## 4.0 Structural Design Criteria, Materials and Conductor Specifications

Lacking a specific design code jurisdiction, fusion project criteria are used for guidance in coil design [1] The referenced FIRE design document allows the primary membrane stress to be based on the lesser of 2/3 of the Yield Strength (Sy) or ½ of the Ultimate Strength (Su). The ASME Code bases the primary stress on 1/3 ultimate. The fusion project based criteria is based on a distinction between coils that are supported by cases and those that are not. For structural elements ASME -like criteria are adopted with membrane stresses remaining below the maximum allowable stress, Sm, where Sm is the lesser of 2/3*yield or 1/3 ultimate. Bending discontinuity, and secondary stresses are treated in a manner similar to the ASME Code. Guidance for bolting and column buckling is taken from AISC, with average net section bolt stresses kept below 0.6*yield. Yield Strength and Tensile Strength properties are taken at the loaded temperature. However because the cryostat must be safely pressure tested at room temperature, stresses will be checked based on the room temperature properties. The room temperature physicals for the proposed 316 bolts are:

High Strength Bolts Specs:
ASTM A193 Grade B8M - Class 2 - Type 316
for 3/4" diameter and under:
Su = 110,000 psi ,
Sy = 95,000 psi

The cryostats are to be qualified in accordance with ASMEVIII. Qualification of all the weld details, shell thicknesses, nozzle reinforcements, and saddle or support details of these vessels will be done at the final design stage. The conceptual design sizing presented here is intended to ensure adequate space allocation and cold mass performance.

The magnet is to be seismically qualified in accordance with the Uniform Building Code.

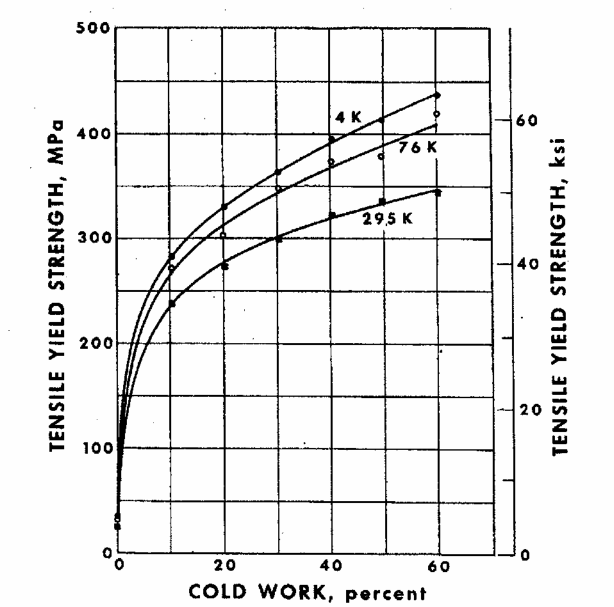



Fig 4-1 NIST Data – Oxygen Free Copper Tensile Properties (4-300K)- C10100 – C10700 Cold Worked

## 4.1 Conductor Properties and Allowables

Mechanical properties for some of structural materials and coil components are given in this section. Tensile yield strength for oxygen free copper is given in Fig. 1 at 4 K, 76 K and at 296 K. Yield and Ultimate strength data is given for several variants of copper at RT and 77K in Table 1.

The inner skin of the bore of the solenoid is allowed to reach the yield stress. - Treating this stress as a bending stress with a 1.5*Sm allowable with Sm based on 2/3 Yield.

The maximum stress in the three segment coil is 166 MPa. Half hard copper should satisfy this requirement at liquid nitrogen temperatures. In order to minimize the difficulties of winding the first layers of the inner solenoid, It is intended that the conductor physical properties and degree of cold work be selected to just satisfy a 166 MPa yield stress.

Table 4-1. Properties of Variants of Copper

| Variant | Yield Mpa at RT | Yield Mpa at 77 K | Ult., Mpa at RT | Ult, Mpa at 77K |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| C10100/C10700 80%CW | 380 | | 420 | 500 |
| C10100 Becker/C-Mod 60%CW | 308 | 373 | 350 | 474 |

Table 4-2 Interpolated values:, Work hardened copper-, OFHC c10100 60% red

| temp deg k | 77 | 90 | 100 | 125 | 150 | 200 | 250 | 275 | 292 |
|---|---|---|---|---|---|---|---|---|---|
| yield | 374 | 369. | 365. | 356. | 347. | 328. | 317. | 312. | 308. |
| ultimate | 476. | 466. | 458. | 439. | 420. | 383. | 365. | 356. | 350. |

The conductor is specified as half hard in the spec. Everson has purchased ¼ hard conductor to ease the bending operation, with the expectation that the cold work associated with the forming process will produce an adequate yield. From Table 4-3, ¼ hard copper would have a yield of 30 ksi or 207 MPa. From Figure 4-1 this would correspond to cold work of about 15%. The bending operation would introduce an additional 6% (see section 4.4) Hardness is assumed to correlate with %cold work. Figure 4-1 plots yield as a function of cold work. Full hard copper would have a yield of about 350 MPa at 77°K, and an ultimate of about 450 MPa which gives a primary membrane allowable (lesser of 2/3Sy or 1/2Su for externally supported coils) of about 200 MPa, At 4°K 30%CW reaches these levels.

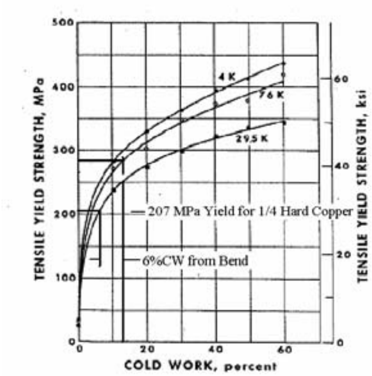



Figure 4.1 Marked-up with Expected Yields. For Segment 1 ID with CW at 100 K, about 270 MPa would be expected

Table 4-3 Room Temperature Properties of Copper, C10200 (OFHC)

| Standard | Former | Yield Min | Yield Max | Tensile Min | Tensile Max | Elong % | Rockwell F |
|---|---|---|---|---|---|---|---|
| O25 | Hot Rolled-Annealed | 11 ksi (2) 76 MPa | | 34 ksi (2) 234 MPa(2) | | 45 | |
| H00 | Eighth Hard | 28 ksi (2) 193 | | 36 ksi (2) 248 MPa (2) | | 30 | 54-82 (1) 60 (2) |
| H01 | Quarter Hard | 30 ksi (2) 207 | | 38 ksi (2) 262 MPa (2) | 25 | 25 | 60-84 (1) 70(2) |
| H02 | Half Hard | 36 ksi (2) 248 MPa (2) | | 42 ksi (2) 290 MPa (2) | | 14 | 77-89 (1) 84(2) |
| H03 | ¾ Hard | | | | | | 82-91 (1) 85(2) |
| H04 | Hard | 40 ksi (2) 276 MPa (2) | | 45 ksi (2) 310 MPa (2) | | 6 to 20 | 86-93 (1) 87 (2) |
| H06 | Extra Hard | | | | | | 88-95 (1) |
| H08 | Spring | 50 ksi (2) 345 MPa (2) | | 55 ksi (2) 379 MPa (2) | | 4 | 90-97 (1) |

(1) ASTM B152
(2) Copper Development Association Web Page www.copper.org flat form

Table 4-4 Room Temperature Properties of Copper, C10100 (OFHC) ( Identical to C10200)

| Standard | Former | Yield Min | Yield Max | Tensile Min | Tensile Max | Elong % | Rockwell F |
|---|---|---|---|---|---|---|---|
| O25 | Hot Rolled-Annealed | 11 ksi (2)<br>76 MPa | | 34 ksi (2)<br>234 MPa (2) | | 45 | |
| H00 | Eighth Hard | 28 ksi (2)<br>193 | | 36 ksi (2)<br>248 MPa (2) | 30 | 30 | 54-82 (1)<br>60 (2) |
| H01 | Quarter Hard | 30 ksi (2)<br>207 | | 38 (2)<br>262 MPa (2) | 25 | 25 to 35 | 60-84 (1) |
| H02 | Half Hard | 36 ksi (2)<br>248 | | 42 ksi (2)<br>290 MPa (2) | | 14 | 77-89 (1) |
| H03 | ¾ Hard | | | | | | 82-91 (1) |
| H04 | Hard | 40 ksi (2)<br>276 MPa (2) | | 45 ksi (2)<br>310 MPa (2) | | 6 to 20 | 86-93 (1)<br>87 (2) |
| H06 | Extra Hard | | | | | | 88-95 (1) |
| H08 | Spring | 50 ksi (2)<br>345 MPa (2) | | 55 ksi (2)<br>379 MPa (2) | | 4 | 90-97 (1) |

(1) ASTM B152
(2) Copper Development Association Web Page www.copper.org flat form

It would be wise to do a tension test of the full copper channel section prior to soldering the superconductor. Surface hardness may not be a reliable indicator of the full section strength.

Typical values of mechanical strength for several different types of composite insulating materials is given in Table 2.

## 4.2 Insulation Allowable

Warp and Fill tensile allowable with a Factor of Safety F.S.=3 or 1/3 ultimate is 167 Mpa. Note that for tension normal to the reinforcement, there is no capacity listed. Normally primary tension in this direction is not allowed. Secondary or strain controlled tensile stresses are nearly unavoidable in bonded conductor arrays. Small cracks often develop near corners, and multi-layered insulations are used to limit the likelihood of through cracks. For MECO magnets, Kapton tape is specified to mitigate the effects of these cracks on electrical insulating integrity and this has the effect of reducing the tensile bond strength. It also reduces the winding pack modulus in the direction normal to the Kapton tape. The interplay between modulus and secondary displacement controlled strains will be resolved with measured properties and strengths of a representative impregnated array of conductors.

Table 4-5. Insulating Material Strengths (Ref 27)

| | Mpa @4°K | Mpa @77°K | Mpa @292°K |
|---|---|---|---|
| Comp.Strength Normal to Fiber | | | |
| G-10CR | 749(Ref 4) | 693(Ref 4) | 420 (Ref 4) |
| G-11CR | 776(Ref 4) | 799(Ref 4)<br>900(Ref 7) | 461 (Ref 4) |
| CTD 101K AR irradiated | 1260 (ave) (Ref 5) | | |
| CTD-112P irradiated | 1200 (ave) (Ref 5) | 1150(Ref 5 p 47) | |
| Polyimide/S2 Glass Laminate | | | 1033 Mpa, Ref [6] |

| | | | |
|---|---|---|---|
| Tensile Strength (Warp) | | | |
| G-10CR | 862 (Ref 4) | 825(Ref 4) | 415 (Ref 4) |
| G-11CR | 872(Ref 4) | 827(Ref 4) | 469 (Ref 4) |
| Tensile Strength (Fill) | | | |
| G-10CR | 496(Ref 4) | 459(Ref 4) | 257 (Ref 4) |
| G-11CR | 553(Ref 4) | 580(Ref 4) | 329(Ref 4) |

Tensile Strain Allowable Normal to Plane

No primary tensile strain is allowed in the direction normal to the adhesive bonds between metal and composite. Secondary strain will be limited to 1/5 of the ultimate tensile strain. In the absence of specific data, the allowable working tensile strain is 0.02% in the insulation adjacent to the bond.

Table 3 provides modulus data for G-10 composite materials.

Table 4-6. Modulus of Elasticity for G-10 at several temperatures.

| Temp Deg. K | G-10 Warp/Fill Gpa | G-10 Normal Gpa | Epoxy Only Gpa |
|---|---|---|---|
| 295 | 27.8 | 14.0 | 3.81 |
| 250 | 29.5 | 16.5 | 5.25 |
| 200 | 31.3 | 18.8 | 6.69 |
| 150 | 32.5 | 20.5 | 7.84 |
| 100 | 33.0 | 21.5 | 8.54 |
| 76 | 33.5 | 21.8 | 8.68 |

### 4.3 Stainless Steel Properties and Allowable

Additional properties for materials used in the BNL magnet system conceptual design are provided in Tables 4-7 to 4-10.

Table 4-7. Tensile Properties for Stainless Steels and Aluminum

| Material | Yield 4 deg K (MPA) | Ultimate 4 deg K, (Mpa) | Yield, 80 deg. K (Mpa) | Ultimate, 80 deg. K (Mpa) | Yield, 292 deg K (Mpa) | Ultimate, 292 deg K (Mpa) |
|---|---|---|---|---|---|---|
| 316 LN SST | 992 | 1379 | | | 275.8] | 613] |
| 316 LN SST Weld | 724 | 1110 | | | 324 | 482 |
| | | | | | | |
| 304 SST 50% CW | | | 1344 (195 ksi) | 1669 | 1089 | 1241 |
| 304 Stainless Steel (Bar,annealed) | | | 282 (40.9ksi) | 1522 | 234 | 640 |
| Aluminum | 362(20K | 496(20K) | 275.8 | | 275 Mpa | 310 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 6061T6 | ) | | | | 40ksi | Mpa 45ksi |
| Alum 6061 Weld | 259(4K) | 339(4K) | | | | |

Table 4-8. Coil Structure Room Temperature (292 K) Maximum Allowable Stresses, Sm = lesser of 1/3 ultimate or 2/3 yield, and bending allowable=1.5*Sm

| Material | Sm | 1.5Sm |
|---|---|---|
| 316 LN SST | 183Mpa (26.6 ksi) | 275Mpa(40ksi) |
| 316 LN SST weld | 160MPa(23.2ksi) | 241MPa(35ksi) |
| 304 SST 50% CW | | |
| 304 Stainless Steel (Bar,annealed) | 156MPa(22.6ksi) | 234 MPa (33.9ksi) |
| Aluminum 6061T6 | | |

Table 4-9. Coil Structure Cryogenic (80 K) Maximum Allowable Stresses, Sm = lesser of 1/3 ultimate or 2/3 yield, and bending allowable=1.5*Sm

| Material | Sm | 1.5Sm |
|---|---|---|
| 304 SST 50% CW | 556 Mpa (80 ksi) | 834 (120 ksi) |
| 304 Stainless Steel (Bar,annealed) | 188MPa (27ksi) | 281 MPa (40.9ksi) |

Table 4-10. Coil Structure Cryogenic (4 K) Maximum Allowable Stresses, Sm = lesser of 1/3 ultimate or 2/3 yield, and bending allowable=1.5*Sm

| Material | Sm | 1.5Sm |
|---|---|---|
| 316 LN SST | 459.6 Mpa (66.7 ksi) | 689 (100 ksi) |
| 316 LN SST Weld | 366MPa (53.2ksi) | 550 MPa (79.7ksi) |
| Alum 6061T6 | 165 MPa | 248 MPa |
| Alum 6061T6 Weld | 113 MPa | 169.5 MPa |

Inconel 718 was used in the C-Mod Drawbars and oblong Pins. Physical properties were measured from samples of the forgings used for these drawbars. This data is summarized in Table 8 . These values are representative of strengths expected for the 718 bolting specified for MECO.

Table 4-11. Inconel 718 Tensile data (hardening for 1 hr. at the most favorable temp, either 1750 or 1950deg F from ref[3])

| | 4 in. Bar | 5/8in Bar | 5/8in. Bar |
|---|---|---|---|
| | 292 degK | 292K | 77degK |
| Yield | 165ksi | 180 ksi | 173ksi |
| Ultimate | 195ksi | 208 ksi | 237ksi |
| Modulus of Elasticity | 29.8e6 | 29.8e6psi | 31.e6 psi |
| Density | .296 lb/in^3 | .296 lb/in^3 | .296 lb/in^3 |

Used as bolting, 718 would have a 0.6*173=100 ksi maximum allowable operating stress

## 4.4 Conductor and Insulation systems design and packing fraction

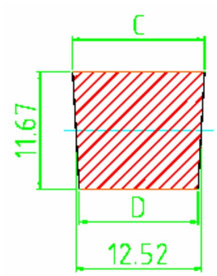
### Conductor Keystoning:

H/(2*r)= .012/.1/2=6% (elastic strain) For Plastic bending, (poisson=.5) the Keystoning contraction is 3%

This is a function of radius. Three Keystone specs are suggested. The keystone geometry for the first segment should be .012/.15/2*.5=2%

The worst case loss in packing fraction is 1%, Average loss is .5%

Keystone allowances in outer two segments are 1.2%, and .86%. Packing fraction losses in outer two segments are .15%, and .007%

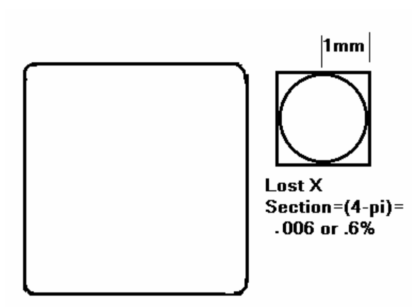



| A | C | D |
|---|---|---|
| 1-st Magnet | 12.65 | 12.39 |
| 2-nd Magnet | 12.62 | 12.42 |
| 3-rd Magnet | 12.57 | 12.47 |

Keystone specifications from MIT-BNL-003.

### Effect of Corner Radius:

Whole Magnet loss of .2%+Corner Loss of .6%=.8%



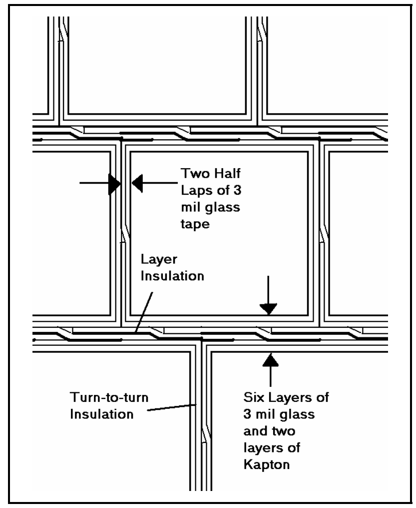

Corner Radius

During a March 9 2004 visit to Everson, This preliminary test bend test was shown, and Everson indicated that the keystoning was “about what was in the spec.”

### Insulation System:

In the axial or “Z” direction, there are four thicknesses of 3 mil glass tape between each conductor. In the radial direction, there are an additional two layers of glass tape, interleaved with Kapton tape.

```
_ data 1,.15,0,.098,1.0,16,16
_ data 2,.2,0,.002,1.0,1,16
_ data 3,.25,0,.098,1.0,16,16
_ data 4,.3,0,.002,1.0,1,16
_ data 5,.35,0,.098,1.0,16,16
_ read n,r,z,dr,dz,nx,ny
_ print "current Densities"
_ print 4.5e6/dr/dz
_ print 4.5e6/dr/dz/100/100
_ clear
let ntpc=624
 print "conductor dimensions"
 let rdim=(dr-(.003*2+.001*2)/39.37)/8-.003*4/39.37
 let zdim=dz/(ntpc/8)-.003*4/39.37
 print "radial dim";rdim;"m";rdim*39.37;"in"
 print "Axial dim";zdim;"m";zdim*39.37;"in"
 print "packing fraction=";ntpc*rdim*zdim/dr/dz
 print
 print "conductor dimensions with 2 millimeter channel tolerance"
 let dr=dr-.002
 let rdim=(dr-(.003*2+.001*2)/39.37)/8-.003*4/39.37
 let zdim=dz/(ntpc/8)-.003*4/39.37
 print "radial dim";rdim;"m";rdim*39.37;"in"
 print "Axial dim";zdim;"m";zdim*39.37;"in"
 print "packing fraction=";ntpc*rdim*zdim/(dr+.002)/dz
 end
```




```
conductor dimensions
radial dim 1.1919799e-2 m .4692825 in
Axial dim 1.2515712e-2 m .49274359 in
packing fraction= .94991124

conductor dimensions with 2 millimeter channel tolerance
radial dim 1.1669799e-2 m .45944 in
Axial dim 1.2515712e-2 m .49274359 in
packing fraction= .92998827
```

These packing fractions are based on the coil winding pack and exclude the channel. If the 2 mm channel is included, the packing fraction drops to .911.