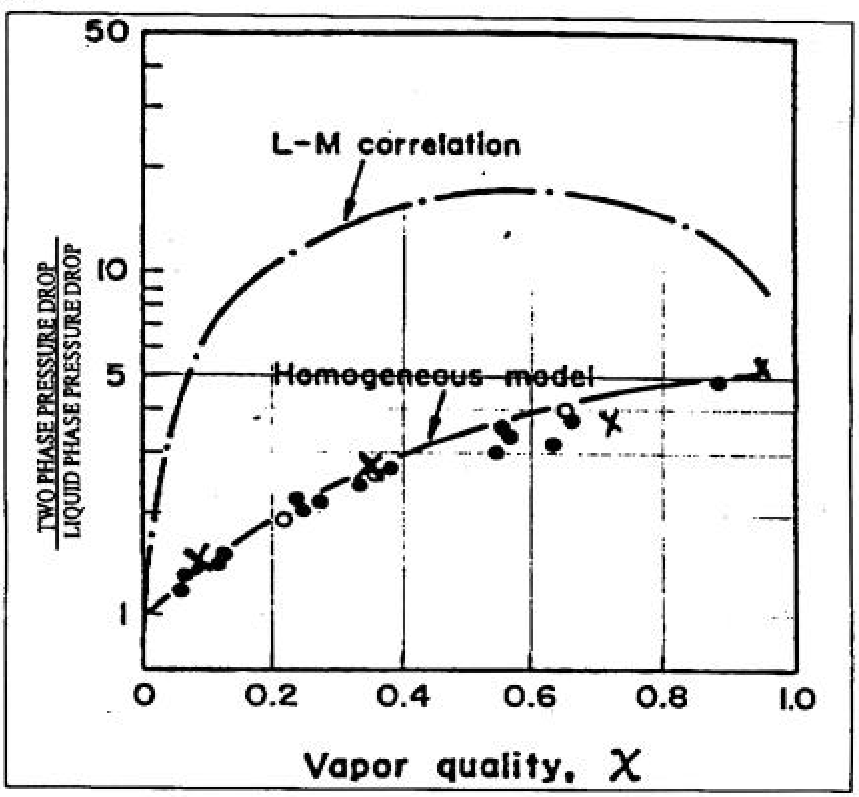

Fig.4. ANSYS FLUID66 element performance in simulating two phase pressure drop (X) matches the Homogeneous Model

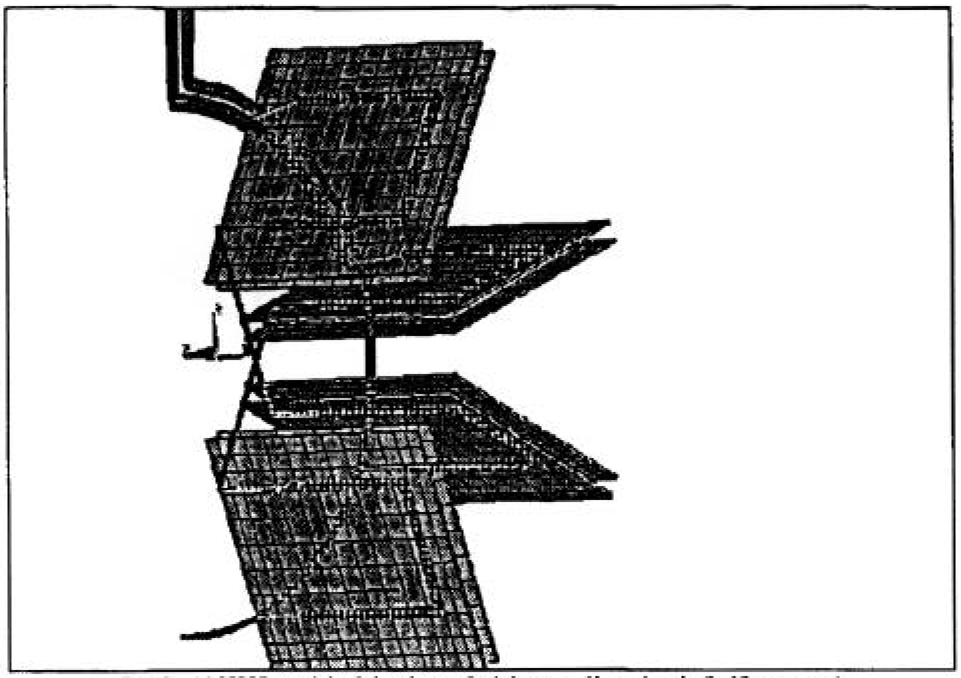

Fig.5. ANSYS model of the thermal-siphon cooling circuit (half symettry)

ANALYSIS RESULTS

A. Steady State Cooling

Using the model shown in Figure 5, the coolant mass flow rate was calculated for a range of heat loads ranging from significantly smaller to significantly larger than that expected in operation. The calculated fluid flow increased as the heat load increased until the vapor quality reached about 25%, and then remained relatively constant as the vapor quality increased with greater heat load, as shown in figure 6. These results are qualitatively consistent with natural circulation behavior reported by Huang and Van Sciver[2].

Further calculations investigated the system behavior if one of the cooling legs were heated more than the others. Non-symmetric heating was evaluated with on leg heated by factors 2, 4 and 8 times the baseline value. As reported in table 1, the total flow rate

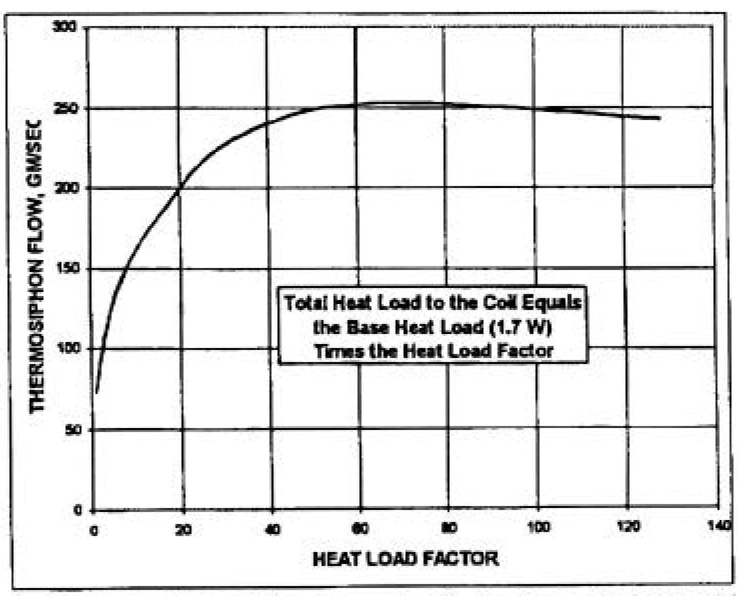

Fig 6. Thermal-siphon cooling mass flow rate as a function heat load. The heat load factor is the

increased along with that of the hot leg, but the "cool" legs did not experience a reduction in flow rate. Therefore, the magnet will be adequately cooled despite individual coils being heated more than others.

For the expected steady state cooling scenario, coils 2, 3, 6 & 7 will each receive about 1.35 watts. Coils 1 and 8 will each receive 2.4 watts, while coils 4 and 5, 2.3 watts. Saturated LHe coolant was assumed to be supplied from the cryo-reservoir at 1.2 atmosphere with an initial temperature of 4.424 K.

Under these conditions, the total LHe flow through the magnet system was calculated to be 79.6 gm/sec with the warmest spot in the coil calculated to be 4.85 K at the outboard corners of coils 1 or 8 (adjacent to the cold mass support rods). This temperature is significantly below the current sharing temperature of the NbTi superconductor (5.9K at 3.63T max, 8k at the outboard corners, 1.6T).

The steady state cooling capability has been demonstrated to be stable for heat loads well over 100 times the normal expected values. Thus, it is obvious that this system design will allow the magnet to recover from a quench (should one ever occur). Further, it will be possible to use the natural circulation mode in the final stages of cooldown.

TABLE 1
CALCULATED HEAT LOADS TO LHe

Heat Source	Magnitude
Cold Mass Support Rods -	2.0 W
Lower Support Pin -	1.88 W
Radiation from shield -	0.75 W
Radiation from windows -	6.0 W
Radiation from target -	0.88 W
Residual Gas -	<1.0 W
Conductor Splices -	1.2 W
Nuclear Radiation -	<1.0 W
Summation (per Coil)	**<1.85 W**

B. Cooldown To Operating Conditions

The magnet design specification required that the magnet be designed for cooldown to operating temperatures within 10 days. The initial phase of this cooldown was to utilize 2.5 g/s helium gas chilled by liquid nitrogen to chill the magnet down to about 80 to 100 K. The remainder of the cooldown would utilize LHe. Although the TJNAF refrigeration system could supply 4 g/s of LHe, this was not sufficient to finish the cooldown in 10 days. However, it was determined that this flow could be supplemented with LHe previously stored in a 10,000 liter dewar.

The final baseline cooldown scenario started with the chilled helium gas entering the magnet at 50K below the magnet hardware temperature. The gas temperature is then reduced at a rate of 1 degree K per hour until the gas is down to 100K. The coolant is changed over to LHe flowing at 10 g/s. Over the next 4 days, the coolant flow is gradually reduced to the steady state value of 4 g/s. At this time the valving can be adjusted to allow natural circulation flow, with the coolant flow provided at such a rate to maintain the LHe reservoir level.

In addition to the capability to transfer the heat into the coolant, this study also investigated the ability to transfer heat through the structure to the coolant channel walls. One of the key issues relating to the cooldown calculations is how to model the transfer of heat through mechanical joints in a vacuum. Many references were reviewed to determine a reasonable basis for modeling this phenomenon. They generally represent the contact heat transfer as a flow of heat per unit area per degree. In essence this is the same as a convection film coefficient for transfer of heat between a solid and a fluid. Typical values for contact thermal resistance in a vacuum were found to be about 1 to 19 KW/m2/K for contact stresses of about 5 to 7 MPa. A value at the middle of this range was selected for these calculations.

The final model represented the thermal mass of key components within the assembly as point masses (MASS71) thermally connected with various types of link elements from ANSYS, including LINK33 for conduction, LINK31 for thermal radiation and LINK34 for thermal convection.

The radiant heating was used to model the heat flow between components which did not have a direct mechanical connection. One area modeled with radiant heat transfer is between the cold mass and the LN2 shield. During the initial phase of the cooldown, the cold mass would be cooled by the LN2 shield, but later it would be part of the heat leaking into the cold mass. It was also used to evaluate cooling of the collimator assemblies by the directly to the coil case side plates. It was determined that a direct conduction path should be established between the collimator and the side plates to assure that their temperatures did not lag too far the rest of the cold mass.

TABLE 2
ANSYS Input File for Pressure Drop Test

```
lcryo1.mac     test of single phase delta-p LHe example from Helium Cryogenics, Van Sciver, page
245
/prep7

! DEFINE VALUES FOR PARAMETRIC VARIABLES
   flodia= .010                                  ! pipe ID,m
   lgth= 30.00                                   ! pipe length,m
   flovel=1.0                                    ! flow vel, m/s
! liq He at 4.0 k, 1.0 atm
   densityl=130.1                                   ! kg/m**3
   viscosl=3.34e-6                               ! N*sec/m**2
   gacc=9.81                                     ! grav acc, m/s^2
   floarea=0.785*flodia**2                       ! flow area, m^2
   flor8=flovel*densityl*floarea*gacc            ! flow weight/sec
   Re=densityl*flovel*flodia/viscosl             ! Reynolds Number
   mffi=4*(0.0791/Re**.25)                       ! Moody frict fctr
   ET,2,FLUID66
   R,2,flodia,floarea,0,gacc,0,0,
   RMORE,0,0, ,1,0,
   mp,dens, 2, densityl                          ! kg/m**3
   mp,kxx,  2, thcond                            ! w/m-deg k
   mp,c,    2, thcap                             ! j/kg-deg k
   mp,visc, 2, viscosl                           ! kg/m-s
   mp,mu,   2, mffi                              ! Moody frict fctr

! CREATE SINGLE ELEMENT MODEL, APPLY B/C & SOLVE
   type,2 $ mat,2 $ real,2
   n,1,0,0,0 $ n,2,lgth,0,0
   e,1,2
/solu
   antype,static
   d,2,press,0 $ f,1,flow,flor8
   solve

! OBTAIN PRESSURE DROP RESULTS
/post1
  *GET,pres1,NODE,1,PRES,
/title,pressure drop is %pres1/1000% KPa vs 2.5 KPa from reference
-----------------------------------------------
```

IV. CONCLUSIONS

These calculations have demonstrated that the G0 magnet cooling system is robust enough to handle the heat loads which could enter the magnet cold mass structure. There is sufficient extra capability to respond to quench transients as well as assist in the completion of the cooldown transient. The thermal-siphon cooling system has been demonstrated to remain stable over a wide range of heating asymmetries.

The ANSYS FLUID66 element has been demonstrated to effectively model natural circulation cooling using two phase helium. However, care must be taken when supplying fluid properties, which are to be supplied on a weight basis. The input listing of table 2 offers an example for benchmarking these calculations.

The cooldown calculations demonstrated that the coolant resources available at the TJNAF could chill the coil below the current sharing temperature within the specified time frame. Additionally, due to the considerable steady state capability of the natural circulation cooling, the final stages of the cooldown will be significantly improved when the transition from forced flow is implemented.

1. S.W. Van Sciver, *Helium Cryogenics*, New York, Plenum Press, 1986

2. X. Huang and S. Van Sciver, "Performance of a venturi flow meter in two-phase helium flow," Cryogenics, Vol. 36, No. 4, 1996.

3. ANSYS Finite element Software, ANSYS, Inc.