LEGIBILITY NOTICE

A major purpose of the Technical Information Center is to provide the broadest dissemination possible of information contained in DOE's Research and Development Reports to business, industry, the academic community, and federal, state and local governments.

Although a small portion of this report is not reproducible, it is being made available to expedite the availability of information on the research discussed herein.

LA-UR--89-3043

DE90 002358

TITLE: THERMAL ANALYSIS OF THE CPFR/ZTH APPARATUS

AUTHOR(S): Norman M. Schnurr

SUBMITTED TO: IEEE 13th Symposium on Fusion Engineering, October 2-6, 1989
in Knoxville, Tennessee

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

By acceptance of this article the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

THERMAL ANALYSIS OF THE CPRF/ZTH APPARATUS

Norman M. Schnurr
 Mail Stop - K-557
 Los Alamos National Laboratory
 Los Alamos, NM 87545

Abstract

The design has been completed for a new-generation Reversed-Field Pinch machine to be assembled at the Los Alamos National Laboratory during FY 1992. The Confinement Physics Research Facility (CPRF) houses the front-end ZTH torus. A series of simulations has been performed to predict temperature levels for various elements within the front end of the CPRF/ZTH apparatus for bakeout conditions and for periodic experiments. A lumped-parameter approach was used to calculate temperatures of various elements as functions of time. Results indicate that temperatures can be held at acceptable levels for 10-min cycles for the 2-MA design condition. The cycle time must be extended to approximately 13 min for 4-MA experiments. Instrumentation temperatures during bakeout were also found to be within acceptable limits.

Introduction

The design has been completed for a new-generation Reversed-Field Pinch machine to be assembled at the Los Alamos National Laboratory during FY 1992. The Confinement Physics Research Facility (CPRF) houses the front-end ZTH torus. This paper discusses the results of thermal analyses performed for the front end of the CPRF/ZTH apparatus. Calculations were carried out for the bakeout phase and for a series of experiments. The bakeout process entails steady Joule heating of the liner to a level that will maintain the tile surfaces at approximately 300°C for a long period of time (24 h or more). The experiments will be performed in an intermittent mode with a 1-s pulse of energy, followed by a cooldown period. The magnitude of the energy pulse will be in the range of 25 to 32 MJ, which corresponds to plasma currents of 2 to 4 MA. The design goal is to provide sufficient cooling to allow satisfactory operation with a cooldown period of 10 min for 2-MA experiments.

A transient analysis was used to calculate temperatures at various locations as functions of time for both a standard shell section and the poloidal-field gap section. A satisfactory design requires that the following conditions be satisfied.

1. The temperature of the electrical diagnostic instrumentation must not exceed 200°C.
2. The temperature of the Nomex should be less than 230°C.
3. The temperature of the outer surface of the shell should be less than 50°C.

The objective of the work described in this paper was to predict the temperature profiles as functions of time for all important components within the cavity, for the bakeout and for the periodic experiments, and to ensure that the design requirements could be met with an adequate safety margin.

Analytical Method

A typical section for analysis is shown in Fig. 1. This region is at the inner mid-plane for the standard shell. A 1-s pulse of energy is deposited on the surface of the graphite tile during an experiment. That energy flows by conduction into the tile causing a rapid increase in the tile temperature. Heat then flows outward to the shell by conduction through the clip, Inconel ring, and liner standoff ring, and by a combination of conduction, convection, and radiation through the clip, liner, and insulation. There is also a lateral heat flow between the liner and the Inconel ring and between the insulation and Nomex and the standoff.

This problem is analyzed by using a lumped-parameter approach. We assume that the temperature is spatially uniform within each lump of material (node). The nodes are interconnected by conductances that may have conductive, convective, and radiative components. An energy balance for the i th node, for a small time step Δt , has the form

$$Q_i + \sum C_{ij}(T_j - T_i) + C_{i,a}(T_a - T_i) = (mc)_i(T_i - T_{i,0})/\Delta t, \quad (1)$$

Fig. 1. Typical section at the inner mid-plane.

where Q_i is the externally supplied energy input rate for node i ; C_{ij} is the total conductance (conduction, convection, and radiation) between nodes i and j ; T is the node temperature at the end of the time step; T_0 is the temperature at the beginning of the time step; and the subscript (a) refers to an ambient node (for example cooling water) with a fixed temperature.

The conductances from the tile to the clip and from the clip to the Inconel liner are radiative only. These elements are inside the vacuum containment, so there is no convection. The tile and clip are in physical contact at some points, but because the contact resistance for conduction is impossible to estimate without knowing the exact shape of both surfaces, the worst case of negligible conduction is assumed. Radiative conductances are calculated from

$$C_r = 4\sigma A_1 T_{av}^3 / (1/\epsilon_1 + 1 + (A_1/A_2)(1/\epsilon_2 - 1) + 1/F_{12}), \quad (2)$$

where σ is the Stefan-Boltzmann constant, T_{av} is the average of the two surface temperatures, ϵ_1 and ϵ_2 are the surface emissivities, A_1 and A_2 are the surface areas, and F_{12} is the view factor from surface 1 to surface 2.

Conductances from the liner to the insulation and from the insulation to the directly opposed shell segment include radiative, convective, and conductive components. The convective conductances are computed from an empirical equation for convection in a horizontal enclosure [1] with the form

$$h = 0.195 (k/\delta) Gr^{0.25} \quad 10^4 < Gr < 4 \times 10^5$$

$$h = 0.068 (k/\delta) Gr^{0.33} \quad 4 \times 10^5 < Gr, \quad (3)$$

where δ is the spacing between the surfaces, k is the thermal conductivity of air, and Gr is the Grashoff number based on δ .

Heat transfer through the clip, Inconel ring, and thermoplastic standoff is by conduction. Those conductances are calculated from

$$C_k = kA/t, \quad (4)$$

where k is the thermal conductivity of the material and A and t are the area and thickness, respectively.

Fig. 2. Equivalent circuit for the inner mid-plane.

A diagram of the equivalent thermal circuit for a typical segment at the inner mid-plane is shown in Fig. 2. Note that the standoff is divided into five segments that correspond to the regions separated by the dashed lines in Fig. 1. This division is necessary because the low conductivity of Fiberite causes a large temperature gradient through the material. The tile is divided into two nodes because the outermost portion is not covered by the clip and radiates directly to the liner. All other elements (liner, clip, ring) can be modeled as single nodes because they have high thermal conductivity or because their thickness is very small in the direction of heat transfer (Nomex, min-K). Thermal resistances between the nodes are indicated in Fig. 2, with the symbols K, C, and R designating conductive, convective, and radiative resistances, respectively. The corresponding conductances are reciprocals of the resistances.

The transient solution is carried out using an implicit, marching procedure. Initial temperatures are specified for each node. Then conductances are calculated and new temperatures are computed for all nodes at the end of a small time step by the simultaneous solution of N equations having the form of Eq. (1). All temperature-dependent conductances must be recalculated for each time step. A computer code (LPH2) was developed to perform these calculations.

A separate numerical analysis was performed to determine the spatial temperature distribution within a tile caused by a pulse of energy at the surface. The two-dimensional, finite-element code, TOPAZ2D [2] was used to calculate the transient temperature distribution in a 1/2 in. thick tile subjected to a 0.11-kW/cm² surface heat flux (the predicted value for the 4-MA experiment) for 1 s. Heat loss from the bottom surface of the tile is assumed negligible for the short term. Results of that calculation indicate that the top surface temperature rises rapidly and is approximately 800°C above the bottom surface temperature after 1 s. After 2 s, however, the temperature distribution in the tile is essentially uniform. This is a very short period of time compared with the cycle time of 10 min or more. It is therefore apparent that the tile can be designated as a single node in the lumped parameter analysis, and the effect of a pulse can be accurately represented as an instantaneous energy addition for that node.

The conductance through the shell to the environment depends on the shell wall construction and the spacing of cooling water channels on the outside surface of the shell. The construction of the standard shell and the shell at the poloidal field gap are given in Table 1.

TABLE 1. CONSTRUCTION OF SHELL WALLS

Layer ^a	Standard Shell		Poloidal Field Gap	
	Material	t (in.)	Material	t (in.)
1	Polyurethane	0.048	Polyurethane	0.048
2	Copper	0.135	S.S. ^b	0.250
3	S.S. ^b	0.750	Copper	0.068
4			Epoxy	0.241
5			Copper	0.068
6			S.S. ^b	0.125
7			Copper	0.068
8			Epoxy	0.241
9			Copper	0.068
10			S.S. ^b	0.500

^a Layers numbered from inside to outside.

^b Stainless steel.

The effective conductances for wall segments cooled by water channels that are spaced some distance apart are calculated using TOPAZ2D. The two-dimensional steady-state temperature distribution is computed for a given (average) heat flux at the inside surface. The outside surface is assumed adiabatic (neglecting free convection to the outside air) except for the small area where energy is transferred by turbulent forced convection to water flowing through the tube. An average effective conductance in the direction normal to the shell surfaces is computed from

$$C = q / (T_s - T_a) \quad (5)$$

where q is the surface heat flux, T_s is the average temperature of the inside surface, and T_a is the temperature of the cooling water and surrounding air. The temperature at the outside surface midway between water channels is also determined as a function of the average inside surface temperature and the water temperature. This functional relationship is used by LPH2 to determine the maximum shell surface temperature.

Results for the 2-MA Case

Calculations were performed using the LPH2 code to predict the transient temperature distributions for 10-min cycles. The energy input for a tile was calculated based on its surface area assuming the 25-MJ energy pulse to be uniformly distributed over all tiles. That energy pulse was added to the tile at the beginning of each cycle. Initial temperatures were determined by a steady-state calculation, assuming a temperature of 200°C for the Inconel ring. This corresponds to initial conditions that would result from maintaining the ring temperature at 200°C by Joule heating over an extended period of time.

Calculations were performed for both the outer and inner mid-planes and for both the standard shell and the gap region. A typical segment for the outer mid-plane is shown in Fig. 3. The highest temperatures were predicted for the outer mid-plane gap. Results for that region are shown in Fig. 4. The Nomex junction temperature is estimated based on a weighted average of the temperatures of the Nomex node and the temperature of the node designated Standoff-1. The passthrough temperature represents the maximum possible temperature of the instrumentation. The calculated Nomex junction and passthrough temperatures for that case are approximately 15 and 500°C below the allowable limits.

These calculations do not account for the radiant energy transfer within the enclosure formed by the tiles. The effect of radiation among the tiles will be a net heat transfer from the tiles having the highest temperatures (outer mid-plane) to those at lower temperatures

Fig. 3. Typical section at the outer mid-plane.

Fig. 4. Temperature profiles for the outer mid-plane gap region; 2-MA, 10-min cycles.

(inner mid plane). The temperatures are therefore slightly over-predicted for the outer mid plane and are under-predicted for the inner mid plane. The predicted Nomex and passthrough temperatures satisfy the design constraints for all cases. The temperature of the outer surface of the shell slightly exceeds the recommended limit of 87°C for the case of the outer mid plane. This occurs only at isolated locations halfway between cooling channels and is not considered a serious problem.

Fig. 5. Temperature profiles for the outer mid-plane gap region; 2-MA, 15-min cycles.

The design goal for the CPRI/ZTII is to perform experiments every 10 min up to 9 h at 2-MA plasma currents. It is interesting, however, to determine the effect of operating with a somewhat longer cycle time. Calculations were performed for the outer mid-plane gap region for cases of 15-min cycles. Results of those calculations are shown in Fig. 5. The effect of the 15-min cycle is to significantly reduce the temperatures.

Results for the 4-MA Case

The power input to the tiles for the 4-MA experiments is 32 MJ per cycle. This increased energy input requires a slightly longer cool-down period between experiments. A cycle time of 13 min was sufficient to maintain temperatures at approximately the same levels as 10-min cycles for the 2-MA case. Results for the outer mid-plane gap are shown in Fig. 6. The longer cycle time causes a larger excursion of the tile temperature than that for the 2-MA case. All other temperatures are nearly identical to those for the 2-MA case with 10-min cycles (Fig. 4). Simulations were also run for the outer mid-plane with the standard shell and for both shell configurations at the inner mid plane. Temperatures were lower than those shown in Fig. 6 for all of these cases.

Bakeout Conditions

The bakeout process requires maintaining the temperature of the tiles at 300°C for a period of 1 day or more. This will be accomplished by steady Joule heating of the liner. The energy generation rate in the liner material will be uniform, but there is approximately 60% more liner material per unit area of tile at the inner mid plane than at the outer mid plane because of the toroidal shape. This implies that the temperature of the inner mid plane tiles will be higher than that of the tiles at the outer mid plane. This difference is much less than would be predicted by the one dimensional analysis described in the previous sections of this report. A more accurate solution is obtained by coupling solutions for the inner and outer mid plane sections. The tiles for these segments are connected by a radiative conductance. This is an approximation to the actual geometry in which there are 22 tiles around the inside surface of the torus between the outer and inner mid plane tiles. The tile temperatures vary monotonically from the inner to outer mid plane tiles. The system analyzed is therefore a reasonable approximation of the actual configuration.

Fig. 6. Temperature profiles for the outer mid-plane gap region; 4-MA, 13-min cycles.

A steady-state code, BKOUT, was developed to perform this calculation. The computation involved reading in all conductances obtained from the LPHT2 code and solving a system of N linear algebraic equations of the form of Eq. (1) with the transient term eliminated. Energy inputs were specified for the two liner nodes in the proper proportion. The total power input was adjusted to obtain temperatures as close to 300°C as possible for the two tiles.

The results of this calculation gave temperatures of 303 and 296°C for the tiles at the inner and outer mid-planes, respectively. The passthrough temperatures were 169 and 141°C. These temperatures are well within the acceptable range. The temperatures of the Nomex at the junction with the ring were 236 and 210°C. The Nomex temperature at the inner mid-plane is slightly higher than the recommended upper limit.

Safety Analyses

A simulation was performed to determine the effect of a loss-of-coolant accident on instrumentation temperatures. The segment considered was the outer mid-plane gap. We assume that the loss of coolant occurs after 8 h of operation immediately following an energy pulse. Heat transfer from the outer shell surface is assumed to be by radiation to the surroundings and by free convection to ambient air at 25°C.

Results of the calculation are shown in Fig. 7. The outside shell temperature suddenly increases but does not exceed 50°C. The inside shell surface temperature also rises somewhat but peaks about 3 h after the loss of coolant at a level slightly above 100°C. The temperatures of all other important elements including the passthrough, drop immediately. This type of accident will not cause a serious thermal problem.

A second scenario that might cause overheating of the instrumentation is a non uniform energy deposition on the tiles. The worst conceivable case is an energy flux of 2 kW/cm² (25 times greater than the uniform heat flux value) on a tile at the outer mid-plane near the end of the day. An approximate analysis was performed to estimate the effect of that occurrence on the temperature of the passthrough nearest that tile. The thermal circuit used in LPHT2 was altered to include radiative conductances from the tile to an equivalent tile representing all other tiles that could exchange radiation with the affected

Fig. 7. Temperature profiles for the outer mid-plane gap region; 2-MA, 10-min cycles; loss of coolant at 8 hr.

tile. That dummy tile began with the same temperature as the affected tile and had a thermal capacity representative of 40 tiles. It was otherwise thermally isolated from the outside, a conservative assumption.

A simulation of that system indicated that the temperature of the affected tile would rapidly increase to more than 800°C but then would drop rapidly because of radiation to other tiles. The temperature of the passthrough would increase to 190°C, an acceptable level.

Summary and Conclusions

A series of simulations were performed to predict temperature levels for various elements within the front end of the CPRF/ZTH apparatus for bakeout conditions and for periodic experiments. Results indicate that temperatures can be held at acceptable levels for 10-min cycles for the 2-MA currents. The cooldown time must be extended to approximately 13 min for 4-MA experiments.

Instrumentation temperatures during bakeout were found to be within acceptable limits. The temperature of the Nomex at the inner mid-plane was slightly above the recommended limit.

An analysis of the type used here is based on several simplifications that introduce some uncertainty in the results. Contact resistances were neglected in all cases. A calculation showed these resistances to be small in most instances because of high radiative conductances between adjacent surfaces at high temperatures. Contact resistances would make the temperatures slightly higher than those calculated here. Lateral conduction through the liner and radiant exchanges between tiles in different parts of the device were also neglected (except in the steady-state bakeout calculation). These effects would tend to decrease the differences in temperatures between the inner and outer mid-planes. The temperatures calculated are believed to have an accuracy of approximately plus or minus 10 to 20°C.

References

1. F. Kreith, *Principles of Heat Transfer*, 3rd Edition (Intext Educational Publishers, New York, NY, 1973).
2. A. B. Shapiro, "TOPAZ2D - A Two Dimensional Finite Element Code for Heat Transfer Analysis, Electrostatic, and Magnetostatic Problems," Lawrence Livermore National Laboratory report UCID 20824 (July, 1986).