SSCL-N-872
SSC Cryo Note No. 94-30

Nitrogen System for the SSC: Continuous Recooling by Injecting Liquid into the Vapor Line

S. Abramovich, J. Demko and M. Thirumaleshwar

Superconducting Super Collider Laboratory*
2550 Beckleymeade Ave.
Dallas, TX 75237

July 1994

*Operated by the Universities Research Association, Inc., for the U.S. Department of Energy under Contract No. DE-AC35-89ER40486.

NITROGEN SYSTEM FOR THE SSC: CONTINUOUS RECOOLING BY INJECTING LIQUID INTO THE VAPOR LINE

S. Abramovich, J. Demko and M. Thirumaleshwar

THE SUPERCONDUCTING SUPER COLLIDER LABORATORY

ASD/CRYOGENICS

February 1994

INTRODUCTION

The Nitrogen system for the SSC is designed to serve as a refrigeration medium for the 84 K shield of the cryostats, to distribute and supply nitrogen used for precooling by the helium refrigeration process, and transport the vapor nitrogen generated in the tunnel to the helium refrigerators for further processing. Details of the design and operation of the 84 K nitrogen system are provided in references [1,2].

The nitrogen system consists of twelve liquid nitrogen inlets with a total input flow of approximately 5000 g/s. The system can be operated with any combination of active intakes. The input liquid flow is designed to be distributed around the two storage rings of the collider and around the HEB ring through the LN2 line in the rings. It can also be distributed by surface transportation by independent distribution to each of the twelve locations of the helium refrigeration plants. The pressure in the nitrogen distribution system depends on the location of the main supplies, the number of pumps installed in the tunnel, the local flow rates, and on the inclination of the lines. The nitrogen system temperature depends on the local heat load, the local flow rate, and on the nitrogen recooling scheme.

The SSC magnet cryostats contain a thermal shield which is cooled with liquid nitrogen. The shield intercepts and absorbs the thermal radiation heat load from the 300K outer casing of the cryostat and the conduction heat load from the magnet supports. The liquid nitrogen is supplied from a nitrogen supply on the surface and flows through the liquid nitrogen line attached to the shield. To limit the temperature rise the nitrogen vapor is periodically recooled in a heat exchanger where a fraction of the liquid is allowed to boil removing the heat being intercepted by the 80K shield. A second line is attached to the 80 K shield through which the vapor nitrogen produced in the periodic recoolers is returned to the surface.

The simplest recooling scheme is based on one compact recooler (heat exchanger) for each string 1 km long, near each feed or end spool (SPRF, SPRE) as suggested in the CDR [3]. This scheme is sufficient as long as the liquid flow rate is high and the heat load is small. For a heat load of 3.2 W/m and flow rates lower than 1100 g/s the LN2 temperature rises by more than 6 K over 4.3 km. This is an unacceptable temperature rise so higher flow rates or additional recoolers are needed. The heat load values are expected to exceed 3.2 W/m so more compact recoolers are required. The heat load is highly dependent on the amount of multi layer insulation (MLI) used, the insulating vacuum, and the shield design. The use of a recooler every 1 km was discussed in [2].

As an alternative, the second line may be used for two phase flow in a way that eliminates the need for periodic recoolers. The two phase flow method of recooling (continuous recooling) of the nitrogen is based on the idea of injecting controlled rates of liquid in the vapor line. Once all of the liquid is evaporated, the heat load is absorbed by the sensible heat of the liquid in the liquid line. There are places in the ring where the lines are horizontal. At these horizontal sections the liquid will not distribute along the line so continuous recooling cannot be used. Additional recoolers are needed.

The design of the continuous recooling is described in this paper. The concept provides a logical approach to the maintenance of the 80K shield at the required temperature and may be used for the initial cooldown of the nitrogen lines. The discussion and analysis contained here could easily be extended to the initial cooldown of the liquid helium lines.

THE CONTINUOUS RECOOLER CONCEPT

The 84 K shield is anchored to two nitrogen lines. One is used for liquid distribution, and the other for vapor return. As the tunnel lays in an inclined plane the cryostats containing the nitrogen lines make an angle of 0.0 to 0.2 degrees to the horizontal depending on the location in the ring. If liquid nitrogen is injected into an inclined section of the vapor line it flows downhill. As the pressure in this line is low enough then boiling of the liquid nitrogen will occur. The boiling pressure determines the temperature of the 84K shield. The continuous recooling process is illustrated in Figure 1 which represents a typical section 1080.m long in the collider. Mv(0) is the inlet vapor flow to the section which may vary from 0.0 to 48 g/s. The nominal vapor flow rate at the end of each section Mv(1) is 16, 32, 48 or 64 g/s, directed to the feed box of the sector and brought to the surface to provide precooling for the He refrigeration plant. This direction is independent of the other flows. Ml is the liquid flow rate injected in the upper side of the section, with a nominal value of 16 g/s, its direction is always downhill. The length of a control volume is dx, q(x) is the nominal heat load, mlv is the mass rate of liquid boiled in the control volume and qwall is a transient amount of heat to be absorbed from the wall. It should be mentioned that the flow direction of the liquid in the liquid line may be clockwise or counterclockwise, uphill or downhill, depending on the supply system and on the distribution scheme in use, which may change from time to time.

Two different schemes for injecting liquid into the vapor line are available including liquid injection at the upstream end and distributed injection along the length of the line. For proper operation of the line in either situation there should be no liquid leaving the lower end of the line. All of the liquid injected into the line should be evaporated prior to the end of the line.

BASIC ASSUMPTIONS AND SIMPLIFICATIONS IN THE ANALYSIS

The nitrogen vapor line will have two phase flow. The flow regime encountered depends on the local vapor and liquid flow rates present along the line. One method to determine the flow regime discussed in Baron [1], is with the Baker diagram as given in Figure 2. The flow in the vapor line is represented approximately as the heavy broken line which lies totally in the stratified flow regime.

For stratified liquid flow the liquid in the vapor line is principally driven by gravity. The liquid-vapor boundary layer effects are ignored. It is assumed that the liquid velocity and flow cross section may be evaluated using the Manning formula for channel flow. The heat conductance of the shield is assumed to be ideal and the temperature difference between the wall and the fluid is assumed to be small so it can be ignored. The maximum allowable (or ideal) input flow rate of liquid is such that the whole length of the line is wet but no liquid is collected at the lower side of the line. To determine this flowrate and the time required to flow liquid along the whole length of the tube the flow development must be understood.

LIQUID FLOW DEVELOPMENT

A constant liquid injection rate is the simplest scenario describing the continuous recooling concept. It provides a basis for understanding other transients needed to operate in this manner. The liquid flow analysis is based on a typical control volume as shown in Figure 1 of length dx. The liquid evaporation rate depends on the heat transfer rate and the latent heat of the liquid. The mass balances of the liquid and vapor for this control volume can be written in terms of the evaporation rate. These equations become:

q(x)= mlv(x)*hfg

dmv(x)=mv(x+dx)-mv(x)=mlv(x)

dml(x)=ml(x+dx)-ml(x)=-mlv(x)

where q(x) is the heat load, mlv(x) is the evaporation rate, hfg is the latent heat, mv and ml are the vapor and liquid flows respectively at a particular x location.

In general various combinations of flow directions for the liquid and vapor lines are possible as shown in Figure 3. For ideal continuous recooling the whole heat load is assumed to be absorbed by the latent heat of liquid in the vapor line for portions where two phase flow exists. The temperature at a given cross section of the cryostat is assumed to be equal to the saturation temperature calculated from the local vapor pressure in the vapor line. For the dry part of the vapor line, the temperature is assumed equal to the local liquid temperature in the liquid line. The qualifying assumption is that there is perfect heat transfer between the lines, the shield and the nitrogen in the shield. If the injection rate is less than ideal then all of the liquid will evaporate prior to the end of the tube.

For transient flow analysis of the initial injection of liquid into the line it is assumed that at x=0 and t=0 that the vapor nitrogen line does not contain liquid and is at a temperature equal to the local liquid temperature achieved by using compact heat exchangers every 4.32 km. For t>0 the injection rate into the first cell dx long, is instantaneously changed from 0.0 to Ml(0). The flow in the cell develops in a shape of a wave as shown in Figure 4. The heat load q which may include a nominal (steady state) and the transient (required to reduce the wall temperature) component is absorbed by evaporating mlv (g/s) of liquid. The total nominal liquid injection rate to the specific section L (m) long can be determined by applying the mass conservation equation to the whole line with the following result:

Ml(0)=Q*L/hfg.

The initial temperature of the nitrogen in the cryostats depends on the flows in the liquid and vapor lines. The vapor flow rate in the vapor line is 32 g/s. Since the recooler located near the string end box generates 64 g/s of vapor and the flow splits equally into two opposite directions. It is assumed that the pressure in the N2 recoolers equals the local pressure in the GN2 return line. The pressure in the vapor return line depends on the boil off vapor flow rate which depends on the heat load. The steady state temperature everywhere in the 80 K shield is defined further based on the initial temperature, on the heat load and on the local mass flow. After sufficient time t the wave front reaches the downstream cell boundary and a flow rate of Ml(1) starts going from cell(i) to cell(i+1). At this moment the previous (i) cell is assumed to be in steady flow and heat transfer conditions. The time to fill up the first cell dt may be calculated from a mass balance as:

Ml(0)*dt-r*Vdx(1)=[q*dx/hfg]*dt

During dt the output mass flow from the last cell containing liquid is zero, r is the liquid density Vdx(1) is the liquid volume in the cell calculated from the Manning equation for steady flow conditions and q is the constant total heat load per unit length.

For the next cell (downstream) the process continues in a similar way using the output mass flow from the previous cell as the input. The flow process is repeated until the vapor line becomes dry or when the downstream boundary of the section is reached.

Because the initial temperature of the cryostat depends on the local liquid flow, the value of qtransient depends on the local liquid flow rate and is evaluated separately for each section and for each LN2 distribution scheme. As an example, Figure 5 shows the flow rates and the expected liquid temperatures for two different schemes. Scheme (a) has a recooler in every string ~4.3 km long and one nitrogen supply at N40. Scheme (b) has a recooler in every string ~4.3 km long with two nitrogen supplies at N15 and at S15. Figure 6 shows the schematic development of pressure and temperature in the nitrogen lines for a given combination of liquid, and vapor flow direction.

THE CALCULATIONS

For a given heat load and LN2 supply scheme the required local liquid and vapor flows, the pressures, and temperatures everywhere in the collider can be calculated. The steady state conditions for a recooler every 4.3 km can also be calculated. Using the slope of the tunnel, the line sizes and the injection rates of the liquid into the vapor line, the liquid velocity in the vapor line and the liquid inventory and the wetted surface can be evaluated. The wetted surface is required for the verification of the heat transfer between the boiling liquid in the vapor line and the walls of the tubes and is needed for detailed evaluation of heat transfer and temperature profiles in the shield.

As the LN2 supply schemes may be perturbed the steady state conditions and the transients (in particular the "dead times") have to be evaluated for different values of slope and liquid injection rate. Figure 7 shows some definitions of the liquid flow parameters in an inclined line.

The nominal liquid injection rate into the vapor line for steady state conditions is constant for nominal arc sections 1080 m long and is equal to 16.0 g/s. The initial conditions are that there is no liquid flow in the vapor line ml=0.0 g/s and the line is dry. At t=0 a given liquid injection rate starts. To fill up the vapor line with liquid and in order to reach the new steady state in a reasonable time, a higher than nominal flow rate is required.This will absorb the local nominal heat load as well as the transient load due to shield higher temperature.

Slope (alpha) = 0.1 degrees, Tube Dia =63.5 mm

Flow rate =18.5 cc/sec:

Flow angle (beta) = 90^{o} and the velocity ~8 cm/sec

The vapor flow in the vapor line is initially equal to half the vapor generation rate in the recooler (32 g/s). After initiating the continuous recooling, the nominal rates at which vapor is generated and the flow at the "end" of each section is 16, 32,48,64 g/s, depending on the location of the section relative to the sector feed box (here we ignore the transient behavior of the vapor flow). The vapor flow direction is towards the sector feed box.

@ x=0 mv(0)= 0,16,32, or 48 g/s

@ x=l mv(l)= mv(0)+mlv(x)dx

TYPES OF TRANSIENTS

The cooldown of the nitrogen line is a transient process in which the heat load to the liquid is given by:

q= qnominal + qtransient

Where qnominal is the load in steady state (assume 3.2 W/m) and qtransient is the heat to be absorbed from the shield and tubes and fluid in order to bring them to the temperature defined by boiling conditions in the vapor line.

A second transient is the response to a flow perturbation around a steady initial condition Ml(0) and q(i). This information is needed to determine the control of the liquid injection to the line. To simplify the calculations here, qtransient was negligible (i. e. the tube was at the same temperature as the liquid).

The model assumes that a liquid wave travels in the front of the changing flow. The velocity of this wave is calculated by means of the input flow to each cell, the change in the cell inventory and flow geometry and velocity using Manning correlation conceptually described earlier. A complete mathematical formulation of the liquid flow process are given by the transient channel flow equations for the conservation of mass and momentum for a control volume. These are discussed in detail in Wiley and Streeter [3]are given by equations (1) and (2). In the momentum equation, the contribution due to hydrostatic pressure head gradient was neglected because of the shallow liquid depths and small inclination angles encountered in the SSC ring.

$$A_t = Q_{evap} - AV_x - VA_x \tag{1}$$

$$V_t = g\sin\alpha - VV_x - \frac{\tau_o}{\rho R_h} - \frac{VQ_{evap}}{A} \tag{2}$$

In these equations A represents the liquid flow area, V the liquid flow velocity, g is the acceleration due to gravity, r is the liquid density, T_o is the frictional shear stress at the wall, R_h is the hydraulic radius defined as the liquid flow area divided by the wetted perimeter, and Q_{evap} is the volumetric evaporation rate of the liquid. The subscripts t and x represent differentiation with respect to time and axial distance respectively.

The wall friction term is modelled by the Manning equation given in (4). The Manning coefficient C_m=1.0, and the friction coefficient n=0.017 are selected to represent a fairly smooth stainless steel tube.

$$Q_{evap} = \frac{Q_{80K}}{\rho h_{fg}} \tag{3}$$

$$\frac{\tau_o}{\rho R_h} = \frac{gn^2V^2}{C_m^2 R_h^{\frac{4}{3}}} \tag{4}$$

The step change in the input flow (instantaneous increase or decrease from m1 to m2 is non linear, so the calculations have to be carried out for each specific step change in flow values.In addition a step change in the heat load needs to be simulated. Starting with a given steady state, and without changing the input flow rate Ml(0), the simulation gives the shapes of the flow and the inventory in each cell until the new steady state is achieved. Other transients that may be modelled are instantaneous failure of vacuum causing a fast increase in the heat load and various changes in the liquid injection rates. All of these results may be needed for developing a robust control loop design.

TRANSIENT SOLUTION NUMERICAL CONSIDERATIONS

The 1000 meter long nitrogen vapor line was divided into 100 segments with 101 nodal locations for the numerical integration of the partial differential equations (1) and (2) discussed previously. A non-uniform grid was used in which the grid spacing varied geometrically. This is described by equations (5) and (6). The ratio r was set to 0.985.

$$\Delta X_i = X_i - X_{i-1} \tag{5}$$

$$r = \frac{\Delta X_{i+1}}{\Delta X_i} \tag{6}$$

The integration was performed using the numerical method of lines (NUMOL) as discussed in Schiesser [2]. Basically in the numerical method of lines, the spatial derivatives are calculated using finite difference representations resulting in a system of first order ordinary differential equations (ODE) in time. The numerical integration of the system of ODE's was performed numerically using LSODES.

For this analysis the spatial derivatives were represented by a first order upwind approximation that is given in equation (7) where S_x represents either an area or velocity x derivative. The velocity in the convective terms such as VV_x and VA_x was taken to be the velocity at upstream or (i-1) location.

$$\Phi_x = \frac{\Phi_i - \Phi_{i-1}}{\Delta X_i} \tag{7}$$

$$\dot{m}_o = \rho A_o V_o \tag{8}$$

For the upstream boundary condition, a fixed velocity and area was applied. The values for the area and velocity were determined through the simultaneous solution of the continuity equation and Mannings uniform flow equation as discussed in White [3].

$$V_o = \frac{1}{n} R_{ho}^{\frac{2}{3}} \sqrt{\tan\alpha} \qquad (9)$$

The hydraulic radius used in equation (9) can be calculated from equations (10)-(12). These equations are for a round tube and can all be expressed in terms of a liquid flow angle that is shown in Figure 8.

$$R_{ho} = \frac{A_o}{P_{wo}} \qquad (10)$$

$$A_o = \frac{R_{tube}^2}{2} (\beta_o - \sin\beta_o) \qquad (11)$$

$$P_{wo} = \beta_o R_{tube} \qquad (12)$$

The downstream boundary condition was specified as a zero liquid flowrate, assuming that all the liquid has boiled-off prior to the last node. For the initial conditions, all locations downstream of the first grid point were assumed to be dry for the cases where the tube was initially filled with liquid. In the cases where a step change in the flow were predicted, the initial conditions were taken from a previous solution at the flow conditions prior to the step change.

STEADY STATE RESULTS

For different flow rates 8, 12, 16, 20, 24, 28, 32 g/s the liquid mass distribution is shown in Figures 9 and 10. In Figure 11 the total mass of liquid in the tube for inclinations in the range of 0.05 - 0.25 degrees are shown.

These calculations should be repeated for each nominal flow rate with different heat loads: 1.0, 2.0, 3.0 w/m

TRANSIENTS AND CONTROL PRINCIPLE

As defined before the transient behavior is modelled as the motion of a wave. The wake of this wave can be regarded as developed flow (for the time being we are not interested in the detailed behavior within the front of the wave). According to this, the major parameter required is the time of motion of the front. In the liquid injection control loop this time is a dead time (i. e. the time required for the change to propagate the length of tube). It has to be evaluated for each individual change in the system. Figures 12 and 13 show the time of motion of the front wave for inclinations of.05 deg and 0.2 deg as functions of the injection rate.Figur shows the time of motion of the front wave as a function of the inclination, for different flow rates.

The first case has liquid flow in the liquid line and liquid flow in the vapor line in the same direction. Without injection of liquid into the vapor line the liquid in the liquid line absorbs the heat as shown schematically by line (ab) in Figure 15. When we start injecting the liquid in the vapor line, the liquid runs downhill wetting the line up to a point?L?. We assume that up to this point the heat is absorbed by the boiling liquid in the vapor line and the temperature of the shield is approximately equal to the local temperature of the boiling liquid (see line (ad) in Figure 15). Further, where the vapor line is dry, the heat load is again absorbed by the liquid line and, the temperature of the shield depends on the liquid flow (see line (de) in Figure 15). In this case a temperature measurement at the end of the liquid line may be used as the feed back value in the temperature control loop. This temperature changes between Tb (when there is no continuous recooling) to Tc (for ideal continuous recooling.

The second case has liquid flow in the liquid line and liquid flow in the vapor line in opposite directions (see Figure 16): For partial continuous recooling the wet part of the vapor nitrogen line cd is at a low temperature. At a point d the line is dry and the temperature changes to that defined by the temperature in the liquid line (point e in Figure 16). In this case a temperature measurement at the end of the section can not serve as the feedback in the temperature control loop (both ends of the section are at a desired temperature). Therefore to cover the possibility of different flow directions for the liquid nitrogen, a temperature measurement is needed in each side of the section as shown in Figure 17.

The continuous recooling system is operated after the 4 km compact recooling system stabilizes. The local injection control valve opens to a predetermined position according to the nominal load and the measured pressure in the liquid line. This will cause a liquid flow rate of m1 in the vapor line. Ideally the first thermometer in the vapor line will detect the presence of the liquid wave after a time t1 (according with Figures 12, 13, 14 this time is in the range of 20-40 minutes). The measured value of t1 may serve to calibrate the valve and to make open loop corrections by changing the valve opening. After a second time t2 the second thermometer measures the presence of the liquid wave front. Again,t2 may be used to calibrate the valve. The moment the wave was detected by the second thermometer, the injection valve is closed. The liquid continues to run until one or both thermometers detect a temperature change.Then the valve is opened again.

a. Assume a step change in Ml(0):

Calculate the velocity of the front wave using step by step integration. Calculate new steady state geometry.

b. Assume a step change in q. Calculate the transients in flow, wall temperature and flow geometry:

Wet parts of the vapor line: heat is removed by boiling

Dry parts of the vapor line: heat is removed by liquid flow in liquid line (assume liquid flow 100,200,300...g/s as required in the different parts of the ring).

As a first approximation of the liquid inventory in the vapor line with an inclination of 0.2 deg is 188 kg/km. If the flow rate to the section is limited to Ml g/s, the fill up will take H hours. During the fill up time some of the fluid is evaporated.This at an initial rate of 0.0 g/s and a final rate equal to the nominal 16 g/s. The total amount of boil off is approximately H*3.6*8 kg/km. For a constant fill up flow of 20g/s the fill up time is 4.35 h. Afterwards the flow has to be lowered to 16 g/s to prevent collecting liquid at the lower end of the line.

One purpose of this analysis is to determine the transient nature of liquid injection at the line inlet. The progression of the liquid front along the line is predicted at inclination angles A=0.1 and 0.2 degrees and liquid mass flow rates of 16g/s and 30 g/s. The inlet vapor flow rate was taken as 975 g/s for all cases, although the interfacial shear force was not included in this present study. In an effort to develope a liquid injection control strategy, the propagation of disturbances in the liquid flow due to step increase and decrease of the inlet mass flow were calculated.

TRANSIENT RESULTS

The transient distribution of liquid nitrogen mass flow for a constant initial injection rate of 16 g/s with a tube inclination angle of 0.1 and 0.2 degrees are shown in Figures 18 and 19. The liquid front is seen to be very steep, and due to evaporation of the liquid along the tube, the flow linearly decreases proceeding down the tube. The predictions indicate that at these conditions it takes 20,000 seconds for the liquid flow to reach a steady state condition at the shallower inclination and about 16000 seconds for the steeper angle.

Figure 20 and 21 provide the transient flow distributions along the tube for a step change in the inlet flow rate to 12 g/s from the steady state condition reached at a flow rate of 16 g/s and 0.2 degrees. From these results it is seen that it takes about 2000 seconds less for the front to propagate the liquid length for the higher inclination angle. A step increase from 16g/s to 20 g/s after steady state has been reached is shown in Figures 22 and 23 for the same inclinations. In the step change cases, the liquid front does not appear to be as steep as the initial front. At this time it is not known for certain if this is due to the actual flow physics or to a numerical diffusion present in the derivative approximations.

In Figures 24 and 25 the results for a complete stopping of the flow are shown for the same inclinations. The liquid front stays at the same location, while a dry out front progresses along the tube. After about 12000 seconds for =0.1 degrees and 8000 seconds for =0.2 degrees all of the liquid in the tube has evaporated.

One purpose of this investigation is to provide some analysis that supports the development of a control strategy for continuous injection of liquid into the nitrogen vapor line of the 80K shield. The previous cases provide some fundamental solutions that provide time scales for filling the tube at a constant mass flow rate of 16g/s, and the times for some perturbations to propagate along the liquid stream. The next few examples contain results for cases where an initial injection rate of 30g/s was applied and after some period reduced to a nominal value of 16g/s in an effort to reduce the time required to supply liquid along the whole length of the nitrogen vapor line.

In Figure 26 are the results for a case where α=0.1 degrees, the initial mass flow rate is 30g/s for 2000 seconds and then stepped down to 16g/s for the remaining time. At t=3000 seconds a liquid pulse is obtained with a peak at approximately X=200 meters. The peak decreases in height as it progresses down the tube. The liquid flow retains a sharp slope at the down stream side of the peak but the upstream slope gradually decreases. For these conditions, the liquid pulse disappears almost coincidently with the arrival of the liquid at the end of the tube. The steady state was reached after about 16000 seconds which is 2000 seconds less than the case with a constant 16g/s liquid injection.

Figures 27 and 28 are for the steeper inclination of 0.2 degrees and different times which the mass flow is stepped down from 30g/s to 16g/s. In Figure 29, the step down occurs 1000 seconds after the start of the 30g/s injection rate. A liquid pulse is seen to develope initially but it disappears after 7000 seconds. In Figure 30 the 30g/s mass flow rate was stepped down after 2000 seconds. It is seen in this figure that the liquid pulse travels the whole 1000 meter length without completely disappearing. For this case the tube contains liquid along its entire length after 12000 seconds which is about 4000 seconds less than the constant injection case.

SUMMARY AND CONCLUSIONS

The numerical method of lines has been applied to the modeling of transient channel flow of liquid nitrogen in a 1000 meter long line. These results provide some basic understanding into the transient flow behavior of the nitrogen vapor line which can be used to develope a liquid injection control strategy for the SSC 80K shield. The analysis has provided times for obtaining liquid along the length of the tube for different inclination angles, different constant liquid injection rates, and variable liquid injection rates. Using a high initial liquid injection rate and stepping down to the required injection after some period of time has been shown to decrease the time required for obtaining liquid along the length of the pipe. Also some times for the evaporation of the liquid front in the event of a stoppage of the flow were calculated.

REFERENCES

1. M. McAshan, M. Thirumaleshwar, S. Abramovich, V. Ganni, and A. Scheidemantle, "84 K Nitrogen System for the SSC", SSCL-Preprint-87
2. M. McAshan, M. Thirumaleshwar, S. Abramovich, and V. Ganni, "Nitrogen System for the SSC",SSCL-592, October 1992
3. R. Barron, "Cryogenic Systems", Oxford University Press, 1985
4. E. B. Wylie and V. L. Streeter, "Fluid Transients", FEB Press, 1982
5. W. E. Schiesser, "The Numerical Method of Lines Integration of Partial Differential Equations", Academic Press, 1992
6. F. M. White, "Fluid Mechanics", McGraw-Hill, 1986

NOMENCLATURE

A - Cross-sectional area of the liquid (m^2)
A_x - Spatial derivative of the cross-sectional area of the liquid (m)
A_t - Time derivative of the cross-sectional area of the liquid (m^2/s)
C_m - Manning coefficient (=1.0)
g - Acceleration of gravity (=9.81 m/s^2).
h_{fg} - Latent heat of the liquid nitrogen (J/g)
L - Total length of two phase nitrogen line (m).
m_l - Mass flowrate of liquid (g/s).
m_v - Mass flowrate of liquid vapor (g/s).
n - Friction coefficient in the Manning Equation (=0.017).)
Q_{evap} - Volume of liquid evaporated per unit time (m^3/s)
Q_{80K} - 80 K shield heat load (W)
q - Shield heat load per unit length (W/m)
R_h - Hydraulic radius of the flow (m).
R_{tube} - Radius of two phase nitrogen line tube (m)
t - Time (sec).
V - Velocity of the liquid (m/s).
V_x, V_{xx} - First and second spatial derivatives of velocity of the liquid (s^{-1}, $m^{-1}s^{-1}$).
V_t - Time derivative of the velocity of the liquid (m/s^2).
x - Distance measured along axis of the nitrogen line (m).
α - Inclination angle of two phase nitrogen line (deg, rad).
τ_o - Wall shear stress calculated using Mannings Equation (N/m^2)
ρ_l - Density of liquid nitrogen (g/cc).
ρ_v - Density of vapor nitrogen (g/cc).
β_o - Wetting angle of the liquid at a cross-section (rad).

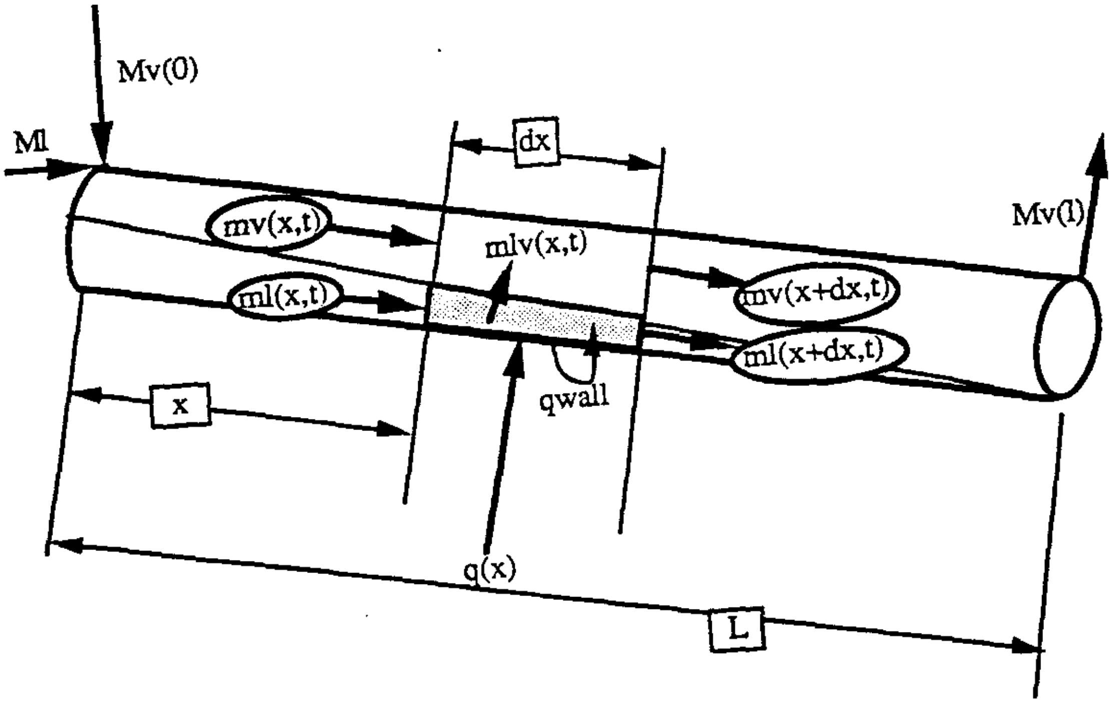


Figure 1: Typical 1080 meter section of the collider showing definitions of the liquid and vapor flows in the vapor return line.

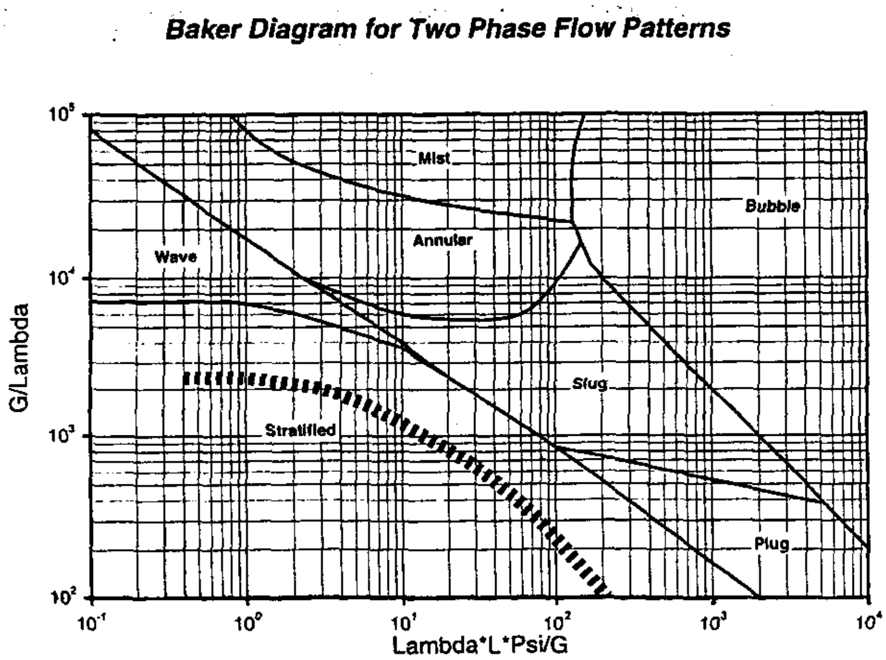


Figure 2: Baker diagram showing two phase flow regimes.

Liquid flow in liquid line	→	→	→	→
Liquid flow in vapor line	→	→	←	←
Vapor flow	→	←	→	←
Inclination	↘	↘	↙	↙

Figure 3: Various combinations of flow directions

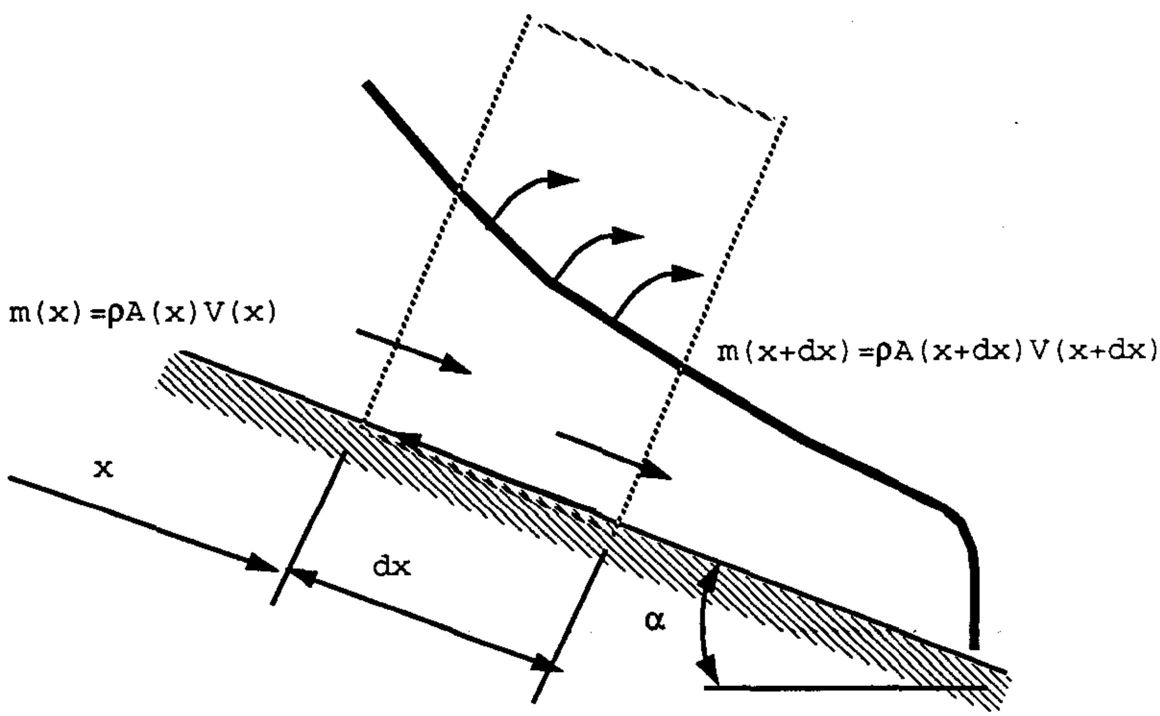


Figure 4: Control volume for application of unsteady-momentum equation (Flow development in the inclined plane).

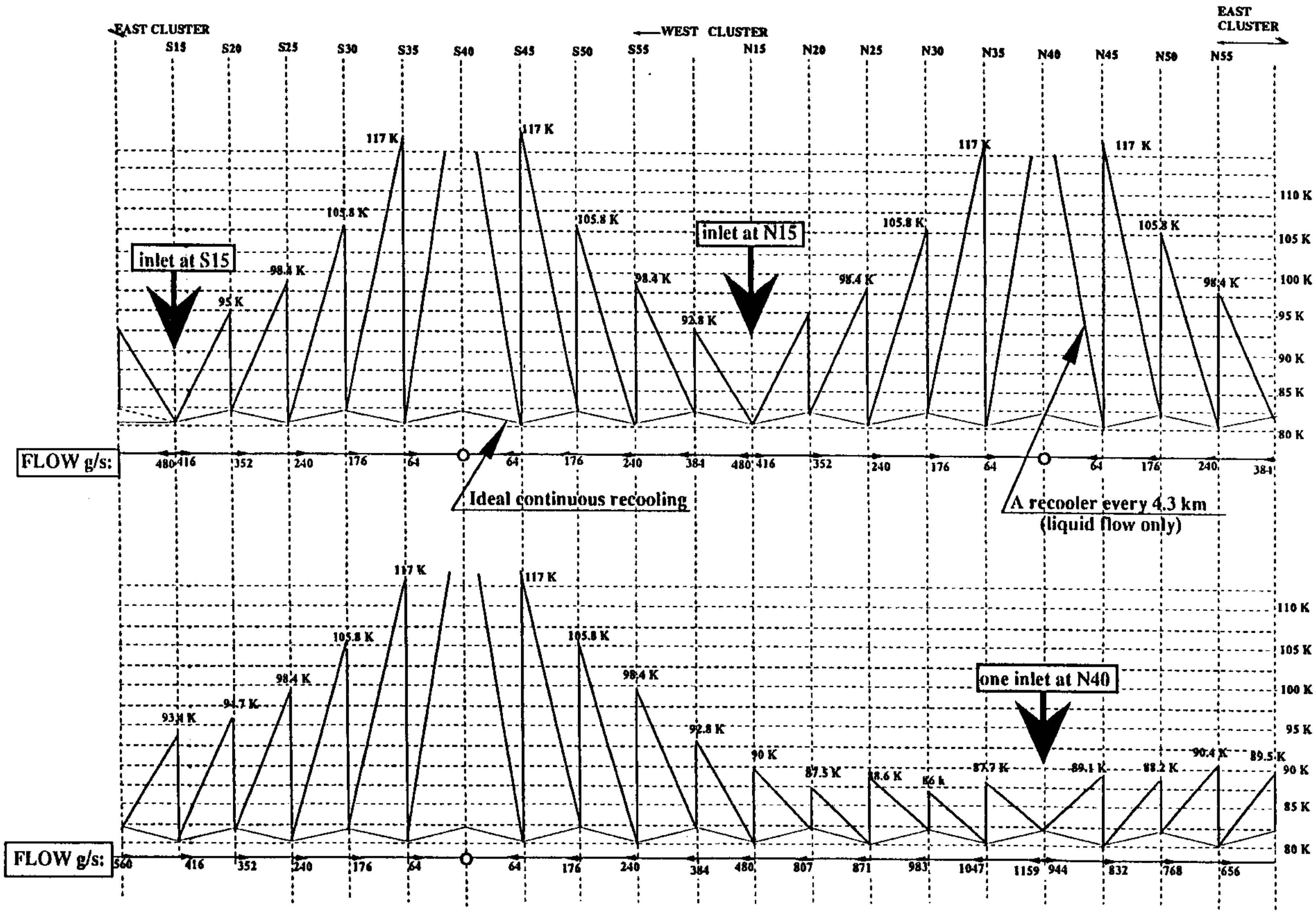
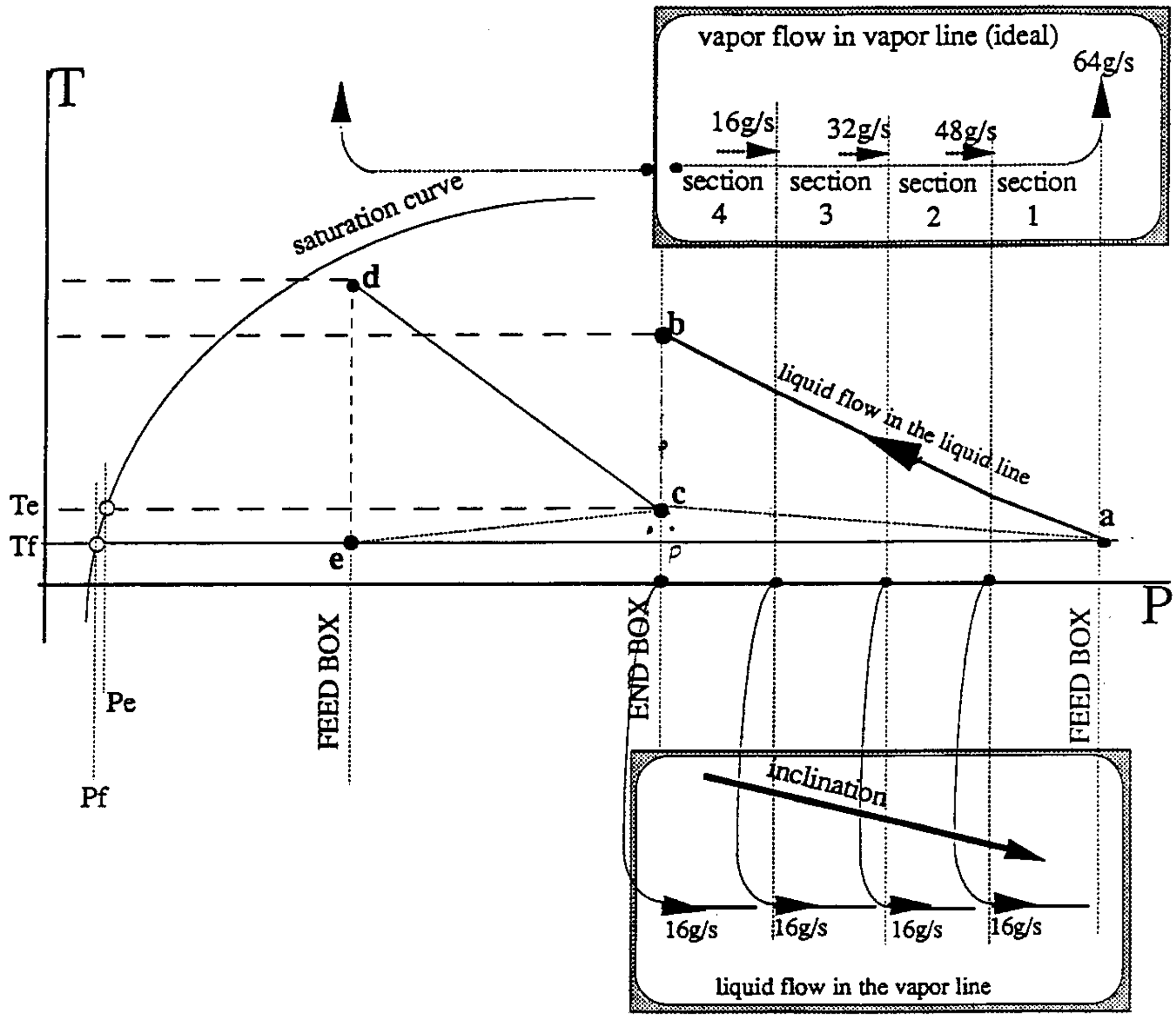


Figure 5: Flow rates and liquid temperatures for two recooling schemes



Te, Pe vapor temperature and pressurein the end box recooler
Tf, Pf vapor temperature and pressure in the feed box recooler
ab liquid flow in the first string a recooler every 4.3 km
cd " " " " second " " " " " "
bc feed box recooler
de end box recooler
ac, ce continuous recooling

Figure 6: Schematic development of temperature and pressure

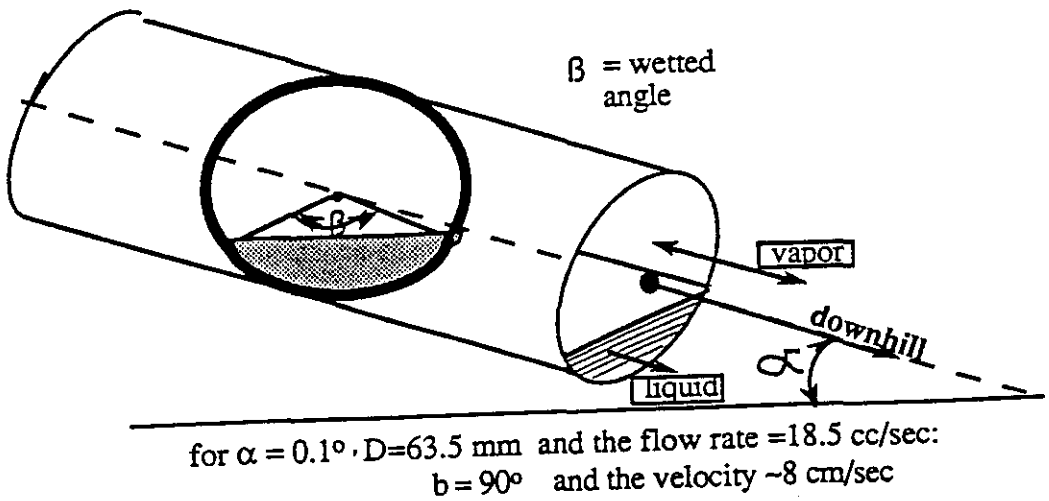


Figure 7: Definition of flow parameters in an inclined tube (see Manning correlation).

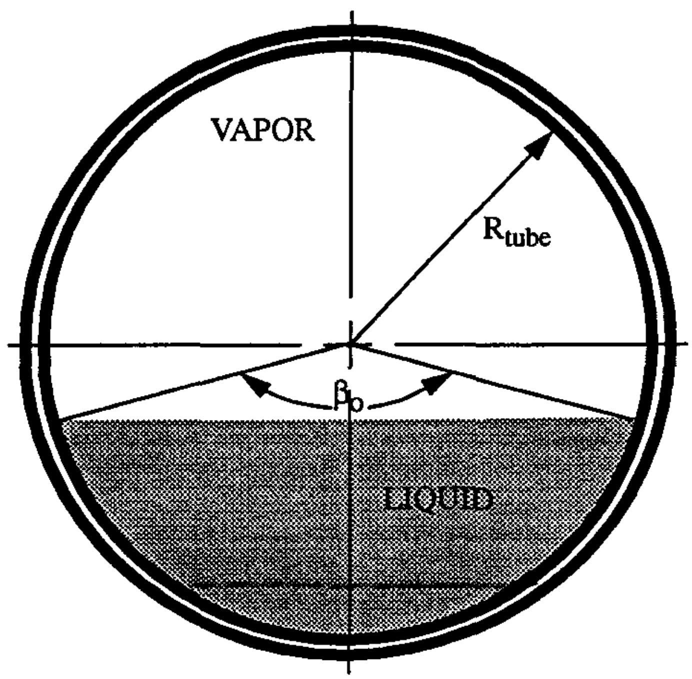


Figure 8: Definition of liquid flow angle β_o used to calculate the liquid area and velocity at the inlet to the nitrogen vapor line

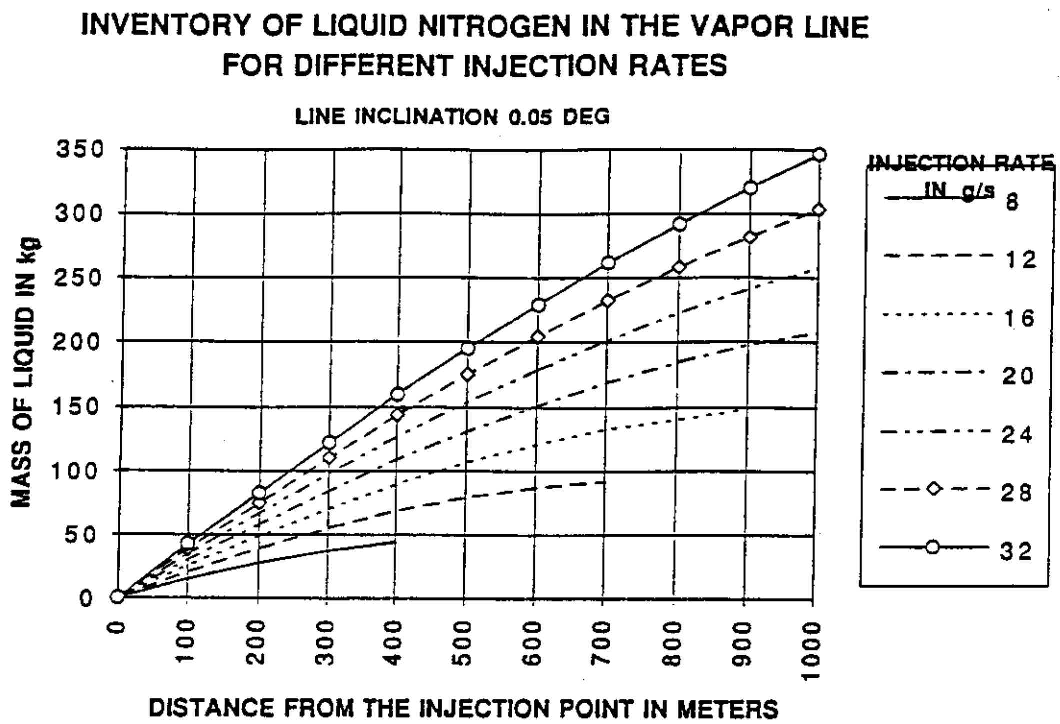


Figure 9: Inventory of liquid nitrogen in the vapor line for different injection rates at an inclination of 0.05 degrees.

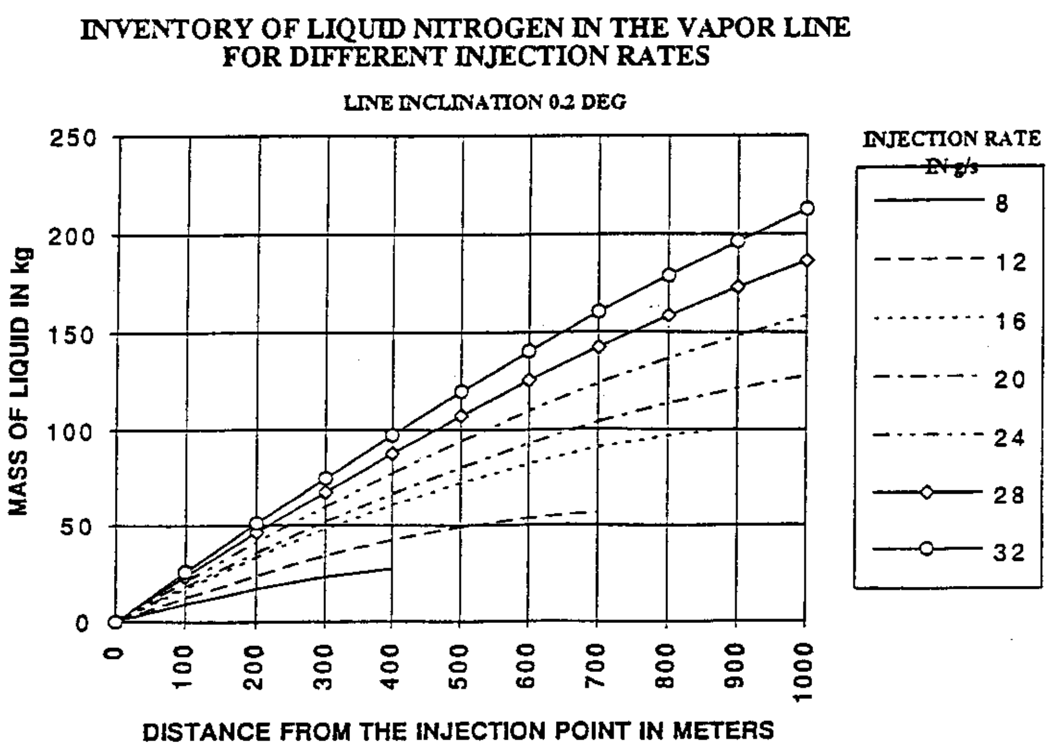


Figure 10: Inventory of liquid nitrogen in the vapor line for different injection rates at an inclination of 0.2 degrees.

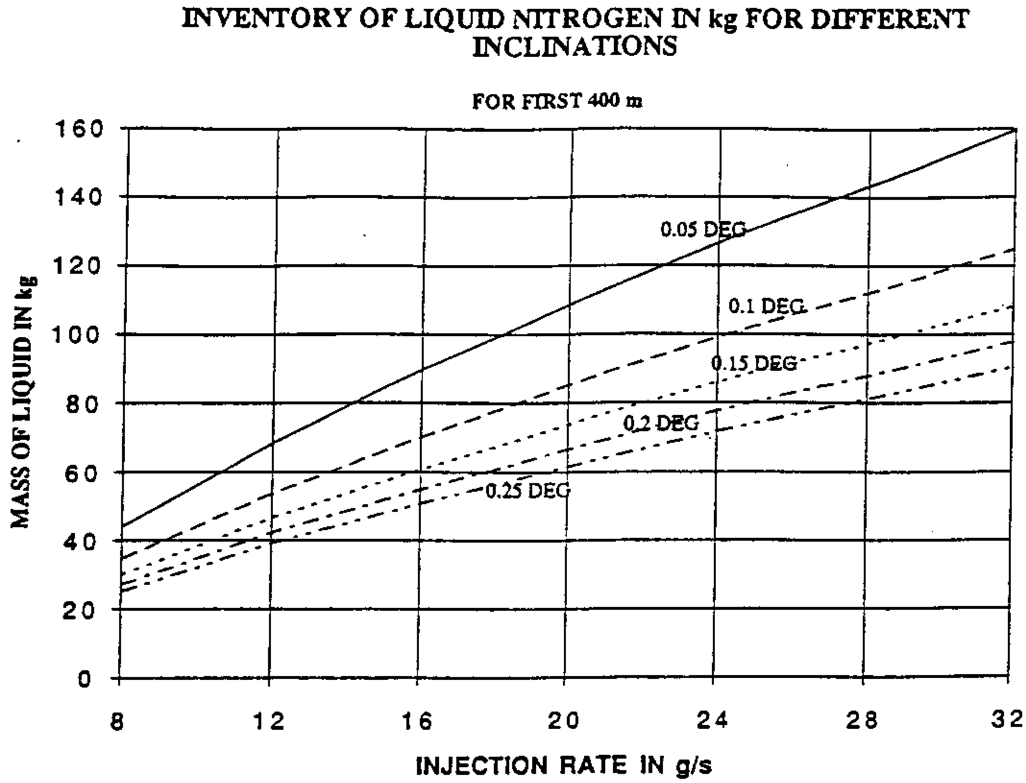


Figure 11:Inventory of liquid nitrogen in the first 400 meters of the line in Kilograms for different inclinations and injection rates.

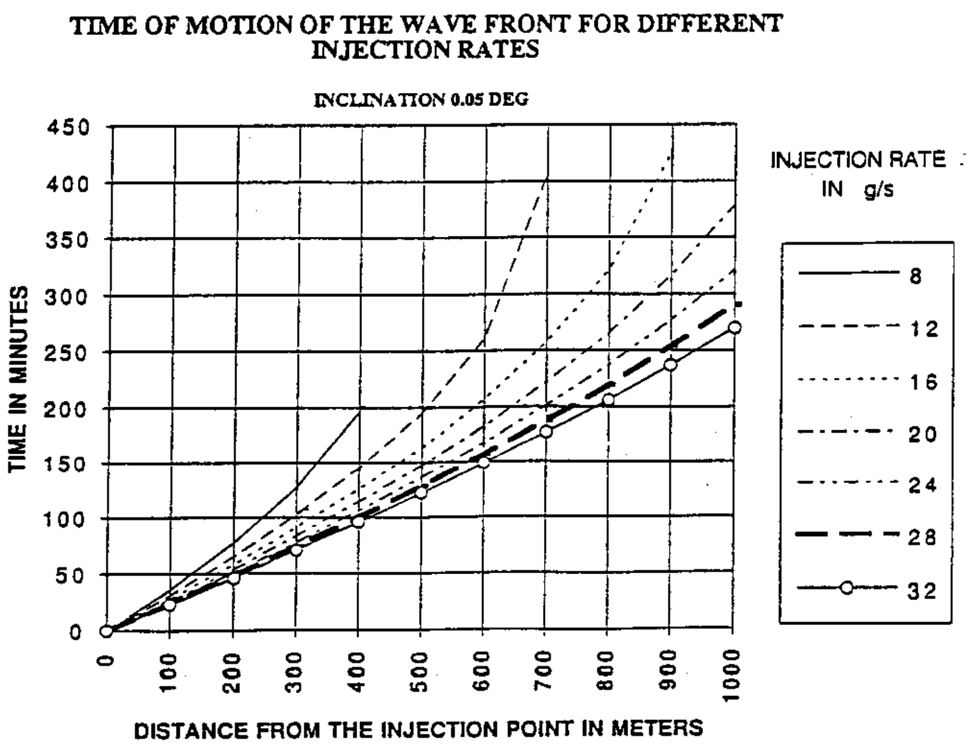


Figure 12:Time motion of wave front for different flow rates and inclinations

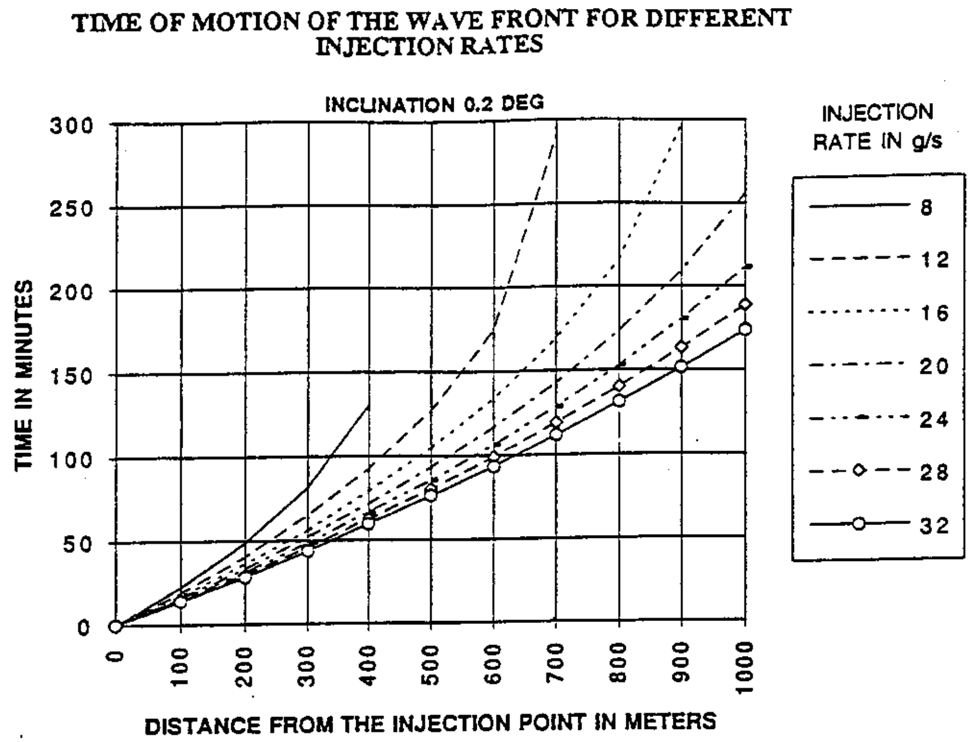


Figure 13:Time motion of wave front for different flow rates and inclinations.

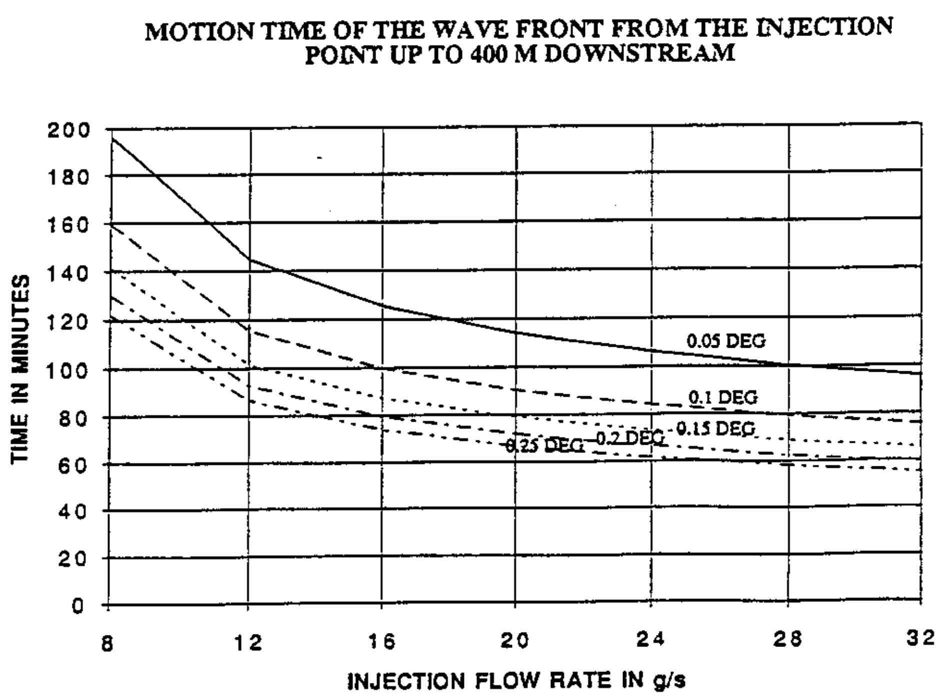
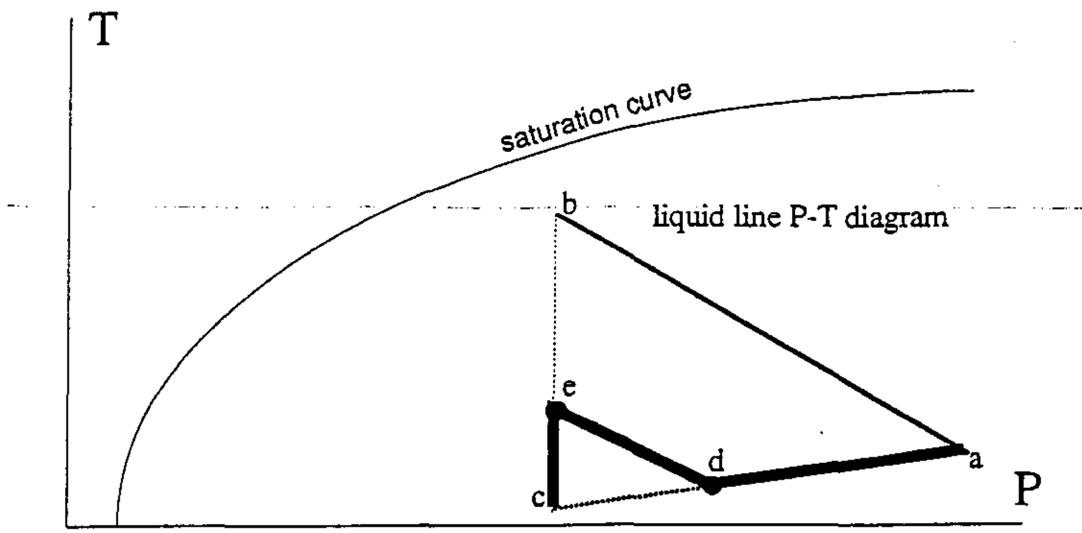


Figure 14:Time motion of liquid front for different injection flow rates at several inclinations.

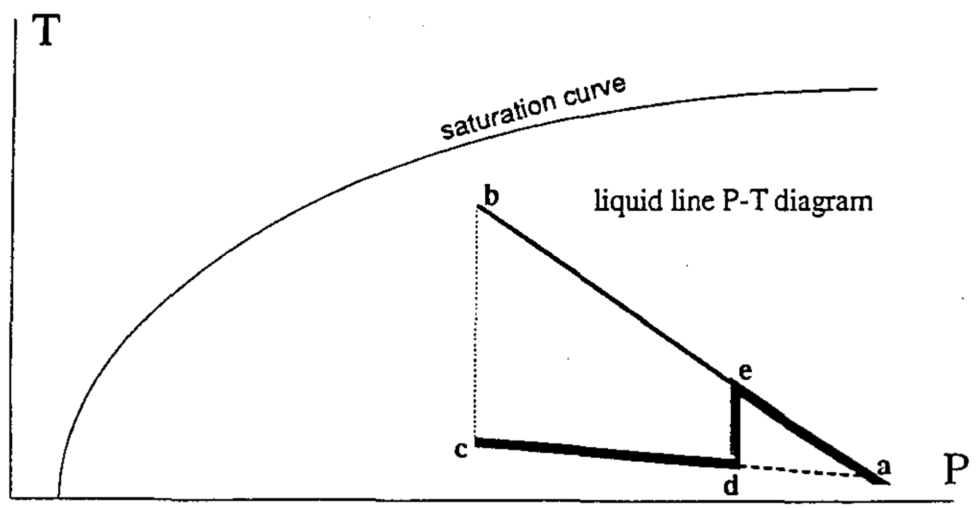


a) LIQUID FLOW IN THE LIQUID LINE AND LIQUID FLOW IN THE VAPOR LINE IN THE SAME DIRECTIONS

ab liquid flow , a recooler every 4km
ac ideal continuous recooling
a_d_e_c partial continuous recooling
bc compact recooler.

LN in the vapor line
LN in the liquid line

Figure 15:Liquid flow in the liquid line and liquid flow in the vapor line in the same directions.



b) LIQUID FLOW IN THE LIQUID LINE AND LIQUID FLOW IN THE VAPOR LINE IN OPOSITE DIRECTIONS

LN in the liquid line
LN in the vapor line

ab liquid flow , a recooler every 4km
ca ideal continuous recooling
c_d_e_a partial continuous recooling
bc compact recooler.

Figure 16:Liquid flow in the liquid line and liquid flow in the vapor line in opposite directions.

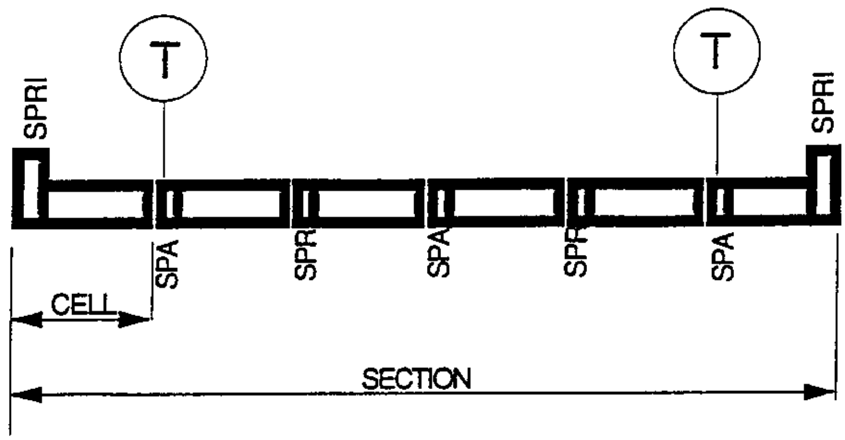


Figure 17:Location of the temperature measurements in the 84 K shield

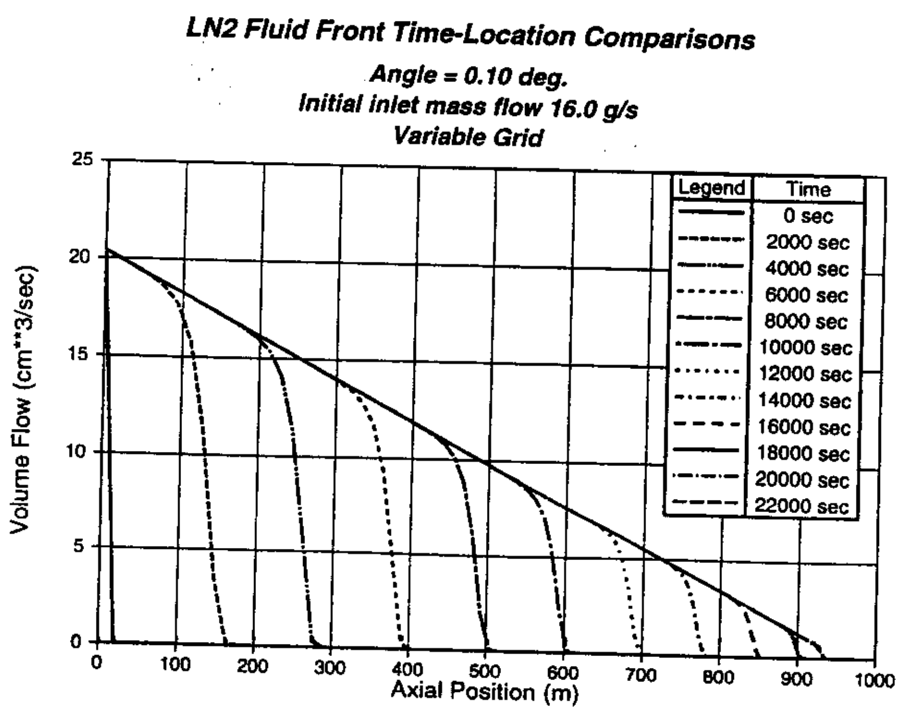


Figure 18:Transient liquid nitrogen distribution for angle of 0.1 degrees

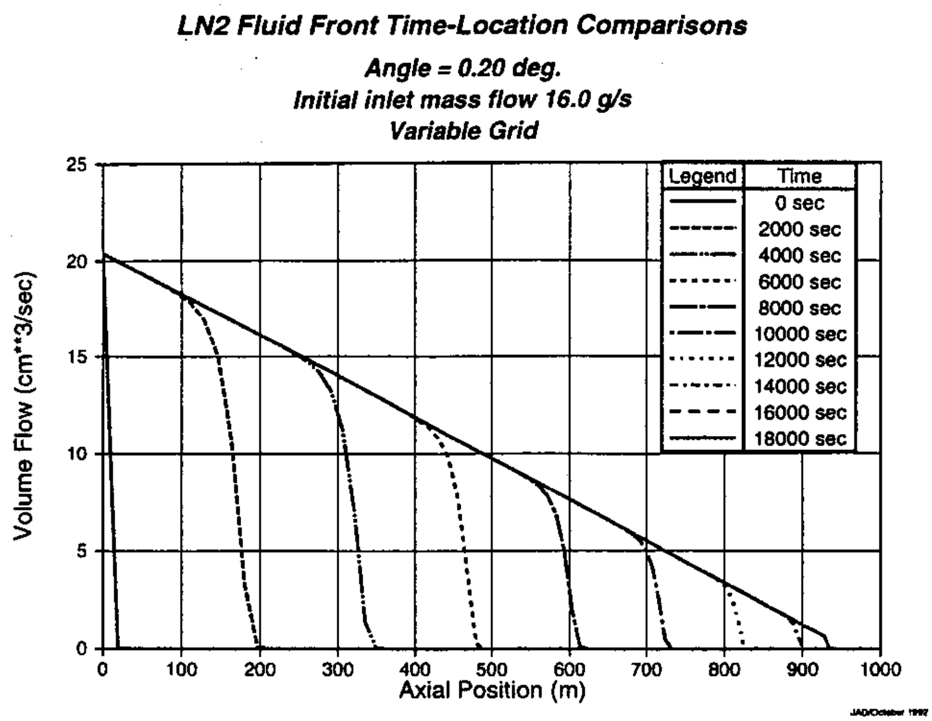


Figure 19:Transient liquid nitrogen distribution for angle of 0.2 degrees

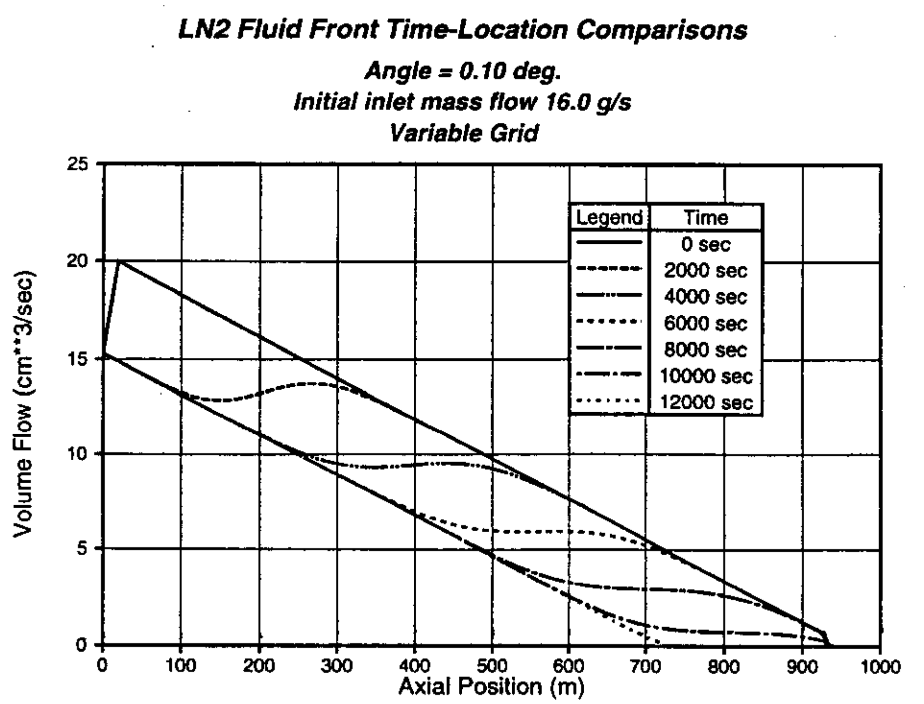


Figure 20:Liquid flow distributions for step change to 12 g/s 0.1 degrees.

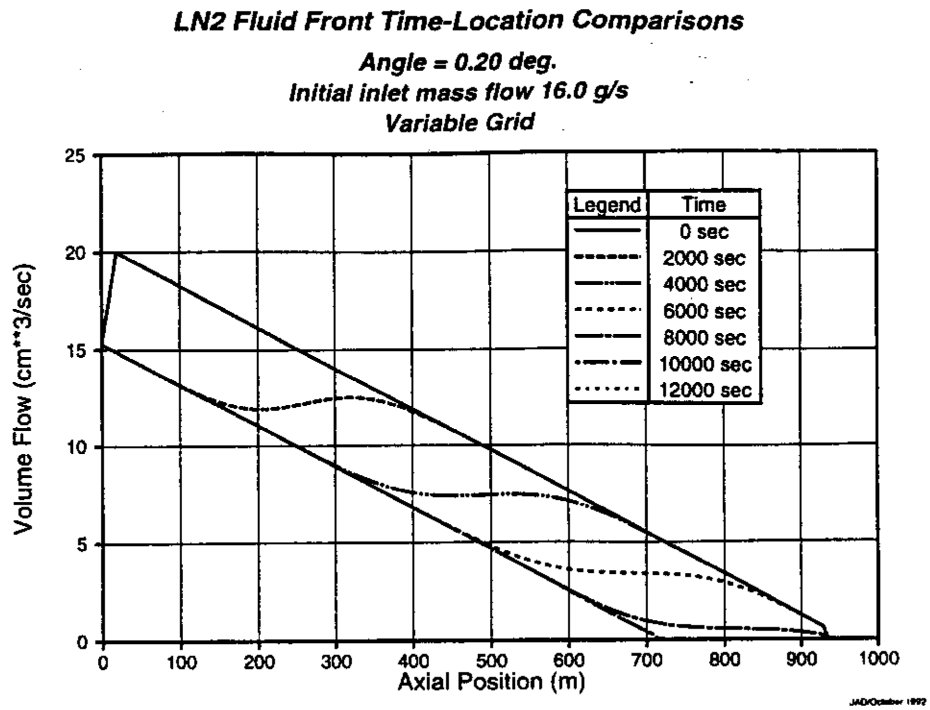


Figure 21:Liquid flow distributions for step change to 12 g/s 0.2 degrees.

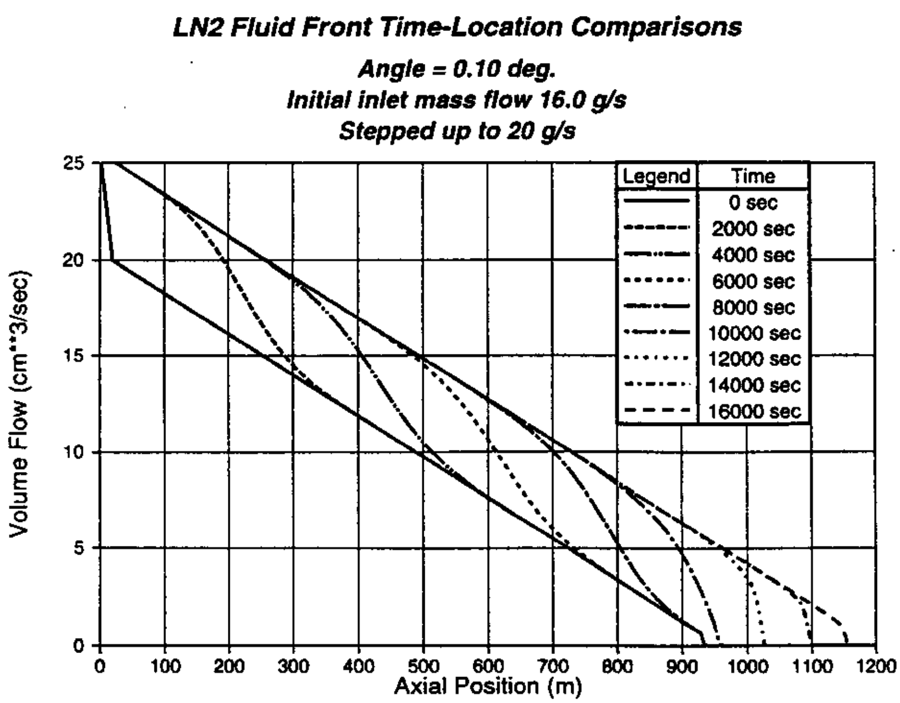


Figure 22:Liquid flow distributions for step change to 20 g/s 0.1 degrees.

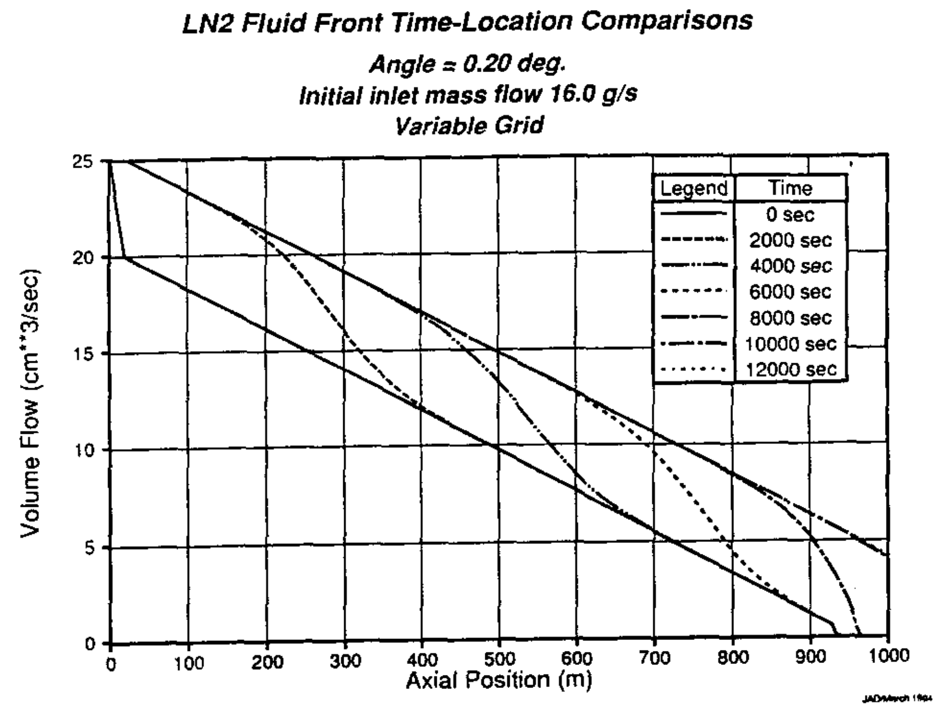


Figure 23:Liquid flow distributions for step change to 20 g/s 0.2 degrees.

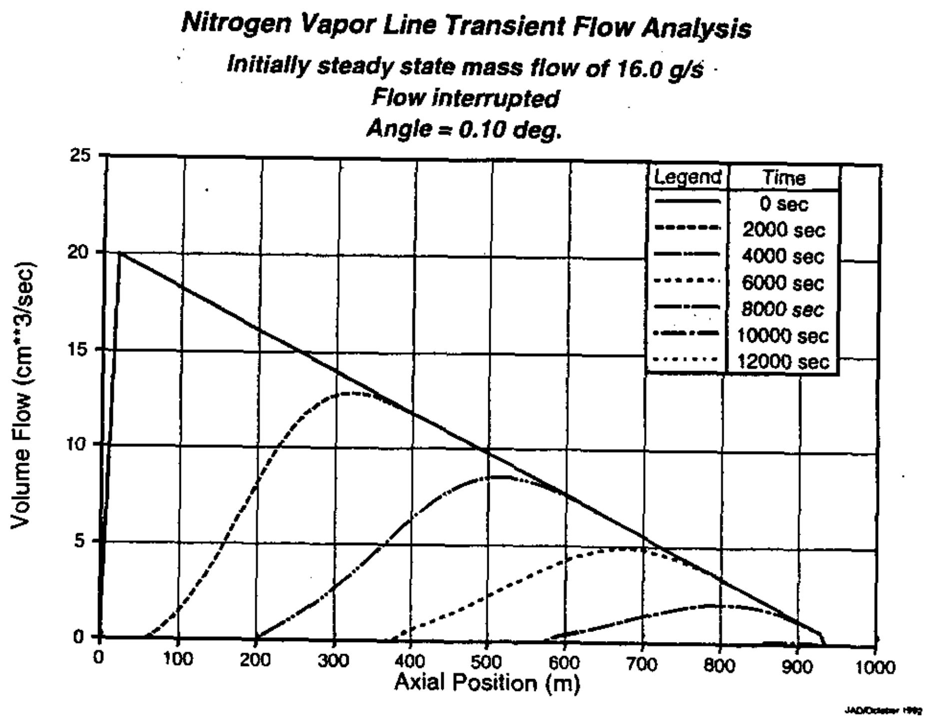


Figure 24:Flow distributions for flow interruption at 0.1 degrees

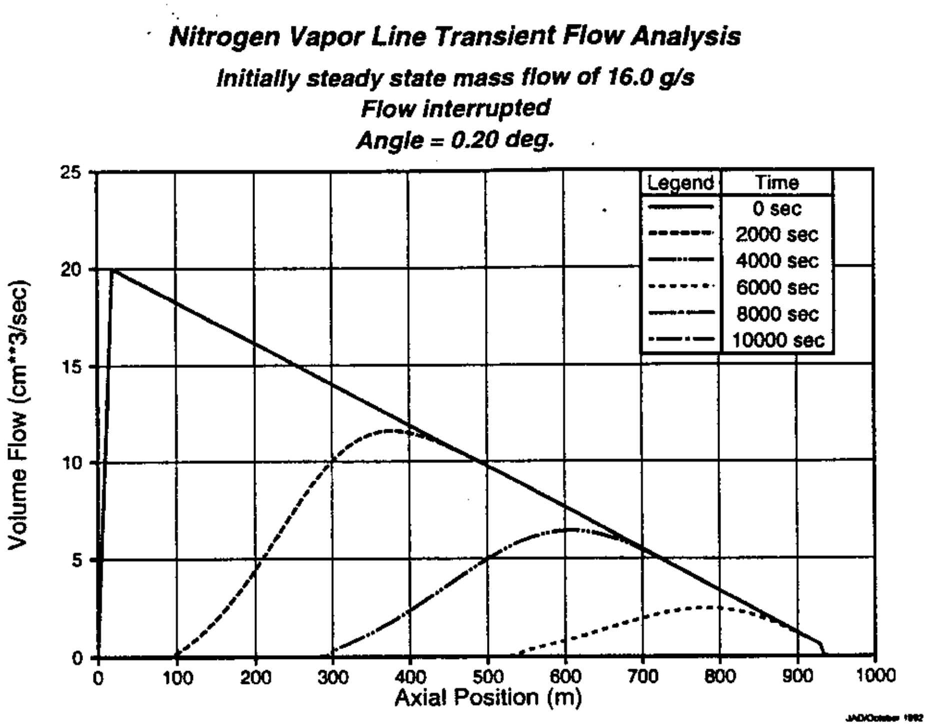


Figure 25:Flow distributions for flow interruption at 0.2 degrees

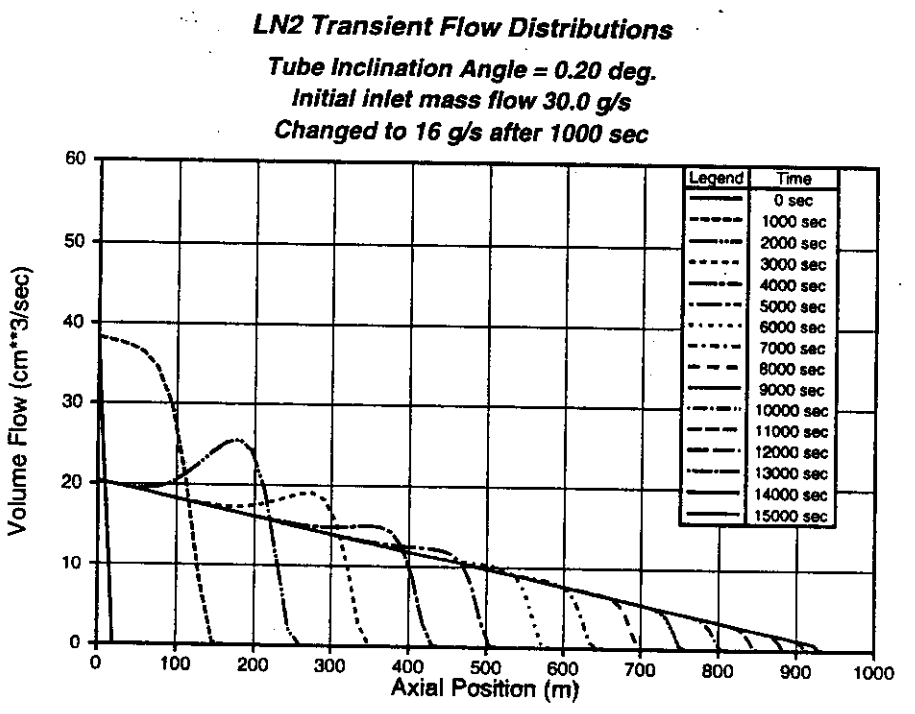


Figure 26:Flow distributions for 30 g/s stepped down to 16 g/s after 1000 sec.

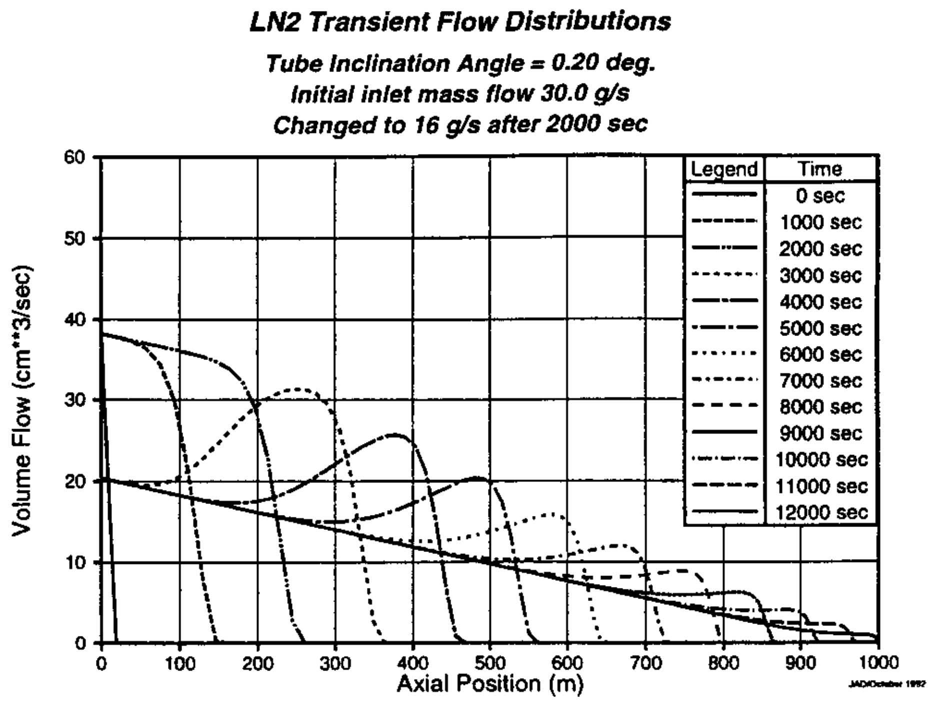


Figure 27:Flow distributions for 30 g/s stepped down to 16 g/s after 2000 sec.

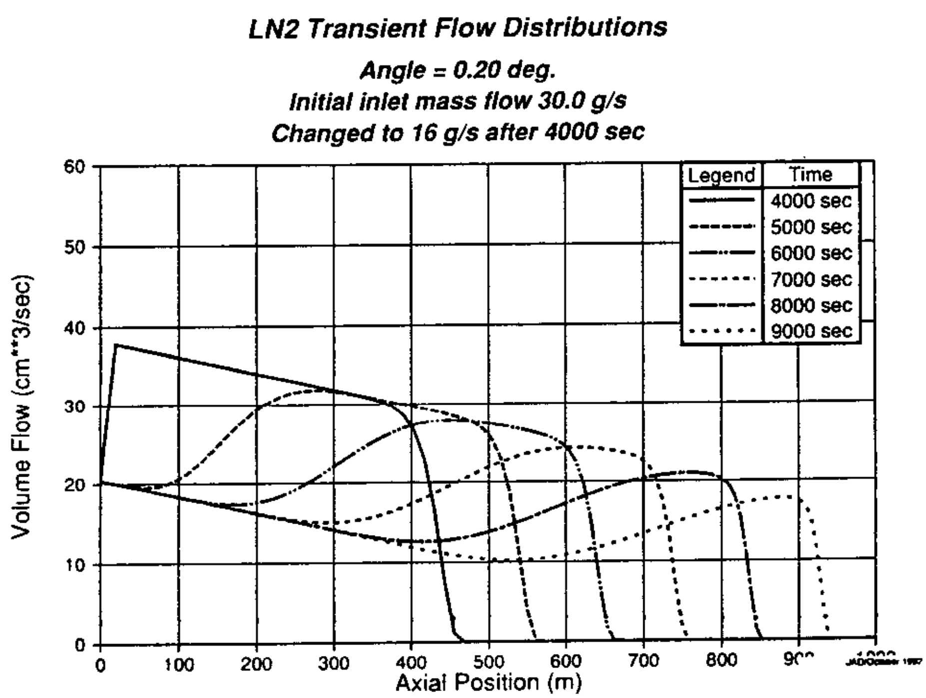


Figure 28:Flow distributions for 30 g/s stepped down to 16 g/s after 4000 sec.