CONF-860652--7

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MASTER

LIQUID NITROGEN COOLING CONSIDERATIONS OF THE COMPACT IGNITION TOKAMAK*

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CONF-860652--7

DE86 012620

ABSTRACT

An analytical procedure was developed to estimate the cooldown time between pulses of the Compact Ignition Tokamak (CIT) utilizing liquid nitrogen. Fairly good agreement was obtained between the analysis results and those measured in the early fusion experimental devices. The cooldown time between pulses in the CIT is controlled by the energy disposition in the inner leg of the TF coil. A cooldown time of less than one hour is feasible for the CIT if fins are used in the cooling channels. An R&D experimental program is proposed to determine the actual cooldown time between pulses since this would be considered an issue in the conceptual design of the CIT.

INTRODUCTION

During the past year, preconceptual design studies have been made on four different concepts for the Compact Ignition Tokamak (CIT) devices to be built in the United States. All of these concepts utilize copper magnets for toroidal field (TF) and poloidal field (PF) coils. An Ignitor-type device has been chosen as the baseline for further conceptual design studies. It is proposed to operate this machine at around liquid-nitrogen temperature to minimize the power requirements for the magnets. The temperature of the magnet systems is allowed to increase during the operating pulse, and cooldown time is initiated at the end of the pulse. One of the design requirements is for cooldown time between full-power pulses to be less than one hour in order to provide the capability for some reasonable number of operating pulses per day. A number of devices such as Alcator-A and C have operated around liquid-nitrogen temperature, but these machines have much shorter pulses and produce no neutrons.² Therefore, the temperature rise

during each pulse is modest and the cooldown is less a problem than an ignited device with burn times of several seconds.

The purpose of this work is to develop a simple model to estimate the cooldown rate of a magnet with various cooling surface configurations. This will help in proposing an optimum configuration which would minimize the cooling time between pulses. Since it is anticipated that TF coil cooling would take longer than PF coils due to higher current density and neutron heating, the analysis has been concentrated on TF coils. The material of the inner leg of the TF coil is composed of 25% Inconel 625, 65% copper alloy (CDA-102), and 10% insulation. The outer leg material is copper CDA-102 with the necessary insulation. The pulse length is about 9.75 s with 3.75 s flat top. Based on the Kaye-Goldston (L-mode) confinement model, the average neutron wall loading is about 7.8 MW/m^2 during operation. Table 1 shows the temperatures and energy deposition in the various sections of the TF and OH coils at the end of the pulse.³ The highest temperature occurs in the inner leg coil, as shown in Table 1. Therefore, the study has been concentrated on the inner leg to minimize the cooldown time between pulses. The CIT horizontal and vertical build is shown in Fig. 1.

Four cooling configuration options have been chosen for cooling the inner leg:

1. Cooling channel at the plasma side of the TF coil inner leg.
2. Cooling channel at the OH side of the TF coil inner leg.
3. Cooling channel inside the TF coil. (Only 5% of available cross-section area is chosen for coolant passage so as not to significantly degrade the load-carrying capability of the inner leg.)

* Research sponsored by the office of Fusion Energy, U.S. Department of Energy, under Contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

Table 1. Temperatures and energy deposition in the TF and OH coils at the end of pulse
(pulse length = 9.75 s; Flat top = 3.75 s)^a

TF coil			OH coil		
Region	Temp. (K)	Energy deposition (MJ)	Region	Temp. (K) (divertor case)	Energy deposition (MJ)
Inboard	332 ^b -342 ^c	750	OH2 ^d	317	460
Outboard	100-125	530	OH1 ^d	222	146
Crown	~170				

^a Neutron wall loading is 7.8 MW/m².

^b Midplane, OH side.

^c Midplane, plasma side.

^d See Fig. G-1 of "Conceptual Design Report" (Ref. 1).

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(ALL DIMENSIONS IN mm)

Fig. 1. CIT horizontal and vertical build.

DISCLAIMER

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4. Cooling only through conduction to the rest of the TF coil.

For the first three options, it is proposed to introduce liquid nitrogen from the bottom of the TF coil to produce a vertical upward flow of gas.

The cooling method proposed for the outer leg uses channels either inside or on the sides of the TF coils, with coolant flow from the bottom to the top of the TF coil.

METHOD OF ANALYSIS

The mechanism of heat transfer between a surface and liquid nitrogen depends on many parameters. It is difficult to obtain an analytical solution or correlation for heat transfer in cryogenic liquids, that could take into account all the prevailing factors. Heat transfer to the coolant is both through the liquid and vapor. Boiling is the mechanism responsible for heat transfer through the liquid. The heat transfer through the vapor is assumed to take place by forced convection. The inner leg of the TF coil could also lose heat to the colder outer leg through conduction.

Since the initial temperature of the magnet is much higher than the saturated temperature of liquid nitrogen, film boiling predominates in the early stages of the cooling. It is followed by nucleate boiling as the surface temperature drops. Therefore, the analysis should be based upon a correlation for film and nucleate boiling in a vertical, upward forced convection flow channel. Due to the unavailability of this information, another correlation based on nitrogen nucleate and film pool boiling was utilized.⁴ This is shown in Fig. 2, where the heat transfer rate is plotted vs the temperature difference between the wall and saturated nitrogen (ΔT) for various coolant pressures and tube diameters. This correlation is assumed to approximate the flow condition in the magnet cooling channel since the liquid velocity is rather low and the liquid subcool level is virtually zero in the nucleate boiling regime. However, the critical heat flux in vertical, upward forced flow was calculated,⁵ and the results indicate that this value is about eight times higher than the critical heat flux for nucleate pool boiling at atmospheric pressure. This suggests that the pool-boiling approach would be a conservative approximation of the real flow condition. The actual cooldown time would, therefore, be shorter than what will be obtained from this analysis.

The analysis shows that the cooldown time is proportional to mass/surface area ratio. The detail of the analysis is reported in Ref. 6. Therefore, a general cooldown curve vs cooldown time would be constructed if initial magnet

temperature is known. Such a generalized curve is constructed for a pure copper magnet at the initial magnet temperature of 300 K and is shown in Fig. 3 for both average and pessimistic approaches. The average approach is to interpolate the heat transfer rate linearly in the transition region. The pessimistic approach is to extrapolate the film pool-boiling regime into the transition region. This figure could also be applied to the TF coil made of the components mentioned in the introduction. This is due to the fact that C_p of the TF coil composites is not very much different than that of pure copper. The cooldown time for the pessimistic approach is 50% higher than for the average approach. Schultz⁷ performed a similar analysis and his result is also shown in Fig. 3. The comparison shows an excellent agreement between the results. It is interesting to note that rapid cooldown is feasible when initial surface temperature is 110 K or less, which corresponds to nucleate boiling. As surface temperature rises above 110 K, not only does the heat transfer coefficient drop, but also the specific heat of copper increases, both of which tend to increase the cooling down time.

Fig. 2. Predictive nucleate and film pool-boiling correlations for nitrogen

The analysis was also extended for a cooling surface with 1-mm glass insulation. The result is also shown in Fig. 3, where the cooldown time is about 50% higher than the case when the surface is not insulated. The insulation causes the nucleate boiling regime, which corresponds to rapid cooldown, to occur at higher temperatures, depending on the insulation thickness and its thermal conductivity. On the other hand, as Fig. 3 shows, the cooldown from about 100 to 80 K is relatively slow due to very small temperature differences, thus a very small heat transfer rate between the wall and the coolant (across the insulation).

The result of this simple model was compared with some available experimental data on Alcator-A and C.² The comparison is shown in Table 2. The results indicate that the agreement between the model and the experimental data is fairly good in view of the simplicity of the model.

Figure 4 presents the universal cooldown time, TAM (Time - Area/Mass) for various initial cooldown temperatures. The final cooldown temperature is 80 K.

Fig. 3. Generalized cooldown time for initial temperature of 300 K.

Table 2. Comparison of model with experimental data on cooling time with LN₂

	Mass (tonne)	Cooling surface area (m ²)	Cooling time (h)	
			Model ^a	Experiment
Alcator-A	5.5	1.73	3.4	2-3
Alcator-C ^b	18	5.5	5.8	5.2

^aThe model is for bare copper surface without any insulation.

^bActual liquid nitrogen consumption is 6.2 tonne for cooling down to 80 K. The model predicts 6.6 tonne, assuming only heat of vaporization contributes to the cooling.

Fig. 4. Universal cooldown time vs initial cooldown temperature.

RESULTS

The shortest cooling time corresponds to the first cooling option in which the coolant channel is at the plasma side of the TF coil inner leg. This is due to the larger available cooling surface area. However, this cooling method is not recommended due to the problem arising from the design of the inlet and outlet of the coolant channel where the coolant should be sealed from the plasma.

The cooldown time for the fourth option is estimated to be about 6 h, assuming the temperature of the outboard leg drops instantly from the initial value of 100 K to 80 K. This cooldown time could be reduced to around 2 h if the outboard leg could be cooled down to 20 K. In this case, coolants such as He or Ne should be considered.

The* cooldown time results down to 80 K for the second and third options are shown in Table 3. These results are for a 1-atm pressure liquid nitrogen flowing from the bottom of the TF coil. The results indicate that the second-option cooldown time is slightly less than the third option. At the same time, the second cooling option is simpler and less expensive to build. This option also provides a means to cool down the OH coil by inserting a solid insulator in the middle of the channel to insulate the TF and OH coils from each other. The appropriate channel width is estimated to be 2 cm, which could cool both TF inner leg and OH coils. The above results correspond to the assumption that only the heat of vaporization of nitrogen is responsible for removal of energy.

An estimate of convective cooling contribution has been made, and the result indicates that it could account for approximately 15% of the total energy removal. In other words, the cooling time drops to 0.85 h from 1 h, as shown in Table 3. This should be verified experimentally.

Table 3. Cooldown time for cooling options No. 2 and 3 of the TF coil inner leg.

	Cooling option 2	Cooling option 3
Cooling surface area, m ² (based on 1 m height)	3.35	3.1
Cooling time, h ^a (no conduction to outboard leg)	1.4	1.5
Cooling time, h (with conduction to outer leg)	1.0	1.1

^aThese results are for bare copper. The values will increase by 50% if a surface insulation with 0.04 thickness is used.

The pressure drops in the cooling channel have been analyzed and are fully discussed in Ref. 6. The results indicate that the maximum total pressure drop is about 0.1 atm, which is easily manageable.

DISCUSSION OF RESULTS

The cooldown time could be reduced by starting the cooldown process with the coolant pressure higher than 1 atm. The cooldown continues at the pressure level up to the point where the critical heat flux limit is reached. The coolant pressure is then reduced in a fashion so that the cooldown would occur at critical heat flux paths (maximum heat flux) down to 1 atm pressure (Fig. 2). For example, the cooldown process could start with 10 atm coolant pressure and continue until the surface temperature drops to 110 K, which is the critical heat flux point corresponding to 10-atm coolant pressure. At this time, the coolant pressure should drop from 10 to 1 atm in a way that the cooldown would occur at the maximum heat fluxes. The surface temperature would drop from 110 K to 90 K in this process. The cooldown from 90 K down to 80 K would occur at 1-atm coolant pressure. An estimate of the cooldown time for this process has been made. The result indicates that a cooldown time reduction of 17% is feasible compared with the case in which the cooldown pressure occurs at a constant 1-atm coolant pressure. This could reduce the cooldown time to approximately 0.7 h. One drawback of this method is that the TF coil may not be able to accommodate higher coolant pressure. This should be investigated further. Another disadvantage would be to reduce the coolant pressure at specific surface

temperatures, which may involve some kind of controlling technique.

Another way to reduce the cooldown time is through increasing the coolant surface area by making machine-cut slits in the nose and in the vertical direction of the TF coil. The center-line slits could be placed 4 mm apart with 2 mm depth. This configuration increases the cooling surface area by a factor of 2. The slits may be treated as fins. The fin effectiveness depends on the temperature difference between the cooling surface and the coolant. A simple analysis shows that the fin effectiveness is about 90%. Therefore, a 90% drop in the cooldown time may be a good estimate for the fin effect. This could reduce the cooldown time to approximately 0.5 h at 1-atm coolant pressure operation. The nose of each TF coil could be undercut at the edges so there will not be any wedging forces acting on the fins. There will not be any electromagnetic forces which could deform the fins during machine operation since there is no bucking.

CONCLUSION

Preliminary results indicate that a cooldown time of less than 1 h is feasible. Thus, limiting the number of pulses to about eight per day. A shorter cooldown time is feasible by increasing the cooling surface area by either making machine-cut fins or increasing the inner leg radial dimension. The latter method will directly impact the capital cost of the device and may not be as effective as the former method. The level of thermal stresses developed due to the rapid temperature drop of the bottom part of the TF coil should also be investigated. An alternative cooling method should be sought if excessive thermal stress levels are found. One approach would be to use helium gas as a coolant in a closed loop slowly cooled down to liquid-nitrogen temperature by heat exchanger equipment. This system would have the added advantage of not releasing radioactive gas to the environment.

An experimental R&D program is proposed to measure the actual cooldown time, since this may be a critical issue in the CIT design.

ACKNOWLEDGMENT

The author thanks D. C. Keeton for reviewing this article.

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