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Final Report: FRC Flux Conserver Cooling

The current generation PFRC has a very short plasma containment period due to the use of solid copper for the Flux Conservers. Copper, while being a good conductor, still has some resistance to passing the electrical currents necessary to induce the magnetic fields which the FRC relies on to keep the plasma contained. Due to the nature of the copper and the variables in place with the FRC, the containment time of the current generation FRC is in the millisecond range. This limits the types of experiments which can be run and the data which can be retrieved from the FRC.

The next generation PFRC will be a scaled up version of the current FRC in several aspects, including the plasma containment. The goal for containment time is for at least an order of magnitude increase in containment time from the 10 ms range to 100 ms range. This requires the use of superconducting materials to keep the magnetic containment fields intact for that period of time. Unfortunately, the superconductors which are feasible for use in the FRC flux conservers require cryogenic temperatures to operate. The added power and duration of the next gen FRC will also add a considerable heat load onto the FRC which must be absorbed. The heat load on the Flux Conservers in the next generation PFRC needs to be quantified to determine the feasibility of using a relatively simple cooling system to maintain cryogenic temperatures for the superconducting tape embedded in the Conservers.

The calculation used to determine the how much thermal energy will be received by each FC is a conservative estimate based on the expected power of the new FRC. Following the calculation below, if the known maximum power is 200 KW, and it is expected that only 120 KW is actually absorbed by the plasma, then a starting point for further calculation exists.

In its initial configuration the machine will have 8 FCs. Containment is set at 25%, but it is expected to be significantly better than that value, meaning that much less than 25% of the energy in the plasma is expected to transfer to the FCs due to thermal energy.

The final power expected to be experienced by each of the FC's becomes 3.75 KW, as seen below. With an initial shot length of .1 sec, this leads to 375 J of thermal energy per shot which must be dealt with.

Item/Calculation	Result
Power Per FC: 200 KW max power, 120 KW absorbed by plasma, 25% containment, 8 FC's	3.75 KW
Initial shot time	.1 sec
Energy/FC/shot	375 J
Tantulum Cladding total mass	209.8 grams
Tantulum Specific Heat	.088 j/GK @80K
Tantulum Temp Rise/shot (Energy/shot/mass*specific heat)	18.3K/shot
Stainless Steel	98.7g
SS Temp Rise /shot	12.7K/shot
Graphite/CFC Estimated Volume: (7cm avg radius, 2 mm thickness, *3)	26.4 cm^3
Graphite mass (average 2.09-2.21 g/cm^3)	56.5g
Carbon Fiber Composite mass (Note this varies	

depending on what matrix/density of fibers are used)	
Graphite Specific Heat	~.7 J/gK
Graphite Temp Rise/shot	9.5 K/shot
CFC Specific Heat	
CFC Temp Rise/Shot	

Bernoulli's equation can be corrected for Major losses (friction caused by fluid no-slip condition) and minor losses (pipe entrance and bending effects). The equation below takes both major and Minor losses into account given that the perquisites of Bernoulli's equation are satisfied:

$$P_1 + \rho g z_1 + \frac{\rho V_1^2}{2} = P_2 + \rho g z_2 + \frac{\rho V_2^2}{2} + \frac{4\rho f L V^2}{2d} + F V_2^2$$

The final term on the right hand side of the equation is the minor loss component due to entrance effects, with "F" equal to the value presented in the chart above. The 2^{nd} to last term on the right hand side is the major loss component, which relies on the friction factor "f". This factor is calculated from the Moody diagram and is dependent on fluid velocity (or Reynolds #) and pipe surface roughness. Using an iterative process it is possible to get the proper friction factors and pipe flow velocities.

The pipe flow slows as the level of fluid in the LN2 tank drops and there is less potential energy available for conversion. If the LN2 were pressurized and oriented such that there was no Potential energy change, the flow rate could be made constant if the pressure was adjusted to be kept constant.

Fluid Flow Properties	

Calculation of Initial Pipe Velocity assuming: 1.25 m tall, 1 m diameter cylinder 1 m above FRC filled with LN2. Using Bernoulli's equation with major and minor losses and assuming Top of tank open to atmosphere, and exit of LN2 open to atmosphere	
Total Length of piping	5m
Initial Friction Factor	.0237
Minor Loss Correction factor for 2 90^o Pipe entrance/exits	.5+.5=1
Initial Velocity	1.51 m/sec
Velocity with Tank ½ full	1.33 m/sec
Velocity at Tank Empty	.97 m/sec
Estimated time to Empty Tank (.25" diameter pipe, average velocity of 1.25 m/sec)	6.88 Hours
Initial Re	37614
Final Re	24120

Cooling Calculations	
Turbulent Flow Cooling Capacity	
Established Turbulent Pipe Flow Nusselt Formula (eq. 4.45,Mills)	$Nu = .023Re_D^{.8}Pr^{.4}$
Re	37614

Prandlt Number	2.43 @77K
Nu	150.1
Convective Cooling Coeffecient (W/m^2K) $h = \frac{Nu*k}{D}$ Where k is the conductivity of the fluid, D is pipe diameter	3237.4 W/m^2K
Cooling Power given .25" pipe half buried in FC (Surface area = .5*2*π*D*L)	64 W/K
Cooling Power (minimum Re=24120)	45.5 W/K

The above calculations were based on turbulent flow in a smooth pipe, which accurately models the experimental set up as long as the flow is separated from any entry effects. The cooling power is sufficient to cool the experimental set up.