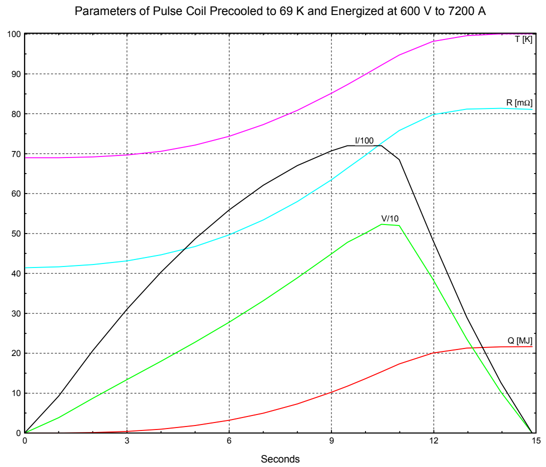
Memo to Bob Weggel, Harold Kirk, George Mulholland, Distribution
From: Peter Titus
Date Oct 17 2002 (revised October25)
Subject: Estimate of cooldown time for LN2 Cooling Mode



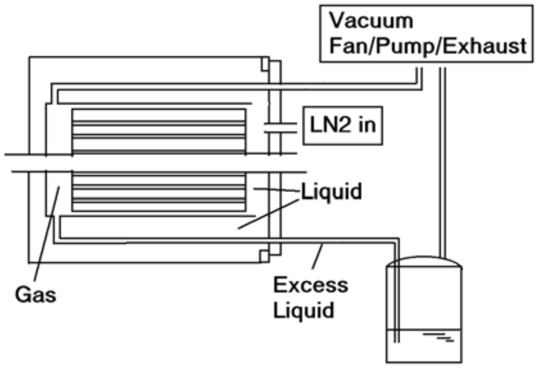
Bob Weggel’s 10-14 analysis of the LN2 magnet operation

For the 100K to 69K cooling in the LN2 mode of operation, a 17 minute cooldown time between shots is possible with some forced circulation through the channels. Without circulation, the cooldown time could be longer than 40 minutes. It all depends on the behavior of the stagnant fluid/gas in the channels. Without clearing the bubbles with some forced circulation, I would envision a “blurp” mode in which a small amount of LN2 enters the channels, .flashes to gas and is expelled at the ends forcing fluid out as well. The channel geometry could be altered, but it will be difficult to obtain something like a pool boiling mode inside the channels which would require vertical free surfaces. An analysis of the coil cooldown with only conduction through the build of the coil yielded a 40 minute cooldown time, but this assumed conduction across the interior channels. If the interior channels act as thermal resistance because they are gas bound, the cooldown could be longer. Bubble clearing is an important issue in superconducting magnets. In MECO we have many flow channels cut into the mandrels in the production solenoid. These are vertically oriented. Channels in the BNL magnet are presently horizontal. In LN2 cooled Tokamaks, cooling is gravity fed with vertical channels or they have forced flow.

One option to get some flow is to pump gas on the exhaust side and cool with a mode where LN2 at the lower part of the magnet boils, and the upper part of the magnet is cooled by gas flow. An analysis of the Nitrogen gas forced flow yielded very long cooldown times. The analysis was similar to the helium cooling analysis with .1kg/sec coolant flow, but the specific heat of N2 gas is a fifth that of Helium gas. This approach doesn’t look viable. The possible “fixes” are:

- Circumferential cuts in the channel ribs might offer some (difficult to quantify) bubble clearing behavior. We can initially block the lower channel inlets so that the LN2 will fill the inlet plenum and LN2 will flow across the top of the magnet and then down through the circumferential cuts. This may be the simplest approach. With this approach the plenum and shroud details would be retained. For subsequent Helium gas operation, the cover of the cryostat would be removed for access to the face of the magnet, and the channel "plugs" removed. With the cover replaced, the magnet would be ready for gaseous He operation.
- Forced flow with a circulator. The existing Helium pump could be used for this? This would potentially yield lower cooldown times than the 17 min quoted above, because true liquid forced flow would be substituted for natural convection.

- Forced flow via pressure differentials is also a possibility. A forced flow concept is presented here The existing drain line would be connected to the downstream side of the plenum to be used to drain LN2 that hasn't been vaporized in the magnet. Fluid level in the upstream side would be mainitained by flow restrictors in the channel inlets



Forced flow Concept

Liquid fills the inlet plenum and passes through the channels forced by a pressure differential between the inlet and outlet sides of the magnet. The pressure differential is maintained by exhaust fans or vacuum pumps. The flow through the channels is needed to clear bubbles. Some LN2 is not converted to gas, and collects on the downstream side of the magnet. This is drained to the dump tank which is used as a phase separator. Ultimately a .2atm pressure is maintained by the vacuum pumps to reach the subcooled temperature of the LN2. Channel flow exiting to the outlet plenum enters as two phase flow. If the dump tank gets filled, the cooling process would be stopped, and the fluid in the dump tank would transferred to the LN2 supply tank by closing valves and pressurizing the dump tank. This process would not carry much more time penalty than the "flush" of Nitrogen that is currently planned. The inventory of LN2 below the drain in the cryostat could be minimized with fillers. A simulation has been done with the transient conduction code previously used for the Helium gas cooling mode. The code was modified to include forced N2 gas cooling, and pool boiling heat transfer coefficients.

Magnet Flow Area Characteristics:

The coolant channel flow area is (.1+.2+.3+.4)+*2*pi*.002= .0126m^2 or about 39 square inches
The wetted perimeter of the channels is (.1+.2+.3+.4)*2*2*pi=12.6 m (ignoring the 2mm ribs)
The channel surface area is 12.6 multiplied by the one meter length of the coil or 12.6m^2
The magnet surface area is .(1+.2*2+.3*2+.4)*2*pi=9.42m^2
The Hydraulic diameter of the channels is 4*.0126/12.6=.004

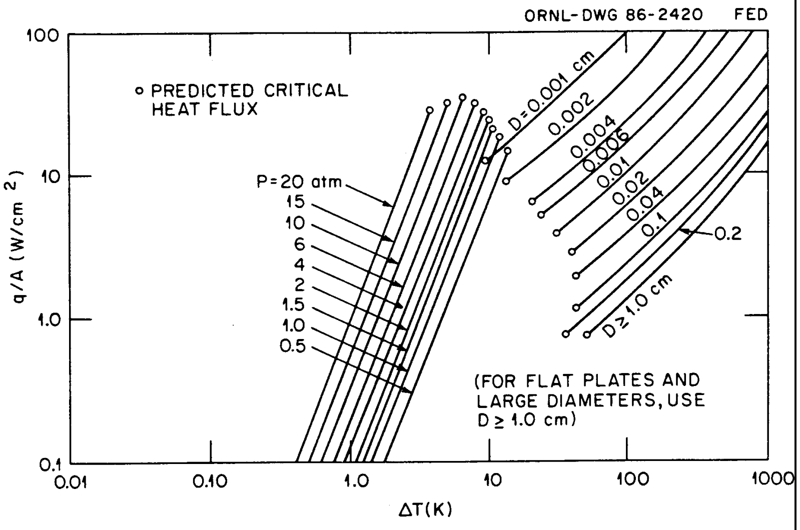


Fig. 4. Nucleate and film pool boiling correlations for nitrogen.

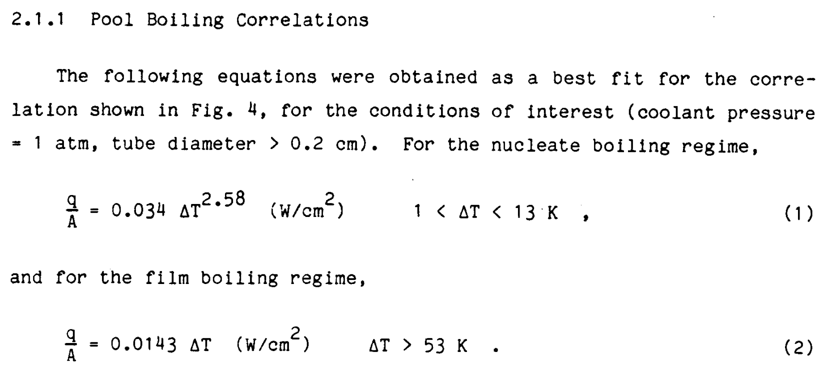
from: ORNL/FEDC-85-10 Dist Category UC20 c,d October 1986

To cool the magnet down from 100 to 69 K, 22 MJ is required. This will be done using 66K subcooled LN2. Approximately, this will vaporize 22e6/199000 = 110 kg of liquid. At 66K, and 1 atm, the specific volume of the gas is .937 M^3/kg. 103.6 m^3 of 66K gas would be produced. If we want to cool down in roughly 20 min, then the flow velocity at the exit of the magnet would be: 103/.0126/(20*60) =6.85 m/sec with a mass flow of 110/(20*60) = .0916 kg/sec. The volume exiting the exhaust is 103/(20*60)=.086 m^3/sec at 66K, and .086*292/66=.38m^3/sec. after heating to room temperature.

The magnet surface area, exclusive of the ends, is 9.42 m^2. The ends are excluded because they will be thermally insulated with the transition filler pieces.

For a 20 minute cooldown, the heat flux will have to be:
22e6/9.42 m^2/1e4/1200=.194 W/cm^2

Using the pool boiling correlations for Nitrogen (the same as G. Mulhulland.) As George points out, The delta Temperature needed to obtain the required heat flux is quite small. Thermal conduction through the winding and insulation needs to be simulated. With LN2 wetting the surface of the magnet, for long conduction paths, the magnet surface may be at the LN2 temperature, making even the small deltaT needed for heat removal unachievable. The conduction/gas flow simulation was modified to incorporate the pool boiling correlations. This is only an approximation inside the channels. Some form of fluid motion will be required to match the convective heat transfer behavior.



2.1.1 Pool Boiling Correlations

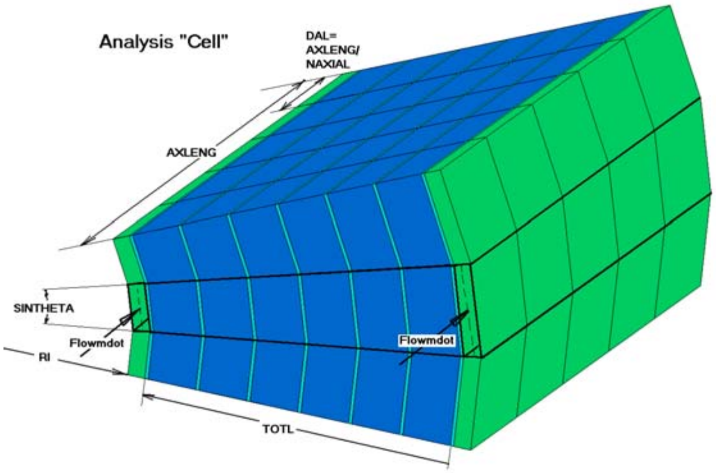
The following equations were obtained as a best fit for the correlation shown in Fig. 4, for the conditions of interest (coolant pressure = 1 atm, tube diameter > 0.2 cm). For the nucleate boiling regime,

$$\frac{q}{A} = 0.034\ \Delta T^{2.58} \quad (\mathrm{W/cm^2}) \qquad 1 < \Delta T < 13\ \mathrm{K}\ , \tag{1}$$

and for the film boiling regime,

$$\frac{q}{A} = 0.0143\ \Delta T \quad (\mathrm{W/cm^2}) \qquad \Delta T > 53\ \mathrm{K}\ . \tag{2}$$

from: ORNL/FEDC-85-10 Dist Category UC20 c,d October 1986. Note that the correlations are not a function of the diameter in the nucleate boiling regime. Equation (1) above is used in the computer simulation. Channel hydraulic diameter was used to estimate the heattransfer coefficient in the film boiling regime.



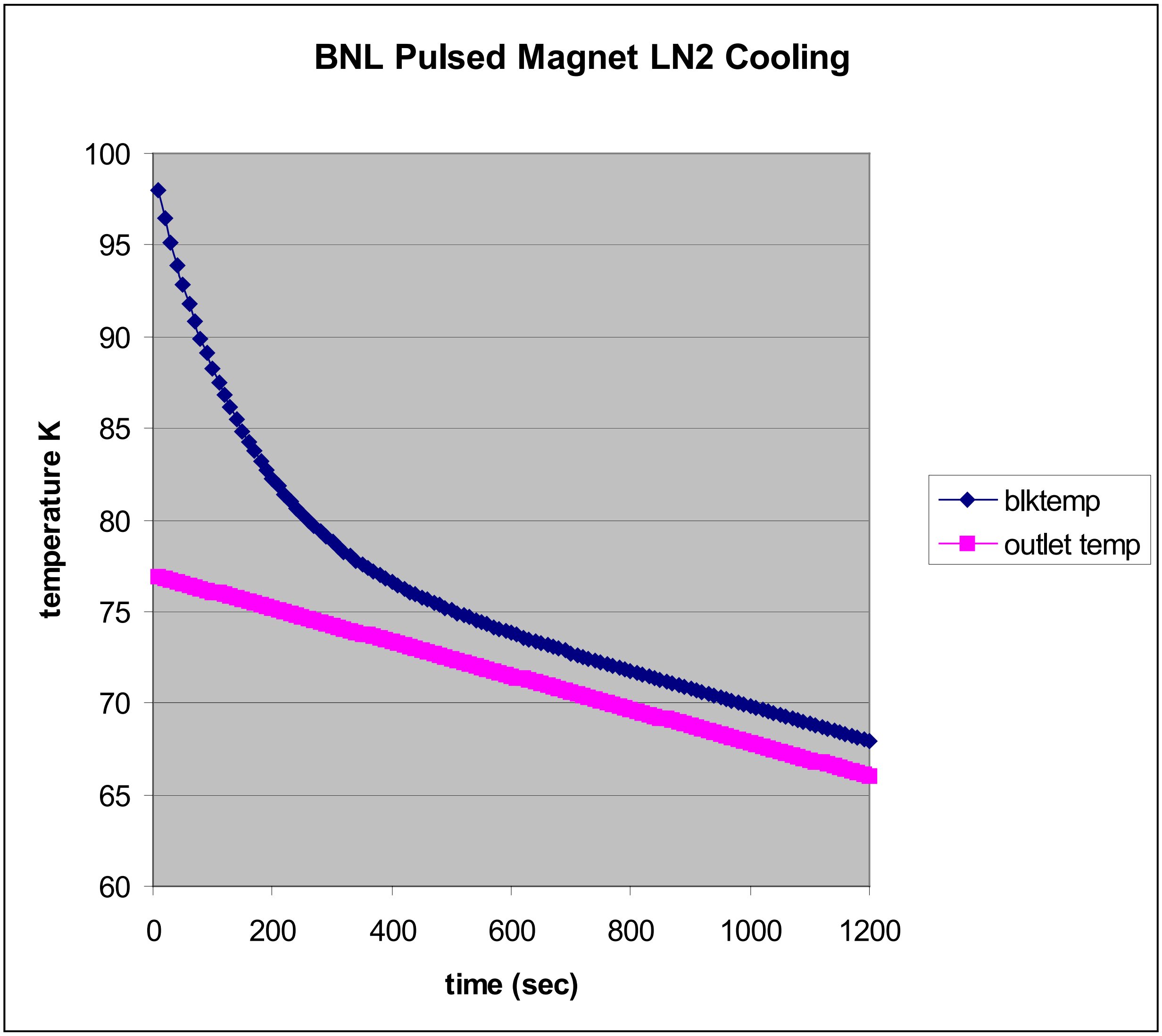
Transient Heat Conduction Model – modified to simulate N2 Gaseous cooling and LN2 cooling

Code Modification for Coolant Temperature Gradual Reduction:

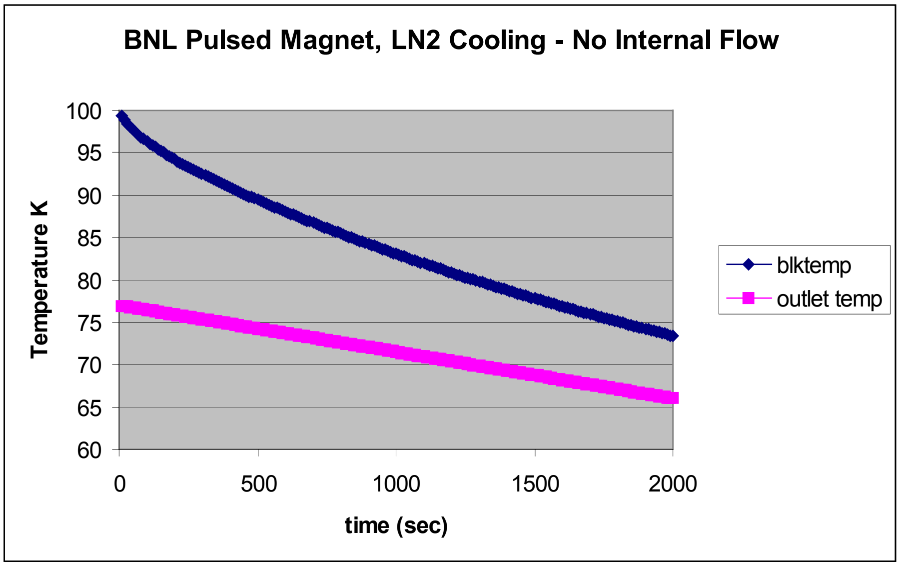
```
if (iwflu.eq.3) then
t(1,k)=77-11.0*etime/tend
t(nleng+2,k)=77-11.0*etime/tend
```

Pool Boiling Heat Transfer Code Modifications

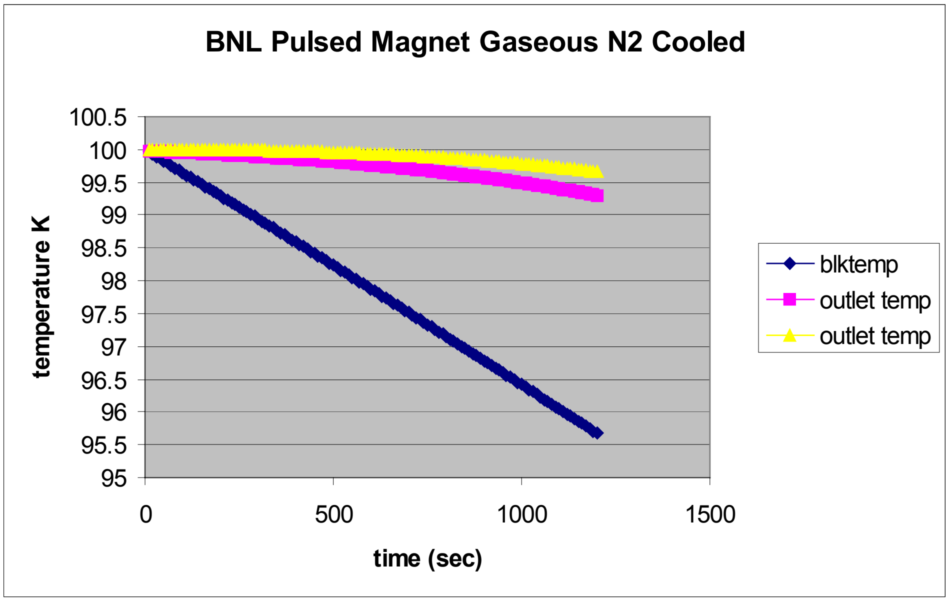
```
if(iwflu.eq.3) then
deltemp=t(2,k)-t(1,k)
if(deltemp.ge.10.0)  HC=10000 ! LN2 film boiling
if(deltemp.lt.10.0)  HC=340*deltemp**1.58
```



Cool down behavior, Fully immersed, but circulating LN2. LN2 pressure gradually reduced from 1atm to .2 atm. Time to 69 degree K bulk temp is about 1000 sec.



LN2 Pool Boiling Cooldown behavior Conduction through the full coil build – Interior channels are ignored. LN2 pressure gradually is reduced from 1atm to .2 atm. If after 2000 sec the LN2 temperature can be maintained at 66K a guestimate for the final coil cooldown to 69K would be about 2500 sec or 42 minutes. – But this assumes conduction across the interior channels



Excessive cooldown times would result with gaseous N2 flow.

Minervini,Antaya,Camille
Circulation is needed. Size the pressure differential based on the assumption of all-gas flow at the exit of the channel.

Alex Zhukovsky
Agrees some circulation is required. – Pointed out "dumb" characterization of wetted channel surface in memo. – This is what is needed. The paragraph was intended to emphasize that conduction through the magnet build could limit the surface heat flux even if the convective coefficient was adequate.

Alex points out that forced convection in two phase flow may not be as good as pool boiling.

Joe Smith:
Agrees circulation is required. Delta P needs to be calculated based on gas flow velocity, ability to sub cool is effected by delta p needed for flow. Believes LN2 circulation pumps should cost of order $1k not $20k – Sites probable cost of LN2 tanker transfer pumps.

Peter Titus:

.1kg/sec is sufficient to cool the magnet in 20 min if all the energy is removed by heat of vaporization

for .1kg/sec at 1 atm. Gaseous N2 simulation predicts 1.3m/s flow velocity, with a pressure drop of 58 pascal or .23 inches of water.