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A COOLDOWN/WARMUP COMPUTER MODEL FOR THE SSC

Examples: Cooldown of SSC magnets as specified in the CDR and warmup of SSC magnets from 4.35 K to 25 K

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SUMMARY

This note describes a computer model to simulate cooldown/warmup of SSC magnets by helium flow through the cooling channels. The model provides the following information along the magnets as a function of time: iron temperature, helium temperature, helium mass flow rate, and helium pressure. With respect to previous cooldown models, this model extends the range of simulations to very low temperatures, it makes full treatment of properties dependence with temperature and pressure, and it can simulate warmup as well as cooldown.

We obtain the partial differential equations that describe the problem and then we solve them using the finite difference method.We discuss how the properties dependence on temperature makes cooldown and warmup behavior different, why high temperature cooldown/warmup approximations are not valid at very low temperatures, and why changes in mass flow rate are significant at very low temperatures.

We describe a computer program that we wrote based in our model, and we show simulation results for two examples: Cooldown of the SSC magnets as specified in the Conceptual Design Report, which consist on 4 successive "cold waves" that cool the magnets down from room temperature to liquid helium temperature, and warmup of the SSC magnets using warm gas from liquid helium temperature to 25 K, which is an option being considered for gas desorption of the beam tube wall.

Cooldown/warmup simulations can be used to provide dynamic information for the cryogenic system, to analyze longitudinal iron temperature profiles for structural purposes (i.e., thermal stresses), to optimize operations, etc. In this note we present a convenient tool to perform those simulations.

CONTENTS

1. INTRODUCTION

This report describes a computer model to simulate cooldown/warmup of SSC magnets by helium gas flow through the cooling channels. Fig. 1 shows a cross section of the dipole magnet which includes the four cooling channels where helium flows /1/. This model considers that all the dipole mass is of iron, it assumes no heat exchange between the iron yoke and the environment, no transverse temperature gradients in the iron (lumped iron mass approach), no longitudinal heat diffusion in the iron, no Helium kinetic energy effects, no Helium transverse temperature distribution, and no Helium phase change. These assumptions are discussed in the section 2.1.

Because Iron and Helium thermal properties depend strongly on temperature, the model considers properties dependence with temperature and, in the case of helium, also with pressure. The Helium properties are calculated using the NBS631 Helium Property Program /2/ (a modified version of the National Bureau of Standards program), and the Iron properties are taken from a table of the CRC Handbook of Chemistry and Physics.

The model provides the following information along the magnet as a function of time: iron temperature, helium temperature, helium mass flow rate, and helium pressure.

In section 2.2 we obtain the partial differential equations that describe the problem, and in section 2.3 we solve them using the finite difference method. We use an explicit scheme optimized to simulate strong heat transport effects in the Helium. We wrote the computer program COOLWARM to solve the resultant set of linear equations. COOLWARM is interactive, user-friendly, and executes in a reasonable CPU time. It is not restricted to SSC magnets, it is a general-purpose program to simulate cooldown/warmup of iron by helium gas flow through cooling channels. We also wrote the post-processing program PLOTRES to make automatic plotting of results given by COOLWARM using the plotting package TOPDRAWER /3/. Section 3 describes the programs in more detail.

We believe that the main contributions of our model with respect to previous cooldown models for superconducting magnets /4/, /5/, /6/, are that it extends the range of simulations to very low temperatures, that it makes full treatment of properties dependence with temperature, and that it can simulate warmup as well as cooldown.

At very low temperatures, neither changes in mass flow rates nor helium heat content effects can be neglected. In appendix B we discuss some limit cases for the differential equations that help to understand why the approximations that are valid at high temperatures cannot be used at very low temperatures and which are the main limiting factors for temperature front propagation along the magnet during cooldown or warmup.

During warmup, the situation is different than during cooldown. During cooldown, we usually have a "cold front" advancing at constant velocity and very sharp (like a step) relative to the length usually considered (hundreds of meters). But during warmup, we don't have a "hot front" advancing at constant velocity. Instead, what we have is a temperature profile advancing at temperature-dependent velocities (higher at lower temperatures), thus very extended over the length. As a result, some methods to evaluate cooldown times (like average heat balance using enthalpies changes for helium and iron) are not valid for warmup because we don't have a step-like output helium temperature dependence.

We will see in section 4 that the basic reason for the above mentioned behavior during cooldown or warmup is the good thermal contact between the iron and the Helium and the way in which properties depend in temperature, in particular the iron specific heat that goes to very small values at very low temperatures (i.e., 0.000382 j/g-K at 4 K) and then increases very rapidly with temperature (i.e., 0.00124 j/g-K at 10 K).

Cooldown/warmup simulations can be used to provide dynamic information for the cryogenic system, such as changes of helium output mass flow rate, helium output temperature, and helium output pressure. Helium inventory information is particularly useful during cooldown/warmup at very low temperatures because of the changes in mass flow rate. For example, during warmup the output mass flow rate is higher than the input, and it may be important to know if the cryogenic system can handle that increased output mass flow rate. It may also be important to know how long the cryogenic system will have to deal with that additional amount of mass, and if it will go down like a step or gradually. The simulations can also be used to analyze longitudinal iron temperature profiles which might lead to mechanical failures.
The simulations provide also global quantities such as total cooldown/warmup times and total amount of helium spent during the process.

Section 4 shows some examples of cooldown/warmup of the SSC magnets. We used COOLWARM to simulate the following cases:

a) Cooldown of the SSC magnets as specified in the Conceptual Design Report (CDR). This cooldown procedure consist on 4 successive "cold waves" that cool the magnets down from room temperature to liquid helium temperature. We simulated each wave, and we present results, analysis and comparison with CDR estimates.

b) Warmup of the SSC magnets from liquid helium temperature to 25 K.
Besides showing the differences between cooldown and warmup behavior, this example has also some practical application. Warming up the SSC magnets a few degrees K using warm gas is an option being considered for gas desorption of the beam tube wall. This operation is expected to take place a few times during the first years of operations of the SSC, and it consist on warming up the beam tube wall a few degrees K (enough to desorpt some trapped gases) and pump the desorpted gases out. Another option is to use electrical heaters to warm the magnets up, but warm gas is preferred because it can provide a more uniform longitudinal temperature distribution in the iron. On the other hand, the use of warm gas will produce significant changes in the mass flow rates. These changes have to be considered from the overall cryogenic system point of view. Of particular importance is the expected increase in output mass flow rate during the beginning of warmup. The input helium mass flow rate has to be selected carefully so the output mass flow rate will not exceed the cryogenic system specifications. We also show that the input helium pressure has a strong effect on the maximum output mass flow rate for a given input mass flow rate.

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2. A COOLDOWN/WARMUP COMPUTER MODEL FOR THE SSC

2.1 Assumptions and approximations

Fig. 1 shows a cross section of the SSC dipole magnet, including the iron yoke and the 4 cooling channels. Helium flowing through the cooling channels exchanges heat with the iron yoke.
In steady state, it is important to consider the (small) heat transfer between the iron yoke and the environment. However, during cooldown/warmup the heat exchange with the environment is negligible compared with the heat exchange between iron and helium, and we can consider that the iron yoke has adiabatic boundaries.
By symmetry we can consider one cooling channel and its associated mass to analyze the problem.
The iron mass is approximately 3/4 of the total dipole mass. The remaining 1/4 consists mainly of coils and stainless steel collar. To simplify the problem, we can assume that from the thermal point of view all the dipole mass is of iron. We can go one step further and "lump" all the iron mass (that is, neglect transverse temperature gradients in iron). This approximation is good if during the time it takes for a diffusion wave to travel from the cooling channel to the bore tube the cooling channel wall temperature doesn't change much. For example, for the SSC magnets the temperature change at the cooling channel wall is approximately 0.8% (relative to the initial value) during the diffusion time. That percentage is about the same at very low temperatures and at high temperatures.
Higher accuracy of the magnet temperature distribution can be obtained by coupling our model with a 2-D thermal model that solves the heat diffusion equation in the iron yoke, collar , and coils region. This coupling is very easy to do, but the solution will take a much longer CPU time. Such degree of accuracy is beyond the scope of this work, and it shouldn't change much the results for the SSC dipole magnet obtained with our simpler model.

We also neglect longitudinal heat diffusion along the iron yoke. This is a safe assumption because the longitudinal temperature gradients in iron turn out to be small and the fact that the yoke is made of laminated iron decreases its longitudinal conductivity.

For helium, we assume negligible kinetic energy effects, no transverse temperature gradients and no phase change. In the case of the SSC, we normally have single-phase flow because the helium pressure is above its critical point.

We think that all the above mentioned assumptions and approximations are reasonable for cooldown/warmup analysis of the SSC dipole magnets. Although the model is not restricted to the SSC case, for other magnets or cooling channels some of the assumptions may not be valid.

We consider properties dependence with temperature and, in the case of helium, also with pressure. The properties dependence with temperature (and pressure) affects strongly the cooldown/warmup results, and it cannot be ignored .
For Helium, the properties are obtained from the (modified) NBS631 Helium Property Program of the National Bureau of Standards /2/, which gives helium properties as a function of temperature and pressure.
For Iron, the properties are taken from tables of the CRC Handbook of Chemistry and Physics.

In the following section we develop the partial differential equations that describe the problem with the above mentioned assumptions and approximations.

2.2 Partial Differential Equations

Fig. 2 shows a control volume for gas and iron. We are going to do a balance of mass and energy for the control volume during the time interval dt.

Helium mass flow rate.

The helium mass flow rate change is related to the helium density change in the control volume by:

$$\left(\frac{\partial w_g}{\partial x} dx\right) dt = -A dx \left(\frac{\partial \rho_g}{\partial t} dt\right) \tag{1}$$

(1) can be written as:

$$\boxed{\frac{\partial w_g}{\partial x} - A \frac{\partial \rho_g}{\partial t} = 0} \tag{2}$$

Helium temperature.

The change in helium "heat content" in the slice during dt is:

$$dQ_c = A dx C_p^g \frac{\partial}{\partial t}(\rho_g T_g)\ dt = A dx C_p^g \left(T_g \frac{\partial \rho_g}{\partial t} + \rho_g \frac{\partial T_g}{\partial t}\right) dt \tag{3}$$

And the net quantity of heat brought into the slice by transport is:

$$dQ_{tr} = C_p^g dx \frac{\partial}{\partial x}(w_g T_g)\, dt = C_p^g dx \left(T_g \frac{\partial w_g}{\partial x} + w_g \frac{\partial T_g}{\partial x}\right) dt \tag{4}$$

The total amount of heat that the helium slice exchanges with the iron slice during dt is:

$$dQ = dQ_c + dQ_{tr} = C_p^g dx \left(A T_g \frac{\partial \rho_g}{\partial t} + A \rho_g \frac{T_g}{\partial t} + w_g \frac{\partial T_g}{\partial x} + T_g \frac{\partial w_g}{\partial x}\right) dt \tag{5}$$

Using (2) in (5), we have:

$$dQ = C_p^g dx \left(A \rho_g \frac{\partial T_g}{\partial t} + w_g \frac{\partial T_g}{\partial x}\right) dt \tag{6}$$

The heat exchange between the helium and the iron can be written using the heat transfer coefficient:

$$dQ = -hP\,(T_g - T_i)\,dxdt \qquad (7)$$

And calling: $\lambda_g = \frac{C_p^g w_g}{hP}$ Helium characteristic length

$\tau_g = \frac{C_p^g A \rho_g}{hP}$ Helium characteristic time

We have, from (6) and (7):

$$\boxed{\tau_g \frac{\partial T_g}{\partial t} + \lambda_g \frac{\partial T_g}{\partial x} = T_i - T_g} \qquad (8)$$

If $\tau_g \sim 0$ and the characteristic time for iron is much larger than τ_g, then we can neglect helium heat content effects and (8) can be written as:

$$\boxed{\lambda_g \frac{\partial T_g}{\partial x} = T_i - T_g} \qquad (8.a)$$

Approximation (8.a) can be used for the SSC at high temperatures (see appendix B)

Helium pressure.

The pressure drop can be written in terms of a friction factor (f) and a pressure head (H):

$$\boxed{\frac{\partial P}{\partial x} = -4\frac{f}{D}H} \qquad (9)$$

Where the pressure head is given by /7/:

$H = (w_g/A)^2/(2\rho_g)$

Iron temperature.

We assume that the iron slice has uniform temperature. During dt the heat exchanged with helium is given by:

$$dQ = C_p^i m_i' dx \frac{\partial T_i}{\partial t} dt \qquad (10)$$

Calling: $\tau_i = \dfrac{C_p^i m_i'}{hP}$ Iron characteristic time

We have, from (7) and (10):

$$\boxed{\tau_i \frac{\partial T_i}{\partial t} = -(T_i - T_g)} \qquad (11)$$

Heat transfer coefficient.

We use the following correlation for the heat transfer coefficient for single-phase turbulent flow through a smooth, round tube /7/:

$$h = \frac{\left(\frac{w_g}{A}\right) C_p^g \, 0.023 \, Re^{-0.2}}{Pr^{2/3} \left(\frac{\mu_w}{\mu_b}\right)^{0.14}} \qquad (12)$$

Friction factor.

We use the following correlation for the friction factor for single-phase turbulent flow through a smooth, round tube /7/:

$$f = 0.046 \, Re^{-0.2} \qquad (13)$$

The assumption of a smooth tube for both, the heat transfer coefficient and the friction factor, is an approximation because the cooling channels of the SSC magnets have rough walls. That means that the real heat transfer coefficient may be higher than (12) and that the real friction factor may be also higher than (13). Since it is very difficult to know which are the real values, the quantities provided by (12) and (13) should be regarded as lower limits, and a safety factor should be applied to the results.

Equations (2), (8), (9) and (11), together with the correlations (12) and (13) describe completely the cooldown/warmup problem of the SSC magnets under the assumptions and approximations already mentioned. By solving them we can obtain spatial and temporal distributions of the iron temperature, the helium temperature, the helium mass flow rate and the helium pressure during cooldown/warmup.

In the next section we solve equations (2), (8), (9) and (11) using the finite difference method.

2.2 Solution of the partial differential equations

We use the finite difference method to solve the partial differential equations (2), (8), (9) and (11). We use an explicit scheme, that is, all the unknowns can be calculated explicitly from the quantities that are already known. Implicit schemes would require us to solve a set of linear equations at every time step. One disadvantage of explicit methods is that the distance and time steps are subject to a "stability criteria", and in some cases this criteria forces those steps to be extremely small. On the other hand, explicit schemes are very convenient when we have coefficients that depend on the unknown and when transport effects are important (i.e., what happens in one node depends mainly on what happen "behind (in front of)" it and not on what happen "in front of (behind)" it. The simplest way to model the transport properties "better" is to use upwind differencing according to the direction of the advection. We found this scheme to be very successful to solve the helium temperature equation. As a result, we use the following approximations for the derivatives:

$$\left[\frac{\partial T_g}{\partial x}\right]_j^n = \frac{T_g(j)^n - T_g(j-1)^n}{\Delta x} \tag{14}$$

$$\left[\frac{\partial T_g}{\partial t}\right]_j^n = \frac{T_g(j)^n - T_g(j)^{n-1}}{\Delta t} \tag{15}$$

$$\left[\frac{\partial w_g}{\partial x}\right]_j^n = \frac{w_g(j)^n - w_g(j-1)^n}{\Delta x} \tag{16}$$

$$\left[\frac{\partial \rho_g}{\partial t}\right]_j^n = \frac{\rho_g(j-1)^n - \rho_g(j-1)^{n-1}}{\Delta t} \tag{17}$$

$$\left[\frac{\partial P}{\partial x}\right]_j^n = \frac{P(j)^n - P(j-1)^n}{\Delta x} \tag{18}$$

$$\left[\frac{\partial T_i}{\partial t}\right]_j^n = \frac{T_i(j)^n - T_i(j)^{n-1}}{\Delta t} \tag{19}$$

Replacing the approximations for the derivatives in the partial differential equations and solving them for the unknown, we obtain:

Helium mass flow rate

$$\boxed{w_g(j)^n = w_g(j-1)^n - A\frac{\Delta x}{\Delta t}(\rho_g(j-1)^n - \rho_g(j-1)^{n-1})} \tag{20}$$

Helium temperature

$$\boxed{T_g(j)^n = \frac{T_i(j)^n + \frac{\lambda_g}{\Delta x}T_g(j-1)^n + \frac{\tau_g}{\Delta t}T_g(j)^{n-1}}{1 + \frac{\lambda_g}{\Delta x} + \frac{\tau_g}{\Delta t}}} \tag{21}$$

Equation (21) is subject (approximately) to the Courant Stability condition:

$$\left(\frac{\lambda_g}{\tau_g}\right)\frac{\Delta t}{\Delta x} < 1 \tag{22}$$

And for accuracy we must satisfy:

$$\Delta t << \tau_g \text{ and } \Delta x << \lambda_g \tag{23}$$

Helium pressure

$$\boxed{P(j)^n = P(j-1)^n - 4\, f\, \frac{\Delta x}{D}\, H} \tag{24}$$

Iron temperature

$$\boxed{T_i(j)^n = T_g(j)^{n-1} + (T_i(j)^{n-1} - T_g(j)^{n-1})\, e^{-\Delta t/\tau_i}} \tag{25}$$

We obtained equation (25) solving analytically its corresponding partial differential equation (11). This is a valid procedure only if $\Delta t << \tau_i$ and $\Delta x << \lambda_g$.

In equations (20), (21), (24) and (25) λ_g, τ_g, f, H and τ_i are evaluated using $w_g(j-1)^n$, $T_g(j-1)^n$, $P(j-1)^n$ and $T_i(j-1)^n$.

In appendix B we discuss some limit cases for the helium temperature partial differential equation. We found that equation (21) is not very convenient if $\tau_g << \tau_i$ because conditions (22) and (23) force Δt to be too small with respect to τ_i. An approximation can be used in this case (see equation 8.a) which is equivalent to set $\tau_g = 0$ in equation (21), so the time step is now limited only by the condition $\Delta t << \tau_i$. In the SSC case, we use this approximation for high temperature simulations.

3. THE PROGRAM COOLWARM

We wrote the program COOLWARM based on equations (20), (21), (24) and (25). COOLWARM is an interactive program, and has some features to make it fast and user-friendly. The user needs to specify the following input data:

- Magnet length to be considered.
- Channel diameter.
- Iron mass per unit length.
- Initial iron temperature.
- Entrance helium mass flow rate.
- Entrance helium temperature.
- Entrance helium pressure.
- Total simulation time.
- Time step.
- Distance step.
- Control information for output.

Before asking for the time and distance steps, the program recommends some values according to the problem that shouldn't be exceeded.

The program takes care internally of the properties dependence with temperature, so the user doesn't have to worry about that.

The output of COOLWARM consist on three output files and a screen output. The screen output provides a summary of results during execution. The output file COOLWARM.RES contains input data and screen output, and the files COOLWARM.LIS and COOLWARM.END contain detailed information of the solution for post-processing.

We wrote the program PLOTRES to make post-processing of results provided by COOLWARM. PLOTRES reads the output files written by COOLWARM and has several plotting options. After the user selects one option, PLTORES writes the output file SAMPLE.TOP, which is an input file for the TOPDRAWER plotting package /3/. SAMPLE.TOP contains all the necessary information to execute TOPDRAWER. Some of the plotting options are: Iron and helium temperature vs distance, mass flow rate vs distance, exit helium temperature vs time, exit mass flow rate vs time, exit pressure vs time, etc. PLOTRES is also interactive, and the user only needs to specify the minimum and maximum scale values of the plot.

COOLWARM has two special features to make it faster: it solves the equations only in regions where the temperature is changing and instead of calling the helium properties routines at every step it interpolates linearly between points of a property table. That table is generated before the time and distance loops, and consist of 100 values for each considered helium property between the minimum and maximum temperatures at the entrance pressure. To generate the table, COOLWARM calls the NBS631 Helium Property Program /2/ that provides helium properties as a function of temperature and pressure. The user should check if the problem involves significant pressure drop. If this is the case, the linear interpolation has to be done also with pressure, and the program needs to be modified.

COOLWARM also uses the high-temperature approximation of the partial differential equations when appropriate (see appendix B), otherwise it would take an extremely long time to execute high temperature cases without adding accuracy.

The execution time is very problem-dependent. Warmup problems take usually longer than equivalent cooldown problems because the temperature front is more extended over the magnet length , thus the number of nodes where the temperature is changing is larger. Typical execution times in the LBL VAX go from a few minutes of CPU for cooldown problems in short magnets (~ 100 m) to a few hours of CPU for warmup problems in long magnets (~ 1000 m).

Appendix C contains a Fortran listing of COOLWARM and PLOTRES.

In the next section we show some examples of the use of COOLWARM and PLOTRES to solve some practical cooldown/warmup problems of the SSC magnets.

4. SIMULATION RESULTS

In this section we present simulation results for cooldown of SSC magnets as specified in the Conceptual Design Report (CDR) and for warmup of SSC magnets from 4.35 K to 25 K. The simulations were done using the program COOLWARM and the plots were done using the post-processing program PLOTRES.

4.1 Cooldown of SSC magnets as specified in the CDR

In the CDR the cooldown of the SSC magnets from room temperature down to liquid helium temperature is planned to be done in 4 waves. Table 1 shows the temperature range of each wave.

Wave number	Magnet initial temperature (K)	Helium entrance temperature (K)
1	300	55
2	55	40
3	40	15
4	15	4.35

TABLE 1: Temperature range of cooldown waves for the SSC magnets.

The basic unit for cooldown operations is a string. A string consist of 21 cells of 12 dipole magnets each, and the string's total length is 4.032 km. The cell's length is 192 m. Due to the high pressure drop during room-temperature gas flow, room-temperature gas is removed from the string through cooldown valves located at every cell. As the cooling progresses down the string, successive valves are closed, and whereas the 300 K helium only flows through one cell of magnets, the 55 K passes through the whole cooled length of the string.

The basic unit for cooldown simulations was a cell. Due to the fact that the cold wave has a step-like temperature front advancing at (almost) constant velocity during cooldown, results can be extrapolated to the whole string very easily.

We used the following parameters in our simulations:

- Magnet length = 192 m
- Channel diameter = 0.03 m
- Iron mass per unit length = 93.25 kg/m (this is the iron mass associated with one channel. The total iron mass per unit length is 373 kg/m / 1 /)
- Entrance helium mass flow rate = 0.025 kg/s (this is the mass flow rate for one channel. The total helium mass flow rate for the 4 cooling channels is 0.1 kg/s / 1 /)

The helium pressure was 10 atm for waves number 1, 2 and 3. For wave number 4 the helium pressure was 4 atm.

Results for wave number 1 (from 300 K to 55 K).

Fig. 3 shows helium and iron temperature profiles along an SSC cell during cooldown from 300 K to 55 K. The maximum longitudinal iron temperature gradient is approximately 16 K/m.

Fig. 4 shows the helium temperature at the end of the cell during cooldown from 300 K to 55 K. The cell cooldown from 300 K to 55 K takes approximately 12.5 hours. During most of this time, the helium temperature at the end of the cell remains at 300 K, and then drops to 55 K relatively rapidly. The maximum rate of helium temperature decrease at the end of the cell is approximately 0.07 K/s.

Fig. 5 shows the helium pressure at the end of the cell during cooldown from 300 K to 55 K. The entrance helium pressure is 10 atm. The pressure drop along the cell decreases as the cold fraction of the cell increases because the pressure drop per unit length for cold helium is lower than for warm helium. Initially, the pressure drop along the cell is 0.5 atm. After the cooldown is completed, the pressure drop along the cell is 0.08 atm. The real pressure drop is probably higher, because the previous estimations were done assuming smooth walls.

The total amount of helium mass spent during cooldown of an SSC cell from 300 K to 55 K is 1118 kg/channel.

We can extrapolate the results for one cell to one string. In this case, cooldown of an SSC string from 300 K to 55 K would take approximately 263 h (11 days) and the total amount of helium mass spent would be 23468 kg/channel or 93870 kg/ring (93.87 ton/ring).

In the CDR it is estimated that cooldown of an SSC string from 300 K to 55 K takes approximately 11 days, which agrees well with our prediction (11 days). We also performed an enthalpy change balance for helium and iron which also predicts approximately 11 days to cooldown an SSC string from 300 K to 55 K.

Results for wave number 2 (from 55 K to 40 K).

Fig. 6 shows helium and iron temperature profiles along an SSC cell during cooldown from 55 K to 40 K. The maximum longitudinal iron temperature gradient is approximately 0.6 K/m.

Fig. 7 shows the helium temperature at the end of the cell during cooldown from 55 K to 40 K, which takes approximately 2.14 hours. The maximum rate of helium temperature decrease at the end of the cell is approximately 0.02 K/s.

The pressure drop along the cell, initially 0.08 atm, decreases to 0.054 atm after cooldown is completed.

The total amount of helium mass spent during cooldown of an SSC cell from 55 K to 40 K is about 193 kg/channel.

Extrapolating the results for one cell to one string, we obtain that cooldown of an SSC string from 55 K to 40 K would take approximately 45 hours (1.9 days) and the total amount of helium mass spent would be 4043 kg/channel or 16170 kg/ring (16.17 ton/ring).

In the CDR it is estimated that cooldown of an SSC string from 55K to 40K takes approximately 1.6 days. An enthalpy change balance for helium and iron predicts about 1.7 days.

Results for wave number 3 (form 40 K to 15 K).

Fig. 8 shows helium and iron temperature profiles along an SSC cell during cooldown from 40 K to 15 K. The maximum longitudinal iron temperature gradient is approximately 3.7 K/m.

Fig. 9 shows the helium temperature at the end of the cell during cooldown from 40 K to 15 K, which takes approximately 0.51 hours.
The maximum rate of helium temperature decrease at the end of the cell is about 0.25 K/s.

The pressure drop along the cell initially 0.054 atm, decreases to 0.017 atm after cooldown is completed.

Fig. 10 shows the helium mass flow rate at the end of the cell during cooldown from 40 K to 15 K. During most of the cooldown time, the helium mass flow rate at the end of the cell is approximately 7% lower than the input helium mass flow rate. When the "cold front" arrives at the end of the cell, the helium mass flow rate at this point increases up to the input value. The helium mass flow rate changes because of the helium density dependence on temperature, and we observe this change because of the relatively high rate of local density change.
Changes in mass flow rate are responsible for the difference in helium mass content in the cooling channels before cooldown and after cooldown. This is always true, even at high temperature. But only at low temperatures the change in helium mass flow rate becomes noticeable because the rate of local density change is high enough to observe the effect.The rate of local helium density change is high at low temperatures because the cold front advances at considerable velocity (10.5 cm/s) due to the low iron heat capacity at these low temperatures. We don't notice any changes in helium mass flow rate in cooldown waves 1 and 2 because the cold front advances very slowly (the iron specific heat is large at high temperatures) so the rate of local density change is very small,and not because the density doesn't change with temperature (in fact, the helium density increases 436% going from 300K to 55 K compared to an increase of 191% going from 40 K to 15 K). As a result of the slow cooldown process at high temperatures, a large change in total mass content can be realized by a very small change in mass flow rate. That small change, integrated during a long time, is responsible for the difference in total helium mass content in the cooling channels before cooldown and after cooldown at high temperatures.

The total amount of helium spent during cooldown of an SSC string from 40 K to 15 K is about 42.5 kg.

By extrapolation of the results for one cell to one string we found that cooldown of an SSC string from 40 K to 15 K would take approximately 10.6 hours (0.44 days) and that the total amount of helium mass spent would be 892 kg/channel or 3570 kg/ring (3.57 ton/ring).

In the CDR it is estimated that cooldown of an SSC string from 40 K to 15 K takes approximately 0.8 days. An enthalpy change balance for helium and iron predicts about 0.4 days, which agrees well with our estimation of 0.44 days.

Results for wave number 4 (from 15 K to 4.35 K).

Fig. 11 shows helium and iron temperature profiles along an SSC cell during cooldown from 15 K to 4.35 K. The maximum longitudinal iron temperature gradient is approximately 2.8 K/m.

Fig. 12 shows the helium temperature at the end of the cell during cooldown from 15 K to 4.35 K, which takes approximately 0.26 hours. The maximum rate of helium temperature decrease at the end of the cell is about 0.35 k/s.

The pressure drop along the cell, initially 0.017 atm, decreases to 0.0043 atm after cooldown is completed.

Fig. 13 shows the helium mass flow rate at the end of the cell during cooldown from 15 K to 4.35 K. During most of the cooldown time, the helium mass flow rate at the end of the cell is approximately 78% lower than the input helium mass flow rate.

Fig. 14 shows the mass flow rate profile along the cell during cooldown from 15 K to 4.35 K. We see that the mass flow rate has a step-like change in the region where the cold temperature front is advancing.

Fig. 15 shows the total helium mass that passed the end of an SSC cell during cooldown from 15 K to 4.35 K. The total helium mass spent is 7.14 kg/channel. We see two slopes in the plot of Fig. 13; the change in slopes is because the mass flow rate at the end of the cell went up to the input value by the end of the cooldown process.

By extrapolation of the results for one cell to one string, we obtain that cooldown of an SSC string from 15 K to 4.35 K would take approximately 5.5 hours (0.23 days) and that the total amount of helium mass spent would be 150 kg/channel or 600 kg/ring (0.6 ton/ring).

In the CDR it is estimated that cooldown of an SSC string from 15 K to 4.35 K takes approximately 0.6 days. An enthalpy change balance for iron and helium predicts about 0.031 days for a mass flow rate of 100 g/s and 0.14 days for a mass flow rate 78% lower. The last number is closer to our prediction of 0.23 days.

Fig. 15a to 15d show some comparative plots of global quantities among cooldown waves 1, 2, 3, and 4.

4.2 Warmup of SSC magnets from 4.35 K to 25 K.

Warmup of the SSC magnets by warm gas is an option being considered for gas desorption of the beam tube wall. This operation is expected to take place a few times during the first years of operation of the SSC. It consists on warming up the beam tube wall a few degrees K (enough to desorpt some trapped gases) and pump the desorpted gases out. Another option is to use electrical heaters to warm the magnets up, but warm gas is preferred because it can provide a more uniform longitudinal temperature distribution in the iron. On the other hand, the use of warm gas will produce significant changes in cryogenic parameters that have to be considered from the overall cryogenic system point of view. Of particular importance is the expected increase in exit helium mass flow rate during the beginning of the warmup operation. The input helium mass flow rate and pressure has to be selected carefully so that the output mass flow rate will not exceed cryogenic system specifications.

We show some simulation results for the warmup of one SSC section from 4.35 K to 25 K. The section is the minimum length of the machine that can be isolated and warmed up for service. There are two types of sections in the SSC: 5-cells or 6-cells. The 5-cells sections have a length of 960 m, and the 6-cells sections have a length of 1152 m. There are 4 sections per string (3 of 5-cells and 1 of 6-cells).

We used the following parameters in our simulations:

- Magnet length = 1000 m
- Channel diameter = 0.03 m
- Iron mass per unit length = 93.25 kg/m
- Entrance helium mass flow rate = 0.0125 kg/s
- Initial iron temperature = 4.35 K
- Entrance helium temperature = 25 K

We run two cases: one with an entrance helium pressure of 5 atm and the other with an entrance helium pressure of 10 atm. We will see that the entrance helium pressure affects the maximum output helium mass flow rate, but not the total warmup time or total amount of helium spent during warmup.

Warmup results for an entrance helium pressure of 5 atm.

Fig. 16 shows helium and iron temperature profiles along an SSC section during warmup from 4.35 K to 25 K and an entrance helium pressure of 5 atm. We immediately notice the difference between the warmup temperature profiles and the cooldown temperature profiles of the previous section. While cooldown temperature profiles are step-like and advance at (almost) constant velocity, warmup temperature profiles are very extended over the length of the magnet and advance at a temperature-dependent velocity, higher at lower temperatures. When the "hot front" arrives to a given point along the magnet, the iron temperature at this point will increase its temperature very fast up to about 8 K, and then the rate of temperature increase will decrease as the iron warms up. The main responsible for this kind of behavior is the iron specific heat dependence on temperature, which goes to very small values at liquid helium temperature and then increases very rapidly with temperature (i.e., 0.000382 j/g-K at 4 K and 0.00124 j/g-K at 10 K). As a result, it requires a little change in helium enthalpy to increase the iron temperature a few Kelvin from liquid helium temperatures, but as the iron temperature goes up the change in helium enthalpy required to increase the iron temperature the same amount also goes up. The difference in the temperature profiles between cooldown and warmup can be then understood because during cooldown the iron temperature decreases, while during warmup the iron temperature increases.

Fig. 17 shows the helium temperature at the end of the section during warmup from 4.35 K to 25 K. The section warmup take approximately 3.7 hours. We see that at about 40 minutes the helium temperature at the end of the section increases very rapidly up to 8 K, and then during the rest of the time keeps increasing with a rate that decreases with temperature.

Fig. 18 shows the helium mass flow rate at the end of the section during warmup from 4.35 K to 25 K with an entrance helium gas pressure of 5 atm. During the first 40 minutes of warmup, the helium mass flow rate at the end of the section is approximately 280% higher than the input mass flow rate !. The reason is because the lower temperature portion of the hot front advances very fast (about 42 cm/s), thus the rate of local helium density change is high enough to produce the observed significant change in helium mass flow rate. But after 40 minutes, the lower temperature portion of the hot front already passed the end of the section. The rest of the hot front is advancing slowly, so the helium mass flow rate at the end of the section drops significantly after 40 minutes and slowly decreases down to the input value.

Fig. 19 shows helium mass flow rate profiles along an SSC section during warmup from 4.35 K to 25 K with an helium entrance pressure of 5 atm. We see that the helium mass flow rate has a step-like change in the region where the low temperature portion of the hot front is advancing.

Fig. 20 shows the total helium mass that passed the end of the section during warmup from 4.35 K to 25 K. The total helium mass spent is approximately 256 kg/channel. We see two slopes in the plot of Fig. 19; the reason is because of the higher helium mass flow rate during the first 40 minutes of the warmup operation.

Fig. 21 shows the helium pressure at the end of the section during warmup from 4.35 K to 25 K. The pressure drop is initially high because we have a high mass flow rate along most of the section. As the low temperature portion of the hot front advances, the fraction of the section with high mass flow rate decreases (see Fig. 18), so the pressure drop along the section decreases. But at the same time, the helium temperature increases, what increases the pressure drop. As a result, the pressure drop as a function of time shows a minimum after which the pressure drop increases mainly because the temperature effect on it has became dominant.

Warmup results for an entrance helium pressure of 10 atm.

We run a simulation with an entrance pressure of 10 atm to see what is the effect of pressure on the warmup results. We found that the total warmup time and total amount of helium spent is almost the same than the 5 atm case, but that the maximum helium mass flow rate is 195% higher than the input mass flow rate for the 10 atm case instead of 280% for the 5 atm case. The reason is because the low temperature portion of the hot front is moving more slowly at 10 atm because the helium velocity is lower (higher density). As a consequence, we have a lower rate of local helium density change at 10 atm that produces a lower increase in the mass flow rate. Another consequence of the lower gas velocity at 10 atm is that the high mass flow rate at the end of the section last 1 hour instead of 40 minutes.

Fig. 22 shows helium and iron temperature profiles along an SSC section during warmup from 4.35 K to 25 K with and entrance helium pressure of 10 atm.

Fig. 23 shows the helium temperature at the end of the section during warmup from 4.35 K to 25 K with an entrance helium pressure of 10 atm.

Fig. 24 shows the helium mass flow rate at the end of the section during warmup from 4.35 K to 25 K with an entrance helium pressure of 10 atm.

5. CONCLUSIONS

We have presented a computer model that we developed to simulate cooldown/warmup of SSC magnets by helium flow through the cooling channels.

We have seen that the properties dependence on temperature, in particular the iron specific heat increase with temperature and the helium density decrease with temperature, determine the cooldown/warmup behavior. For example, direct consequences of the way in which properties depend on temperature are: At very low temperatures, the limiting factor on cold or hot temperature front propagation along the magnet is mainly the helium velocity, whereas at high temperatures the limiting factor is mainly the amount of iron mass per unit length; at very low temperature changes in mass flow rate are significant during either cooldown or warmup (and larger during warmup than during cooldown between the same temperature range), whereas at high temperature changes in mass flow rate are negligible,; and warmup temperature fronts are very extended over the magnet length compared to cooldown temperature fronts at all temperatures.

The above mentioned behaviors are illustrated with several practical cooldown/warmup simulation examples for the SSC that we presented in this note. We think that the simulation results are reasonable and consistent with the theory. When possible, we verified them using change of enthalpy balance methods.

The simulations were done using the program COOLWARM and its post-processor PLOTRES that we also presented in this note.

We think that cooldown/warmup simulations can help to determine dynamic parameters for the cryogenic system of the SSC and that they can also help in magnet structural analysis by providing longitudinal iron temperature gradients.

6. REFERENCES

/1/ "SSC Conceptual Design", SSC-SR-2020, March 1986

/2/ K.C. Wu, "Implementation of the NBS631 Helium Property Program for the IBM Personal Computer", SSC-N-173, May 2, 1986.

/3/ "TOPDRAWER", SLAC Computation group, Stanford, California, CQTM No. 178, revised November 1980.

/4/ D.P. Brown and K.C. Wu, "Cooldown Calculations for SSC magnets", SSC-N-21, Nov. 8, 1984.

/5/ R.P. Shutt, "Cooldown of SSC magnets", SSC-N-133, March 26, 1986.

/6/ G. Horlitz and H. Lierl, "Computer Calculations on Steady-State and Different Modes of Cool Down and Warm Up of the Hera Superconduction Proton Ring", DESY HERA 85-20.

/7/ C.A. Bailey, "Advanced Cryogenics", Plenum Press (1971).

7. FIGURES

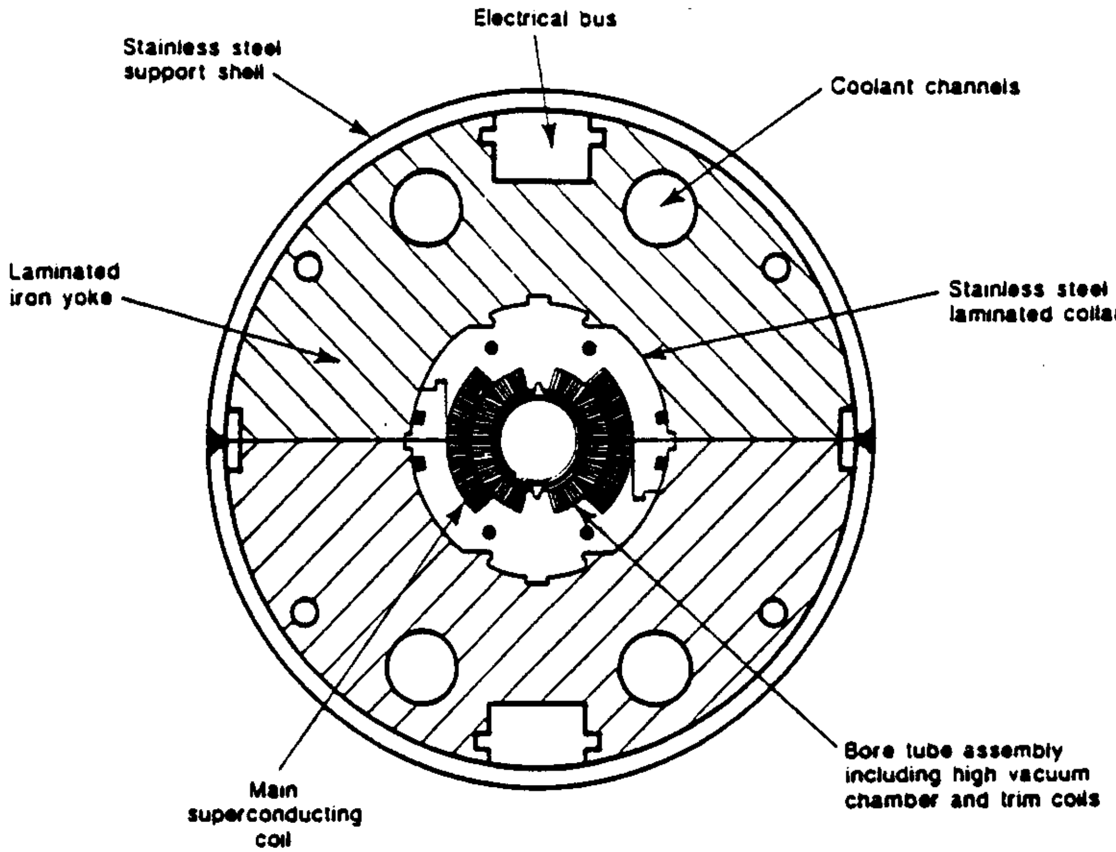

Fig. 1: Cross section of the SSC dipole magnet

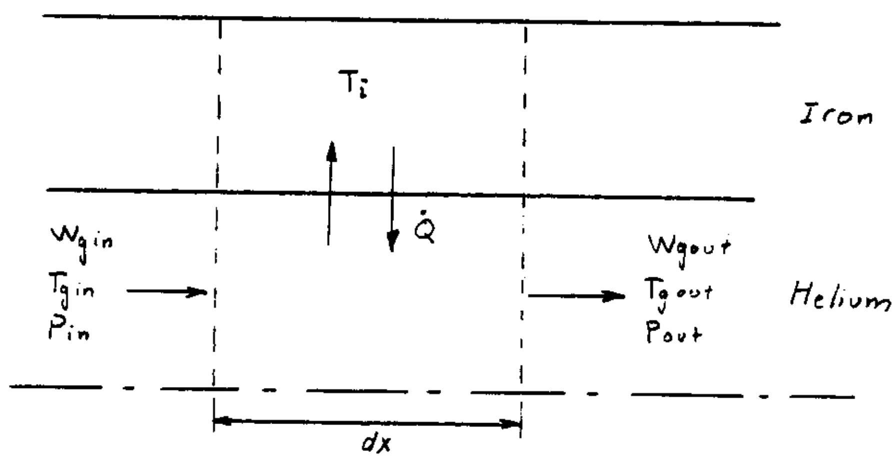

Fig. 2: Control volume for helium and iron

COOLDOWN WAVE NUMBER 1

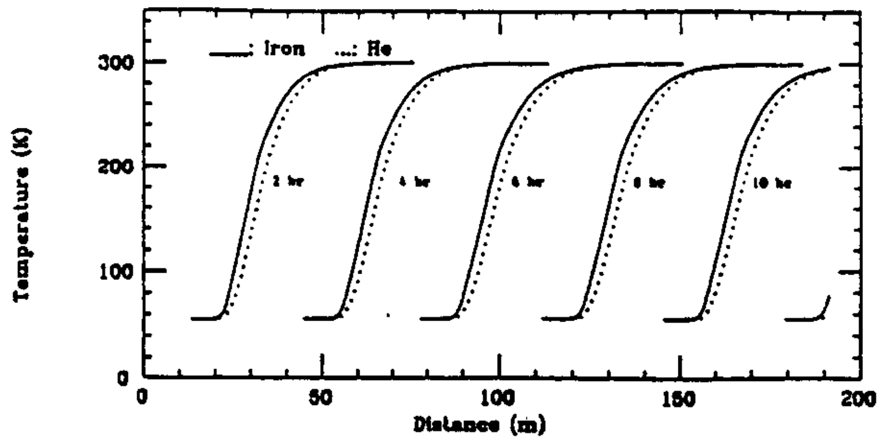

Fig. 3: Helium and iron temperature profiles along an SSC cell during cooldown from 300 K to 55 K.

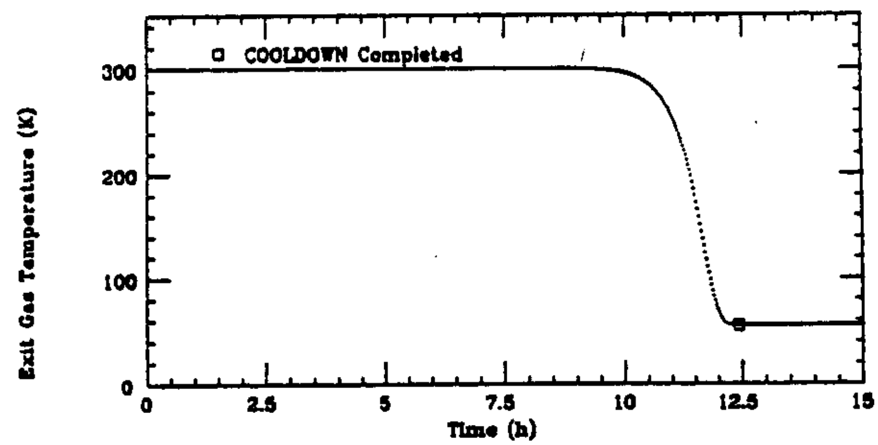

Fig. 4: Helium temperature at the end of the SSC cell during cooldown from 300 K to 55 K.

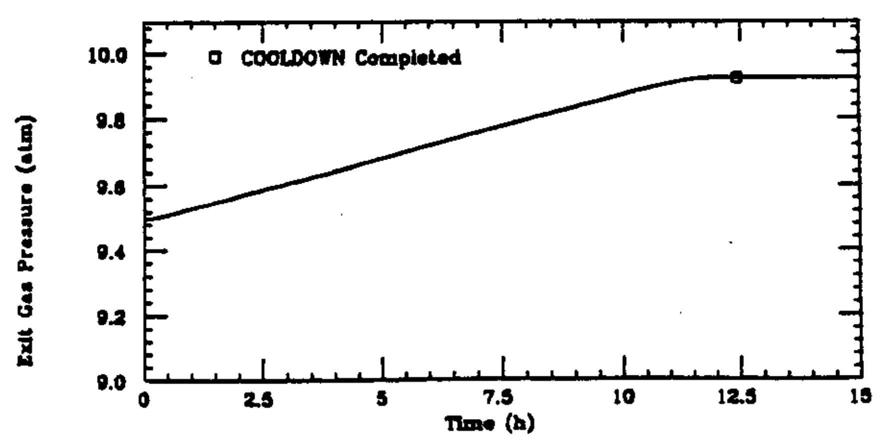

Fig. 5: Helim pressure at the end of the SSC cell during cooldown from 300 K to 55 K.

COOLDOWN WAVE NUMBER 2

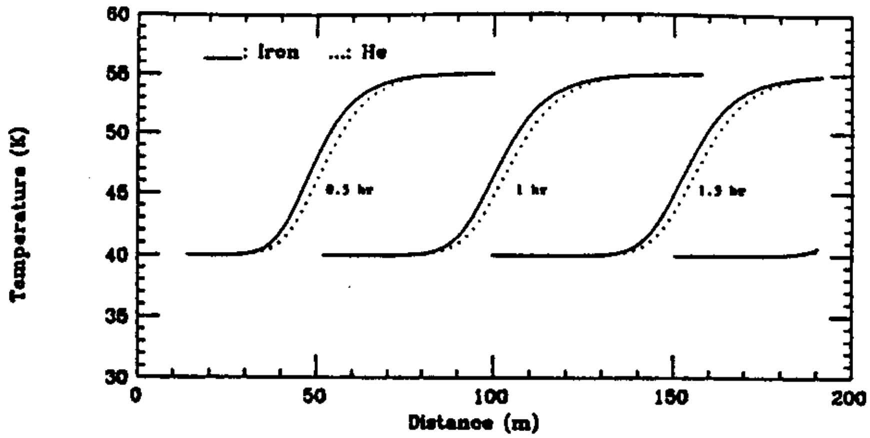

Fig. 6: Helium and iron temperature profiles along an SSC cell during cooldown from 55 K to 40 K.

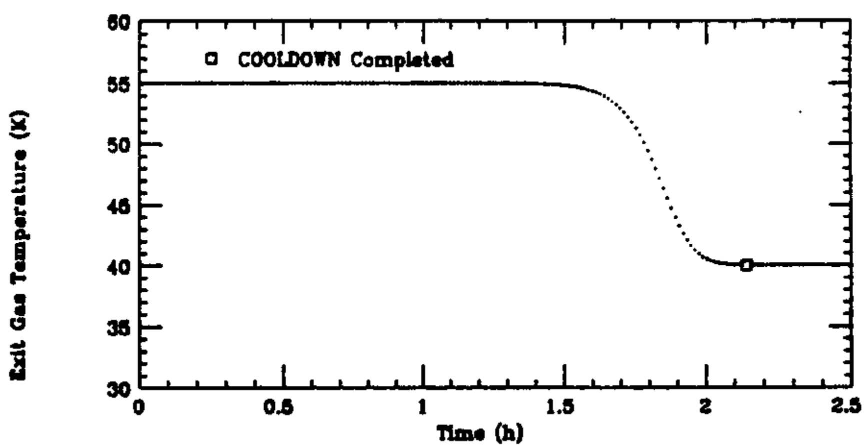

Fig. 7: Helium temperature at the end of the SSC cell during cooldown from 55 K to 40 K.

COOLDOWN WAVE NUMBER 3

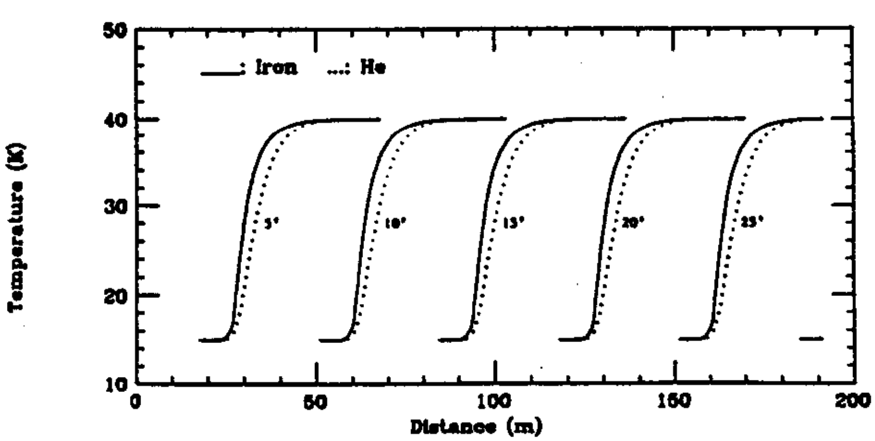

Fig. 8: Helium and iron temperature profiles along an SSC cell during cooldown from 40 K to 15 K.

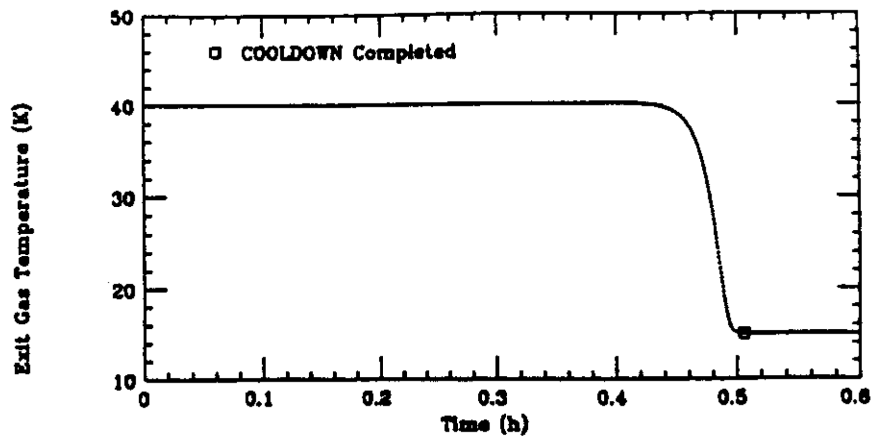

Fig. 9: Helium temperature at the end of the SSC cell during cooldown from 40 K to 15 K.

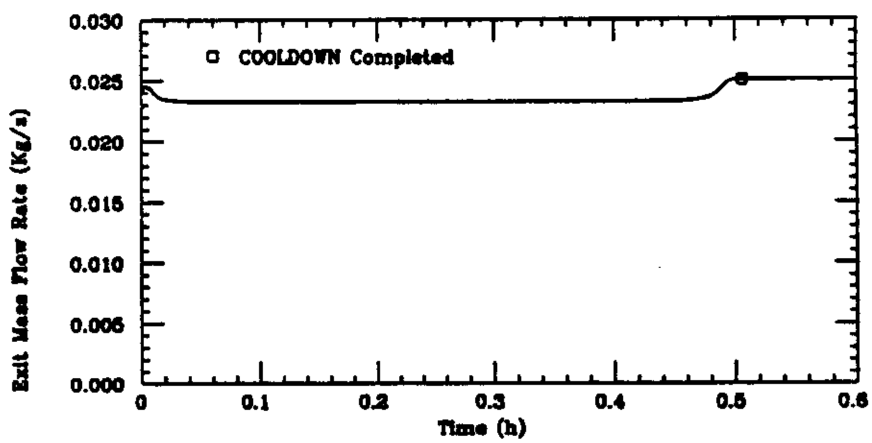

Fig. 10: Helium mass flow rate at the end of the SSC cell during cooldown from 40 K to 15 K.

COOLDOWN WAVE NUMBER 4

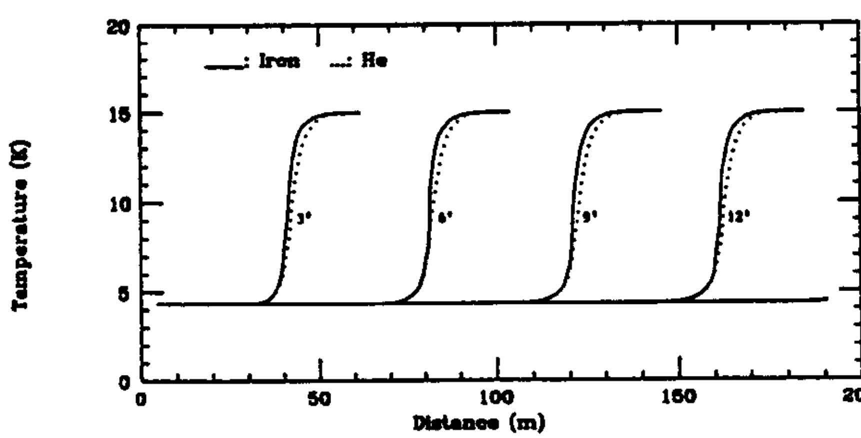

Fig. 11: Helium and iron temperature profiles along an SSc cell during cooldown from 15 K to 4.35 K.

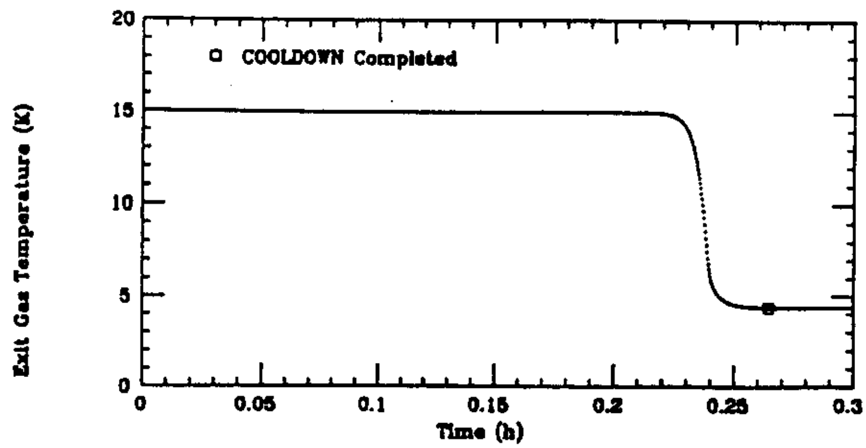

Fig. 12: Helium temperature at the end of the SSC cell during cooldown from 15 K to 4.35 K.

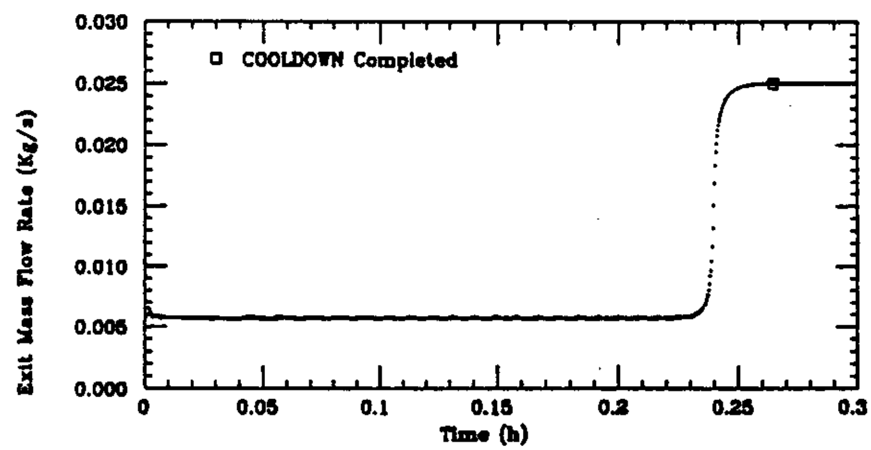

Fig. 13: Helium mass flow rate at the end of the SSC cell during cooldown from 15 K to 4.35 K.

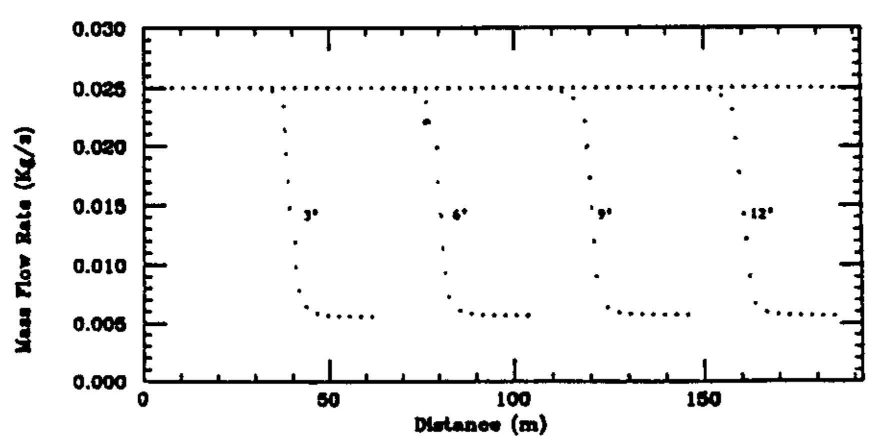

Fig. 14: Helium mass flow rate profiles along an SSC cell during cooldown from 15 K to 4.35 K.

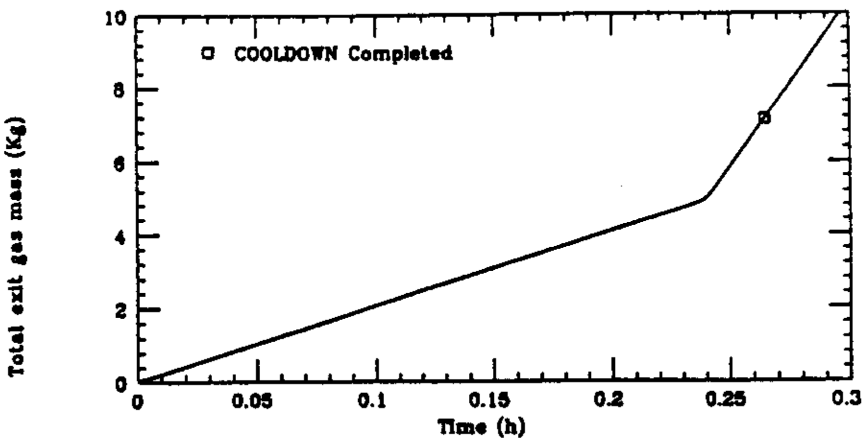

Fig. 15: Total helium mass that passed the end of the SSC cell during cooldown from 15 K to 4.35 K.

COMPARATIVE PLOTS

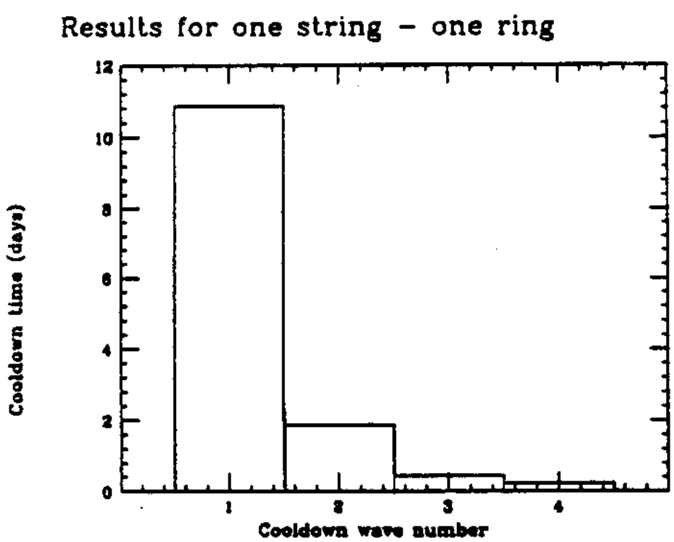

Fig. 15a

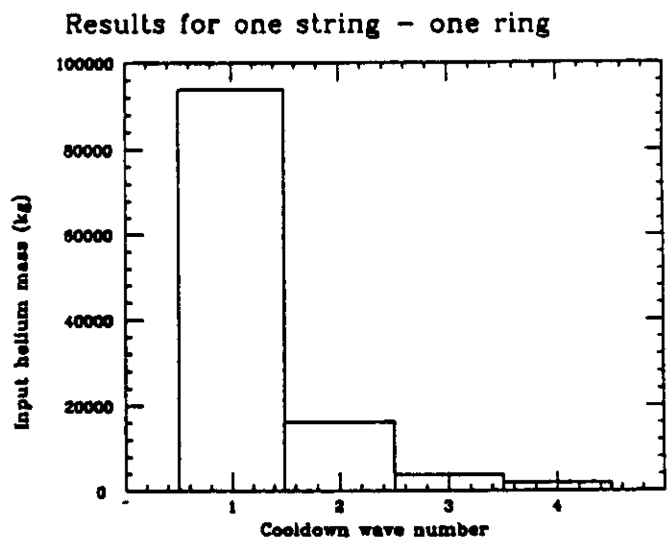

Fig. 15b

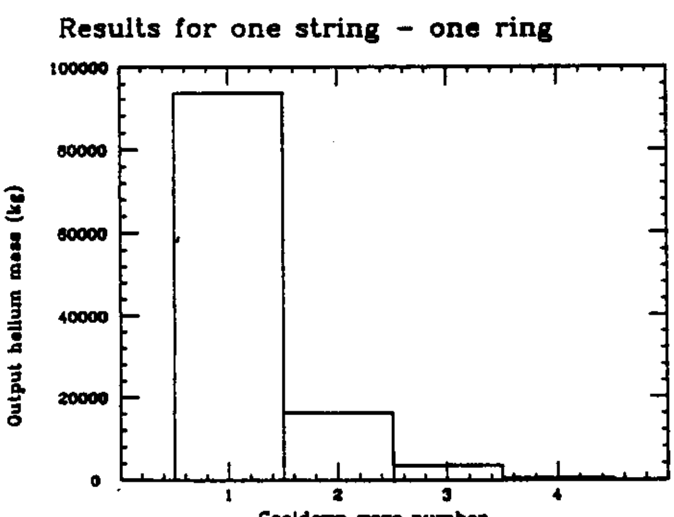

Fig. 15c

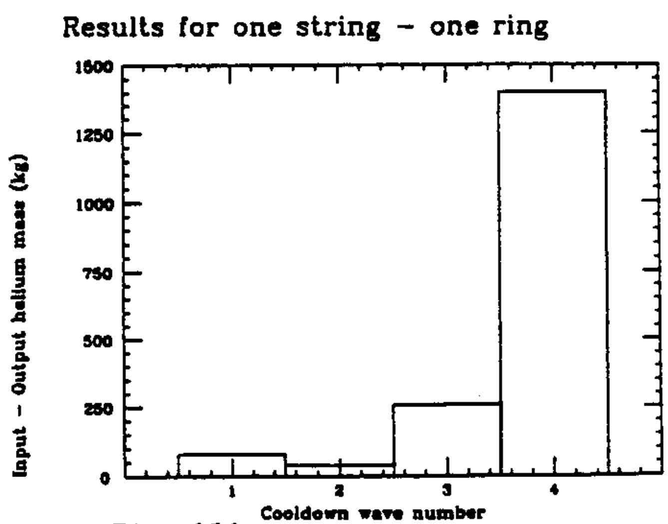

Fig. 15d

HELIUM ENTRANCE PRESSURE: 5 atm.

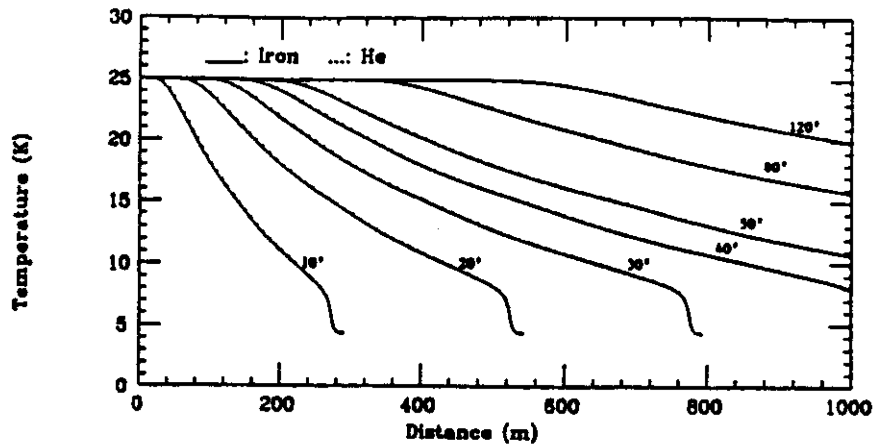

Fig. 16: Helium and iron temperature profiles along an SSC section during warmup from 4.35 K to 25 K.

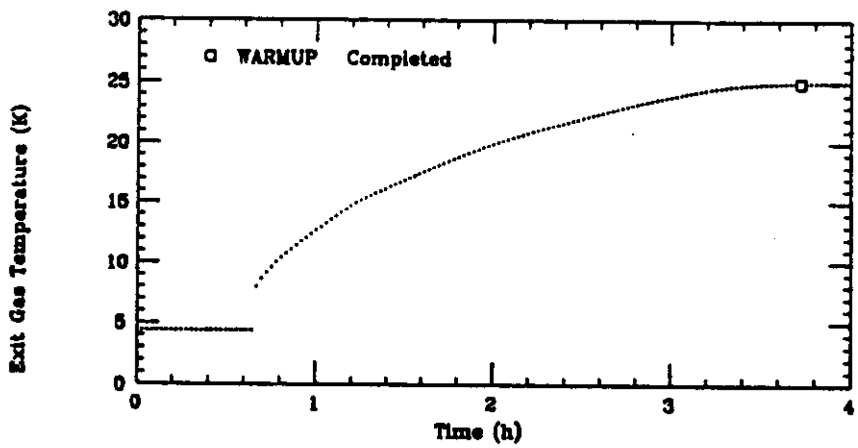

Fig. 17: Helium temperature at the end of the SSC section during warmup from 4.35 K to 25 K.

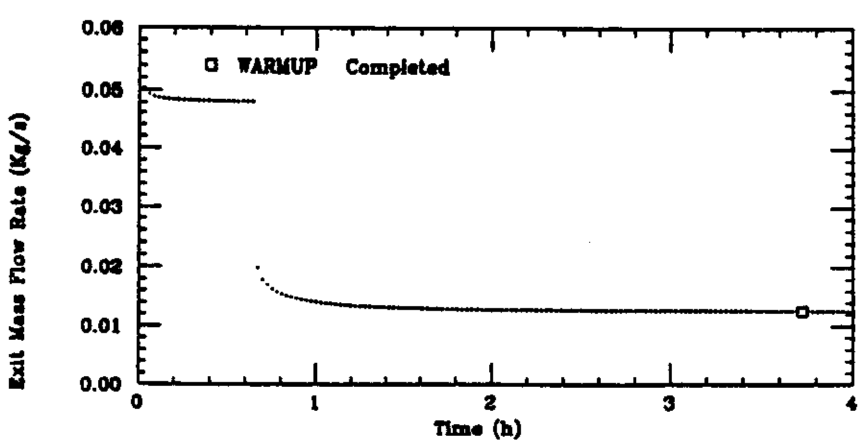

Fig. 18: Helium mass flow rate at the end of the SSC section during warmup from 4.35 K to 25 K.

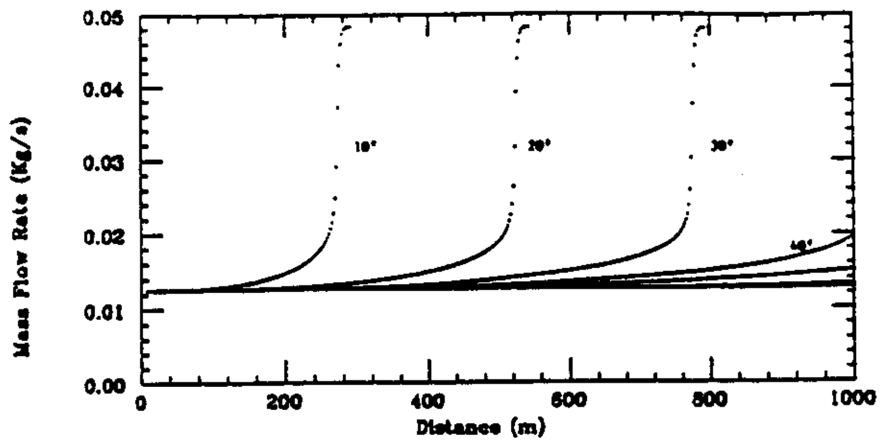

Fig. 19: Helium mass flow rate profiles along an SSC section during warmup from 4.35 K to 25 K.

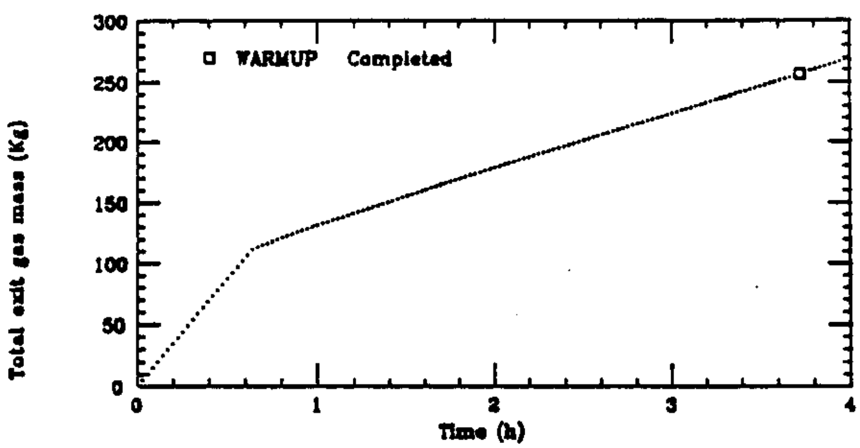

Fig. 20: Total helium mass that passed the end of the SSC section during warmup from 4.35 K to 25 K.

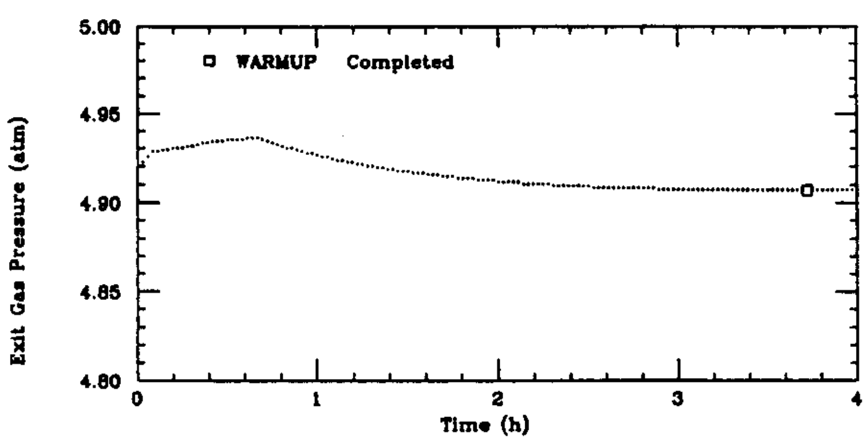

Fig. 21: Helium pressure at the end of the SSC section during warmup from 4.35 K to 25 K.

HELIUM ENTRANCE PRESSURE: 10 atm.

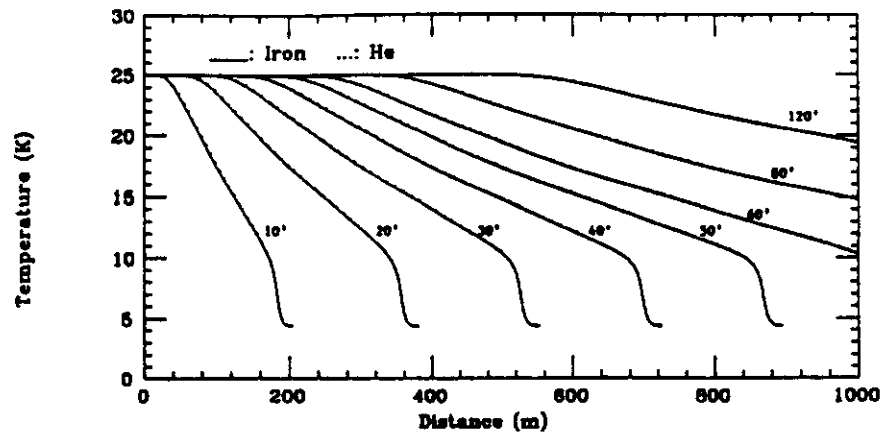

Fig. 22: Helium and iron temperature profiles along an SSC section during warmup from 4.35 K to 25 K.

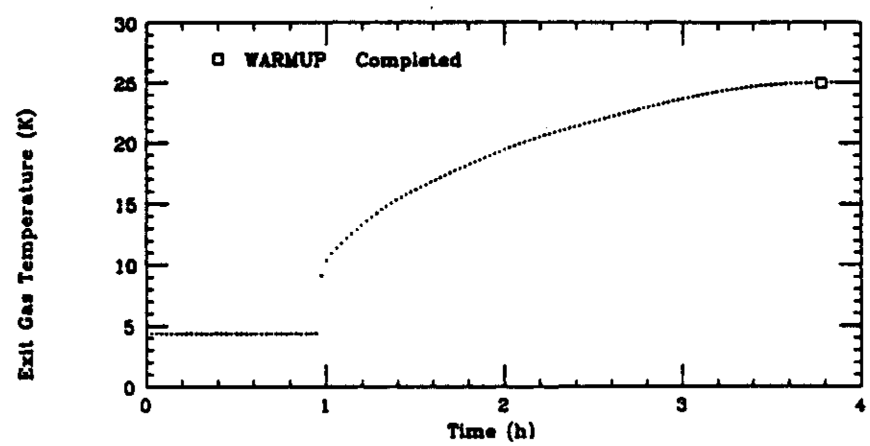

Fig. 23: Helium temperature at the end of the SSC section during warmup from 4.35 K to 25 K.

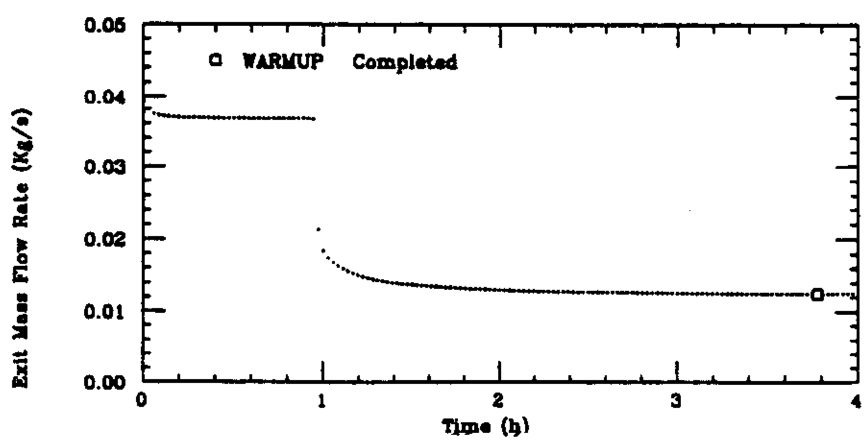

Fig. 24: Helium mass flow rate at the end of the SSC section during warmup from 4.35 K to 25 K.

8. APPENDIX A: Nomenclature

A : Cooling channel cross-section area

C_p^i: Iron specific heat

C_p^g: Helium specific heat

D : Cooling channel diameter

f : friction factor

h : heat transfer coefficient

H : Pressure head

m_i: Iron mass per unit length

P : Cooling channel perimeter

P_r : Prandtl number

Q : Total heat exchanged in the control volume

Q_c: Helium heat content

Q_{tr}: Helium heat transport

R_e : Reynolds number

t: : Time

T_i: Iron temperature

T_g: Helium temperature

w_g: Helium mass flow rate

x : Distance along the cooling channel

ρ_g: Helium density

τ_i : Iron characteristic time

τ_g : Helium characteristic time

λ_g : Helium characteristic length

μ_b : Helium viscosity at the bulk temperature

μ_w: Helium viscosity at the wall temperature

9. APPENDIX B: Some limit cases for the PDE.

In this appendix we discuss some limit cases for the partial differential equations obtained in section 2.2. The limit cases help to understand the basic mechanism of cooldown/warmup at different temperatures. We are going to restrict our discussion to the SSC case, so when we talk about "low temperature approximation" or "high temperature approximation" it is implied that we are talking about the SSC conditions.

We start by calculating the characteristic time for helium (τ_g), the characteristic length for helium (λ_g), and the characteristic time for iron (τ_i) for different temperatures. Table B.1 shows the results.

T (K)	λ_g (m)	τ_g (s)	$v_g=\lambda_g/\tau_g$ (m/s)	τ_i (s)
4.35	2.7	11.5	0.23	1.4
7	3.6	11.8	0.31	1.6
10	4.1	7.3	0.56	2.5
15	3.6	3.5	1.0	5.3
20	3.3	2.3	1.4	9.7
25	3.2	1.7	1.9	16.1
30	3.1	1.4	2.2	15.7
100	2.6	0.35	7.4	400.0
300	2.2	0.10	22.0	718.0

Table B.1: Characteristic coefficients dependence on temperature.

We see that, while the characteristic length for helium doesn't change much, the characteristic times depend very strongly on temperature. τ_g dependence on temperature is dominated by the helium density dependence on temperature, so it decreases with temperature. On the other hand, τ_i dependence on temperature is dominated by the iron specific heat dependence on temperature, so it increases with temperature. This opposite behavior of the characteristic times for helium and iron with temperature allow us to identify two "limit cases": one for low temperatures and the other for high temperatures.

Limit case A: Low temperature approximation.

$$\tau_i \cong 0, \quad \tau_g >> \tau_i$$

In this case, we have instantaneous heat diffusion in the iron. The iron temperature will follow the gas temperature without delay. Equation (8) can be written as:

$$v_g \frac{\partial T_g}{\partial x} + \frac{\partial T_g}{\partial t} = 0 \qquad \text{(B.1)}$$

This equation represents a wave propagating at velocity v_g. This limit case help to understand the basic mechanism of cooldown/warmup at very low temperatures. The helium velocity is the main limiting factor in the cold or warm temperature front propagation. At the same time, the helium velocity at very low temperatures is much lower than at high temperatures because of the increase in density with decreasing temperatures.

Limit case B: High temperature approximation.

$$\tau_g \cong 0, \quad \tau_i >> \tau_g$$

In this case, we have instantaneous heat diffusion in the helium. This approximation is equivalent to neglect changes in the helium heat content in the control volume during dt. As a result, we can write equation (8) as:

$$\lambda_g \frac{\partial T_g}{\partial x} = T_i - T_g \qquad \text{(B.2)}$$

We see that according to equation (B.2), the helium temperature "adjust" itself to changes in the iron temperatures instantaneously (there is no time dependence), so the limiting factor for cold or warm temperature front propagation at high temperatures is given by the characteristic time for temperature changes in iron (because of the high iron specific heat at high temperatures), which is proportional to the iron mass per unit length that we want to cooldown or warmup.

Equation (B.2) is not a bad approximation of equation (8) at high temperatures. It was used in ref. /6/ for cooldown and warmup computer calculations of the Hera superconducting proton ring. In our model, we also use equation (B.2) when appropriate. Otherwise, using equation (8) at high temperatures would require an extremely small time step to satisfy the condition $\Delta t << \tau_g$ and the results would be almost the same than using equation (B.2) with a larger time step.

Equation (B.1) in not a good approximation of equation (8) at low temperatures, so we use equation (8) to solve low temperature cases.

10. APPENDIX C: FORTRAN listing of COOLWARM and PLOTRES

```
C PROGRAM COOLWARM
C   RUBEN H. CARCAGNO, JULY 1987
C
C------------------------------------------------------------------------
C   THIS PROGRAM EVALUATES COOLDOWN/WARMUP PARAMETERS FOR THE SSC DIPOLE
C   MAGNETS.
C------------------------------------------------------------------------
C
C ** PROPERTIES **
C   FOR HELIUM: INTERFASE WITH NBS631 HELIUM PROPERTY SUBROUTINES (MODIFIED)
C   FOR IRON: TABLE WITH CP AS A FUNCTION OF TEMPERATURE. THE PROGRAM MAKES
C   LINEAR INTERPOLATION BETWEEN TABLE POINTS.
C
      REAL LAMBDA
      COMMON /PROP/CID(21),TD(21),RO(101),U(101),TK(101),TGD(101)
      COMMON /PAR/TL,DX,TT,DT,D,WG,WI,TI0,TG0,TMIN,TMAX,DTE,A,P
      COMMON /RES/ TG(0:20000),TI(0:20000),PG(0:20000)
      COMMON /MASS/GF(0:20000),DG(0:20000),DGOLD(0:20000)
      DIMENSION ISTORE(0:20000)
C
      MAXDIM=20000
C
C -- IRON SPECIFIC HEAD DATA
      DATA CID /.382,.615,.90,1.24,
     1          2.49,4.5,7.5,12.4,29.,55.,136.,216.,245.,275.,304.,
     2          333.,480.,392.,421.,450.,450./
      DATA TD /4.,6.,8.,10.,15.,20.,25.,30.,40.,50.,75.,100.,125.,
     1         150.,175.,200.,225.,250.,275.,300.,325./
C
C -- INPUT DATA
      WRITE(*,10)
10    FORMAT(' ENTER TOTAL MAGNET LENGTH (M)')
      READ (*,*)TL
      WRITE(*,30)
30    FORMAT(' ENTER TOTAL SIMULATION TIME (SEC)')
      READ(*,*)TT
      WRITE(*,50)
50    FORMAT(' ENTER CHANNEL DIAMETER (M)')
      READ(*,*)D
      WRITE(*,60)
60    FORMAT(' ENTER GAS FLOW RATE PER CHANNEL (KG/S)')
      READ(*,*)WG
      WRITE(*,70)
70    FORMAT(' ENTER IRON MASS PER UNIT LENGTH PER CHANNEL (KG/M)')
      READ(*,*)WI
      WRITE(*,80)
80    FORMAT(' ENTER INITIAL IRON TEMPERATURE (K)')
      READ(*,*)TI0
      WRITE(*,90)
90    FORMAT(' ENTER GAS ENTRANCE TEMPERATURE (K)')
      READ(*,*)TG0
      WRITE(*,95)
95    FORMAT(' ENTER GAS ENTRANCE PRESSURE (ATM)')
      READ(*,*)PG0
C
C-- DEFINE PROPERTIES TABLES
```



```
      CALL INIT
      CALL PROPTAB(100,TG0,TI0,PG0)
C
C -- MISCELLANEOUS
      TMIN=AMIN1(TI0,TG0)
      TMAX=AMAX1(TI0,TG0)
      DTE=TMAX-TMIN
      TCMIN=1.0001*TMIN
      TCMAX=0.9999*TMAX
      IF(TG0.LT.TI0)MODE=1
      IF(TG0.GT.TI0)MODE=2
      PI=3.1415927
      A=PI*(D/2.)**2
      P=2.*PI*(D/2.)
C
C -- CHARACTERISTIC LENGTH AND TIMES
      GF(2)=WG
      TG(2)=TMIN
      TI(2)=TMIN
      PG(2)=PG0
      CALL PARAM(-2,GLAM1,TAU1,X,X,TAUG1)
      TG(2)=TMAX
      TI(2)=TMAX
      CALL PARAM(-2,GLAM2,TAU2,X,X,TAUG2)
C
      ROMIN=FINDD(PG0,TMIN,-1)*1000.
      HECMIN=ROMIN*A*TL
      ROMAX=FINDD(PG0,TMAX,-1)*1000.
      HECMAX=ROMAX*A*TL
C
      WRITE(*,9876)TMIN,GLAM1,TAUG1,TAU1,GLAM1/TAUG1,HECMIN,
     1             TMAX,GLAM2,TAUG2,TAU2,GLAM2/TAUG2,HECMAX
9876  FORMAT(/' *** CHARACTERISTIC LENGTH AND TIMES *** : '//,
     1      '        MINIMUM TEMPERATURE: ',F7.3/,
     2      '     CHARACTERISTIC LENGTH FOR GAS (M).: ',F7.3/,
     3      '     CHARACTERISTIC TIME FOR GAS (S)....: ',F7.3/,
     4      '     CHARACTERISTIC TIME FOR IRON (S)..: ',F7.3/,
     C      '     GAS VELOCITY AT TMIN,P0 (M/S)......: ',F7.3/,
     A      '     GAS TOTAL MASS IN THE CHANNEL (KG): ',F7.3//,
     5      '        MAXIMUM TEMPERATURE (K): ',F7.3/,
     6      '     CHARACTERISTIC LENGTH FOR GAS (M).: ',F7.3/,
     7      '     CHARACTERISTIC TIME FOR GAS (S)....: ',F7.3/,
     8      '     CHARACTERISTIC TIME FOR IRON (S)..: ',F7.3/,
     D      '     GAS VELOCITY AT TMAX,P0 (M/S)......: ',F7.3/,
     E      '     GAS TOTAL MASS IN THE CHANNEL (KG): ',F7.3/)
C
C -- SELECTION OF APPROXIMATION AND STEPS
C    IAP=1: HOT TEMPERATURE APPROXIMATION (TAUG=0)
C    IAP=2: COLD TEMPERATURE (NO APPROXIMATIONS)
C
      IF (TAU1/TAUG1.GT.10.)THEN
      IAP=1
      DT=0.1*TAU1
      DX=0.1*GLAM1
      WRITE(*,9877)DT,DX
9877  FORMAT('  *** HOT TEMPERATURE APPROXIMATION USED ***'/,
```

```
     3         ' RECOMMENDED STEPS: TIME (S) LESS THAN...: ',F7.3/,
     1         '                    LENGTH (M) LESS THAN : ',F7.3//)
C
      ELSE
      IAP=2
      RATIO=TAUG1/GLAM1
      WRITE(*,8978)0.1*TAU1,0.1*GLAM1,RATIO
8978  FORMAT(' RECOMMEDED STEPS: TIME (S) LESS THAN....: ',F7.3/,
     2      '                   LENGTH (M) LESS THAN..: ',F7.3/,
     1      '                   DT/DX LESS THAN...... : ',F7.3//)
      ENDIF
C
      WRITE(*,97)
97    FORMAT(' ENTER TIME STEP (M)')
      READ(*,*)DT
      WRITE(*,98)
98    FORMAT(' ENTER DISTANCE STEP (SEC)')
      READ(*,*)DX
      IF (IAP.EQ.2) THEN
      WRITE(*,8979)DT/DX
8979  FORMAT(/' YOUR DT/DX IS: ',F7.3/)
      ENDIF
      WRITE(*,99)
99    FORMAT(' ENTER 1 TO PLOT RESULTS OR 0 TO SKIP')
      READ(*,*)IPLOT
      WRITE(*,100)
100   FORMAT(' ENTER PRINT STEP')
      READ(*,*)NPRINT
C
C -- OPEN FILES
C     COOLWARM.RES: TO PRINT SCREEN INFORMATION EVERY NPRINT STEPS
C     COOLWARM.END: TO PLOT EXIT PARAMETERS AS A FUNCTION OF TIME
C     COOLWARM.LIS: TO PLOT PARAMETERS AS A FUNCTION OF DISTANCE
C                   (AND TIME).
C
      OPEN(UNIT=2,FILE='COOLWARM.RES',FORM='FORMATTED',
     1     TYPE='UNKNOWN')
C
      IF (IPLOT.EQ.1)THEN
      OPEN(UNIT=3,FILE='COOLWARM.END',FORM='UNFORMATTED',
     1     TYPE='UNKNOWN')
C
      OPEN(UNIT=1,FILE='COOLWARM.LIS',FORM='UNFORMATTED',
     1   TYPE='UNKNOWN')
      ENDIF
C
C -- CALCULATES NUMBER OF DISTANCE STEPS
      NDX=ABS(TL/DX)
      NDXP=NDX+1
      IF (NDXP.GE.MAXDIM) THEN
      WRITE(*,5839)NDXP,MAXDIM
5839  FORMAT(//' ** NUMBER OF NODES (',I5,') EXCEEDS DIMENSION (',
     1        I5,') **'/,'  EXECUTION TERMINATED')
      ENDIF
C
C -- CALCULATES NUMBER OF TIME STEPS
```



```
      NDT=ABS(TT/DT)
      NDTP=NDT+1
      NEND=1
      IF (NDT.GT.100) NEND=NDT/100
C
C -- WRITE PARAMETERS INFORMATION
      IF (IPLOT.EQ.1)THEN
      WRITE(1)TL,DX,TT,DT,D,WG,WI,TI0,TG0,PG0,NPRINT,NDX,NDT
      ENDIF
C
      WRITE(*,6798)TL,DX,TT,DT,D,WG,WI,TI0,TG0,PG0
      WRITE(2,6798)TL,DX,TT,DT,D,WG,WI,TI0,TG0,PG0
6798  FORMAT(' TOTAL LENGTH (M).............: ',F8.3/,
     1       ' DISTANCE STEP (M)............: ',F8.3/,
     2       ' TOTAL TIME (SEC).............: ',F10.3/,
     3       ' TIME STEP (SEC)..............: ',F8.3/,
     4       ' DIAMETER (M).................: ',F8.3/,
     5       ' GAS MASS FLOW (KG/S).........: ',F8.3/,
     6       ' IRON MASS/LENGTH (KG/M).......: ',F8.3/,
     7       ' INITIAL IRON TEMPERATURE (K)..: ',F8.3/,
     8       ' INITIAL GAS TEMPERATURE (K)...: ',F8.3/,
     9       ' ENTRANCE GAS PRESSURE (ATM)...: ',F8.3//)
C
      WRITE(2,9876)TMIN,GLAM1,TAUG1,TAU1,GLAM1/TAUG1,HECMIN,
     1             TMAX,GLAM2,TAUG2,TAU2,GLAM2/TAUG2,HECMAX
C
C
C -- CALCULATES INITIAL TEMPERATURE DISTRIBUTIONS FOR IRON AND GAS
C
      ICOUNT=0
      TIME=0.
C
      DO 3 I=0,NDX
      ISTORE(I)=0
      TI(I)=TI0
      GF(I)=WG
3     CONTINUE
C
      PG(0)=PG0
C
      IF (IAP.EQ.1) THEN
C
C -- IAP=1
      TG(0)=TG0
      DO 500 I=1,NDX
      CALL PARAM (I-1,LAMBDA,TAU,DPG,X,X)
      TG(I)=TI(I-1)+(TG(I-1)-TI(I-1))*EXP(-(DX/LAMBDA))
      PG(I)=PG(I-1)+DPG
500   CONTINUE
C
      ELSE
C
C -- IAP=2
      TG(0)=TI0
      DGOLD(0)=FINDD(PG0,TI0,-1)*1000.
      DO 1000 I=1,NDX
```

```
      TG(I)=TI0
      CALL PARAM(I-1,LAMBDA,TAU,DPG,X,X)
      PG(I)=PG(I-1)+DPG
      DGOLD(I)=FINDD(PG(I),TI0,-1)*1000.
1000  CONTINUE
C
      ENDIF
C
C------------------------ TIME LOOP ---------------------------
C
      TG(0)=TG0
C
      DO 2000 K=1,NDT
C
      TIME=K*DT
C
      I=0
      CALL PARAM (-1,LAMBDA,TAU,DPG,DGF,TAUG)
      DPG=0.
      DGF=0.
      TI(0)=TG(0)+(TI(0)-TG(0))*EXP(-DT/TAU)
C
C------------------------ SPATIAL LOOP ------------------------
C
      ICOUNT=0
C
      DO 3000 I=1,NDX
C
      ISTORE(I)=0
C
      IF (MODE.EQ.1)THEN
      IF (TG(I).LT.TCMIN.AND.TI(I).LT.TCMIN) GOTO 3000
      ENDIF
C
      IF (MODE.EQ.2)THEN
      IF (TG(I).GT.TCMAX.AND.TI(I).GT.TCMAX) GOTO 3000
      ENDIF
C
      ISTORE (I)=1
      ICOUNT=ICOUNT+1
      CALL PARAM(I-1,LAMBDA,TAU,DPG,DGF,TAUG)
C
C-- PRESSURE DROP
      PG(I)=PG(I-1)+DPG
C
C-- IRON TEMPERATURE
      TIOLD=TI(I)
      TI(I)=TG(I)+(TI(I)-TG(I))*EXP(-DT/TAU)
C
C-- GAS TEMPERATURE
      IF (IAP.EQ.1) THEN
      GF(I)=GF(I-1)+DGF
      TG(I)=TI(I-1)+(TG(I-1)-TI(I-1))*EXP(-DX/LAMBDA)
      ELSE
      GF(I)=GF(I-1)+DGF
      DIG=LAMBDA/DX
```



```
      TIG=TAUG/DT
      TG(I)=(TIOLD+DIG*TG(I-1)+TIG*TG(I))/(1.+DIG+TIG)
      ENDIF
C
      IF (GF(I).LE.0.)GOTO 1999
C
      IF (MODE.EQ.1)THEN
      IF (TG(I).GT.TCMAX.AND.TI(I).GT.TCMAX) THEN
      IF (I.LT.NDX)THEN
      DO 586 L=I+1,NDX
      PG(L)=PG(L-1)+DPG
      GF(L)=GF(I)
586   CONTINUE
      GOTO 1999
      ENDIF
      ENDIF
      ENDIF
C
      IF (MODE.EQ.2) THEN
      IF (TG(I).LT.TCMIN.AND.TI(I).LT.TCMIN) THEN
      IF (I.LT.NDX)THEN
      DO 587 L=I+1,NDX
      PG(L)=PG(L-1)+DPG
      GF(L)=GF(I)
587   CONTINUE
      GOTO 1999
      ENDIF
      ENDIF
      ENDIF
C
3000  CONTINUE
C
C------------------------ END SPATIAL LOOP ------------------------
C
1999  CONTINUE
C
C -- PRINTOUT CHECK
      IF (ABS(K/NPRINT)*NPRINT.EQ.K)THEN
      WRITE(2,200)TIME,TI(0),TI(NDX/2),TI(NDX),TG(0),TG(NDX/2),
     1            TG(NDX),PG(NDX)-PG(0),GF(NDX)
      WRITE(6,200)TIME,TI(0),TI(NDX/2),TI(NDX),TG(0),TG(NDX/2),
     1            TG(NDX),PG(NDX)-PG(0),GF(NDX)
200   FORMAT(' ** SOLUTION AT TIME (SEC): ',F10.3,' **'/,
     1       '  TIRON(0)=',F7.2,'  TIRON(L/2)=',F7.2,'  TIRON(L)=',F7.2/,
     2       '  TGAS(0) =',F7.2,'  TGAS(L/2) =',F7.2,'  TGAS(L) =',F7.2/,
     3       '  PRESSURE DROP (ATM) = ',E10.3/,
     5       '  EXIT MASS FLOW RATE (KG/S) = ',F8.4//)
C
C -- PLOTTING CHECK
      IF (IPLOT.EQ.1)THEN
      WRITE(1)TIME,ICOUNT
      DO 4000 I=0,NDX
      IF (ISTORE(I).EQ.1)THEN
      X=I*DX
      WRITE(1) X,TG(I),TI(I),PG(I),GF(I)
      ENDIF
```

```
4000  CONTINUE
      ENDIF
      ENDIF
C
      IF (IPLOT.EQ.1)THEN
      IF(ABS(K/NEND)*NEND.EQ.K)THEN
      WRITE(3)TIME,TG(NDX),TI(NDX),PG(NDX),GF(NDX)
      ENDIF
      ENDIF
C
2000  CONTINUE
C
C---------------------------- END TIME LOOP -----------------------------
C
      STOP
      END
C
C************************************************************* SUBROUTINE PARAM
      SUBROUTINE PARAM(MM,LAMBDA,TAU,DPG,DGF,TAUG)
C*****************************************************************************
C
C----------------------------------------------------------------------------
C  THIS SUBROUTINE CALCULATES CHARACTERISTIC LENGTH, CHARACTERISTIC TIMES,
C  PRESSURE DROP AND CHANGE OF MASS FLOW RATE.
C----------------------------------------------------------------------------
C
      REAL LAMBDA
      COMMON /PROP/CID(21),TD(21),RO(101),U(101),TK(101),C(101),TGD(101)
      COMMON /PAR/TL,DX,TT,DT,D,WG,WI,TI0,TG0,TMIN,TMAX,DTE,A,P
      COMMON /MASS/GFLOW(0:20000),DG(0:20000),DGOLD(0:20000)
      COMMON /RES/ TGAS(0:20000),TIRON(0:20000),PGAS(0:20000)

      I=ABS(MM)
      IF (MM.EQ.-1)I=0
C
      TG=TGAS(I)
      TI=TIRON(I)
      GF=GFLOW(I)
      PG=PGAS(I)
      G=GF/A
C
      DO 125 K=1,21
      IF (TI.GE.TD(K)) THEN
      IF (TI.LT.TD(K+1)) THEN
      M=K
      GOTO 126
      ENDIF
      ENDIF
125   CONTINUE
      WRITE(*,131)TI
131   FORMAT(' ERROR. TI OUTSIDE TABLE RANGE. TI: ',F7.2)
      STOP
C
126   CONTINUE
C
      CI=CID(M)+(CID(M+1)-CID(M))*(TI-TD(M))/(TD(M+1)-TD(M))
```



```
C
      N=100
      NM1=101
      L=ABS(((TG-TMIN)/DTE)*N+1.)
      M=ABS(((TI-TMIN)/DTE)*N+1.)
C
      IF (L.LT.101)THEN
      ROG=RO(L)+(RO(L+1)-RO(L))*(TG-TGD(L))/(TGD(L+1)-TGD(L))
      CG=C(L)+(C(L+1)-C(L))*(TG-TGD(L))/(TGD(L+1)-TGD(L))
      UG=U(L)+(U(L+1)-U(L))*(TG-TGD(L))/(TGD(L+1)-TGD(L))
      TKG=TK(L)+(TK(L+1)-TK(L))*(TG-TGD(L))/(TGD(L+1)-TGD(L))
      ELSE
      ROG=RO(L)
      CG=C(L)
      UG=U(L)
      TKG=TK(L)
      ENDIF
C
      PR=UG*CG/TKG
C
      IF(M.LT.101)THEN
      UW=U(M)+(U(M+1)-U(M))*(TI-TGD(M))/(TGD(M+1)-TGD(M))
      ELSE
      UW=U(M)
      ENDIF
C
C
      RE=G*D/UG
      A1=G*CG*0.023*RE**(-0.2)
      A2=(PR**(2./3.))*(UW/UG)**0.14
      ALPHA=A1/A2
C
      LAMBDA=G*A*CG/(P*ALPHA)
      TAUG=CG*A*ROG/(P*ALPHA)
      TAU=WI*CI/(P*ALPHA)
C
C PRESSURE DROP IN DX
      IF(MM.GE.0)THEN
      HEAD=G**2./(2.*ROG)
      F=0.046*RE**(-0.2)
      DPG=-4.*F*DX*HEAD/D
C CONVERT TO ATM
      DPG=DPG*0.9869E-5
C
C CHANGE OF MASS FLOW RATE
      DG(I)=ROG
      DGF=-A*DX*(DG(I)-DGOLD(I))/DT
      DGOLD(I)=ROG
      ENDIF
C
      RETURN
      END
C
C************************************************************ SUBROUTINE PROPTAB
      SUBROUTINE PROPTAB(I,TG0,TI0,PG0)
C*****************************************************************************
```

```
C
C-----------------------------------------------------------------------
C THIS SUBROUTINE USES THE NBS631 HELIUM PROPERTY PROGRAM TO CREATE A TABLE
C OF HELIUM PROPERTIES OF 100 POINTS BETWEEN THE MINIMUM TEMPERATURE AND
C THE MAXIMUM TEMPERATURE. THE PROGRAM THEN MAKES LINEAR INTERPOLATION
C BETWEEN POINTS.
C-----------------------------------------------------------------------
C
      COMMON /PROP/CID(21),TD(21),RO(101),U(101),TK(101),C(101),TGD(101)
C
      TMIN=AMIN1(TG0,TI0)
      TMAX=AMAX1(TG0,TI0)
C
      DTE=(TMAX-TMIN)/I
C
      TGD(1)=TMIN
      DO 10 K=2,I+1
      TGD(K)=TGD(K-1)+DTE
10    CONTINUE
C
      DO 20 K=1,I+1
      T=TGD(K)
      ROG=FINDD(PG0,T,-1)
      RO(K)=ROG*1000.
      U(K)=VISCDT(ROG,T)/10.
      C(K)=CP(ROG,T)*1000.
      TK(K)=THCON(ROG,T)/10.
20    CONTINUE
C
      RETURN
      END
```

```
C
C PROGRAM PLOTRES
C    RUBEN H. CARCAGNO, JULY 1987
C
C-----------------------------------------------------------------
C    THIS PROGRAM WRITES INPUT FILES FOR TOP DRAWER OF RESULTS GIVEN BY
C    THE PROGRAM COOLWARM.
C-----------------------------------------------------------------
C
      CHARACTER *10 PROCESS
      COMMON /RES/ X(0:20000),TG(0:20000),TI(0:20000),
     1             PG(0:20000),GF(0:20000)
C
      WRITE(*,10)
10    FORMAT(///' SELECT ONE OF THE FOLLOWING OPTIONS: '//,
     1       '   1: PLOT GAS AND IRON TEMPERATURE AS A FUNCTION'/,
     2       '      OF DISTANCE (PARAMETER: TIME)'/,
     3       '   2: PLOT MASS FLOW RATE AS A FUNCTION OF DISTANCE'/,
     4       '      (PARAMETER: TIME)'/,
     5       '   3: PLOT EXIT GAS TEMPERATURE AS A FUNCTION OF TIME'/,
     6       '   4: PLOT EXIT IRON TEMPERATURE AS A FUNCTION OF TIME'/,
     7       '   5: PLOT EXIT GAS PRESSURE AS A FUNCTION OF TIME'/,
     8       '   6: PLOT EXIT MASS FLOW RATE AS A FUNCTION OF TIME'/,
     9     '   7: PLOT EXIT CUMULATIVE GAS MASS AS A FUNCTION OF TIME'//)
C
      READ(*,*) KEY
C
      OPEN (UNIT=1,FILE='COOLWARM.LIS',FORM='UNFORMATTED',
     1      TYPE='UNKNOWN')
      OPEN (UNIT=3,FILE='COOLWARM.END',FORM='UNFORMATTED',
     1      TYPE='UNKNOWN')
C
      READ(1)TL,DX,TT,DT,D,WG,WI,TI0,TG0,PG0,NPRINT,NDX,NDT
C
      WRITE(*,20)TL,TT,D,WG,WI,TI0,TG0,PG0
20    FORMAT(' TOTAL LENGTH (M)............: ',F8.2/,
     A       ' TOTAL SIMULATION TIME (S)...: ',F8.2/,
     1       ' CHANNEL DIAMETER (M)........: ',F7.5/,
     2       ' GAS FLOW RATE (KG/S)........: ',F7.5/,
     3       ' IRON MASS/LENGTH (KG/M).....: ',F6.2/,
     4       ' INITIAL IRON TEMP. (K)......: ',F6.2/,
     5       ' ENTRANCE GAS TEMP. (K)......: ',F6.2/,
     6       ' ENTRANCE GAS PRESSURE (ATM).: ',F6.2)
C
      IF(TG0.LT.TI0)THEN
      MODE=1
      PROCESS=' COOLDOWN'
      ENDIF
      IF(TG0.GT.TI0)THEN
      MODE=2
      PROCESS=' WARMUP'
      ENDIF
C
      TGAS=0.
      TOLD=0.
      DO 131 I=1,30000
```



```
      READ(3,ERR=134,END=134)TIME,TGS,TIS,PGS,GFS
      DTIME=TIME-TOLD
      TOLD=TIME
      TGAS=TGAS+GFS*DTIME
C
      IF (MODE.EQ.1) THEN
      IF (TIS.LT.(1.001*TG0))THEN
      TTIME=TIME
      GOTO 132
      ENDIF
      ENDIF
C
      IF (MODE.EQ.2) THEN
      IF (TIS.GT.(0.999*TG0)) THEN
      TTIME=TIME
      GOTO 132
      ENDIF
      ENDIF
C
131   CONTINUE
134   WRITE (*,135)PROCESS,TIME/3600.,TIS,TGAS
135   FORMAT(/' ',A10,'NOT COMPLETED BY TIME (h) = ',F7.3/,
     A        ' END IRON TEMPERATURE (K) = ',F7.3/,
     1        ' TOTAL HELIUM MASS SPENT (Kg) = ',F10.3/)
      TTIME=1.E+10
      GOTO 136
C
132   WRITE (*,133)PROCESS,TTIME/3600.,TGAS,WG*TTIME
133   FORMAT(/' ',A10,'TIME (h) (99.9% OF FINAL TEMPERATURE)= ',F7.3/,
     1        ' TOTAL OUTPUT HELIUM MASS SPENT (Kg) = ',F10.3/,
     2        ' TOTAL INPUT HELIUM MASS SPENT (KG)  = ',F10.3/)
136   CONTINUE
C
      OPEN(UNIT=2,FILE='SAMPLE.TOP',FORM='FORMATTED',
     1     TYPE='UNKNOWN')
C
      IF (KEY.GE.3) WRITE(*,137)
137   FORMAT(' TIME IN HOURS')
      WRITE(*,3010)
3010  FORMAT(//' ENTER XMIN')
      READ(*,*)XMIN
      WRITE(*,3020)
3020  FORMAT(' ENTER XMAX')
      READ(*,*)XMAX
      WRITE(*,3030)
3030  FORMAT(' ENTER YMIN')
      READ(*,*)YMIN
      WRITE(*,3040)
3040  FORMAT(' ENTER YMAX')
      READ(*,*)YMAX
C
      WRITE(2,4010)XMIN,XMAX,YMIN,YMAX
4010  FORMAT(' SET FONT DUPLEX'/,
     1       ' SET SIZE 13 BY 10'/,
     2       ' SET WINDOW X 2. 12. Y 3.5 8.5'/,
     3       ' SET LIMITS X ',F10.4,1X,F10.4,' Y ',F10.4,1X,F10.4/,
```

```
     4        ' SET TITLE SIZE 2.'/,
     5        ' SET SYMBOL')
C
      GOTO (100,100,200,200,200,200,200) KEY
100   CONTINUE
      WRITE (2,4020)
4020  FORMAT(' TITLE BOTTOM "Distance (m)"')
      IF (KEY.EQ.1)THEN
      WRITE (2,4030)
4030  FORMAT(' TITLE LEFT "Temperature (K)"')
      WRITE (2,4031)
4031  FORMAT(' TITLE 3. 8. "___: Iron   ...: He"')
      ELSE
      WRITE (2,4040)
4040  FORMAT(' TITLE LEFT "Mass Flow Rate (Kg/s)"')
      ENDIF
C
      DO 1000 I=1,NDT/NPRINT+1
      READ (1,ERR=500,END=500)TIME,ICOUNT
      WRITE(*,2013)TIME
2013  FORMAT (/' ----> SOLUTION AT TIME (SEC): ',F8.2)
      DO 2000 J=1,ICOUNT
      READ(1,ERR=500,END=500) X(J),TG(J),TI(J),PG(J),GF(J)
2000  CONTINUE
C
      WRITE(*,29)X(1),X(ICOUNT)
29    FORMAT(' TEMPERATURE CHANGE FROM X1 = ',F8.2,'   TO X2 = ',F8.2)
      WRITE(*,30)TI(1),TI(ICOUNT/2),TI(ICOUNT),
     1            TG(1),TG(ICOUNT/2),TG(ICOUNT)
30    FORMAT('    TIRON(X1)=',F7.2,'   TIRON((X2-X1)/2.)=',F7.2,
     1       '    TIRON(X2)=',F7.2/,
     2       '    TGAS (X1)=',F7.2,'   TGAS ((X2-X1)/2.)=',F7.2,
     3       '    TGAS (X2)=',F7.2)
C
      WRITE(*,40)
40    FORMAT(/' ENTER: 0 TO CONTINUE, 1 TO PLOT, -1 TO EXIT')
      READ(6,*)N
      IF (N.EQ.-1) GOTO 500
      IF (N.EQ.0) GOTO 501
      IF (N.EQ.1) THEN
C
      IF (KEY.EQ.1)THEN
C
      DO 5000 K=1,ICOUNT,10
      WRITE(2,5010)X(K),TG(K)
5000  CONTINUE
      WRITE(2,5001)
5001  FORMAT(' JOIN DOTS')
      DO 5002 K=1,ICOUNT,10
      WRITE(2,5010)X(K),TI(K)
5002  CONTINUE
      WRITE(2,5003)
5003  FORMAT(' JOIN SOLID')
C
       ELSE
C
```



```
      DO 5004 K=1,ICOUNT,10
      WRITE(2,5010)X(K),GF(K)
5004  CONTINUE
C
      ENDIF
5010  FORMAT(3X,E11.4,3X,E11.4)
C
      ENDIF
501   CONTINUE
1000  CONTINUE
C
200   CONTINUE
      WRITE (2,4050)
4050  FORMAT(' TITLE BOTTOM "Time (h)"')
      if (KEY.EQ.3)WRITE(2,4060)
      IF (KEY.EQ.4)WRITE(2,4070)
      IF (KEY.EQ.5)WRITE(2,4080)
      IF (KEY.EQ.6)WRITE(2,4090)
      IF (KEY.EQ.7)WRITE(2,5013)
4060  FORMAT(' TITLE LEFT "Exit Gas Temperature (K)"')
4070  FORMAT(' TITLE LEFT "End Iron Temperature (K)"')
4080  FORMAT(' TITLE LEFT "Exit Gas Pressure (atm)"')
4090  FORMAT(' TITLE LEFT "Exit Mass Flow Rate (Kg/s)"')
5013  FORMAT(' TITLE LEFT "Total exit gas mass (Kg)"')
      REWIND 3
      TGAS=0.
      TOLD=0.
      ISYM=0
C
      DO 8030 I=1,30000
C
      READ(3,ERR=500,END=500)TIME,TGS,TIS,PGS,GFS
      IF (ISYM.EQ.1)THEN
      WRITE(2,5012)
5012  FORMAT(' SET SYMBOL')
      ISYM=2
      ENDIF
C
      IF ((TIME).GE.TTIME.AND.ISYM.EQ.0) THEN
      WRITE(2,5016)PROCESS
5016  FORMAT(' TITLE 3. 8. "3 ',A10,'Completed"'/,
     1       ' CASE       "O                "')
      WRITE(2,5017)
5017  FORMAT(' SET SYMBOL 30')
      ISYM=1
      ENDIF
C
      IF (KEY.EQ.3)WRITE(2,5010)TIME/3600.,TGS
      IF (KEY.EQ.4)WRITE(2,5010)TIME/3600.,TIS
      IF (KEY.EQ.5)WRITE(2,5010)TIME/3600.,PGS
      IF (KEY.EQ.6)WRITE(2,5010)TIME/3600.,GFS
      IF (KEY.EQ.7)THEN
      DTIME=TIME-TOLD
      TOLD=TIME
      TGAS=TGAS+GFS*DTIME
      WRITE(2,5010)TIME/3600.,TGAS
```

```
      ENDIF
8030  CONTINUE
C
500   STOP
      END
C
```