Equation-based Dynamic Simulator for the Cryogenic System of the Superconducting Super Collider

by

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Abstract

This report describes the development of an equation-based dynamic simulator for the cryogenic system for the proposed Superconducting Super Collider (SSC) using SPEEDUP (Simulation Program for Evaluation and Evolutionary Design of Unsteady Processes).

1. Introduction

This report describes the development of an equation-based dynamic simulator for the cryogenic system for the proposed Superconducting Super Collider (SSC) using SPEEDUP (Simulation Program for Evaluation and Evolutionary Design of Unsteady Processes). The principal tasks of this project were :

  1. Incorporation of Helium Thermodynamic models in SPEEDUP

  2. Development of models for the individual units and

    assembling them to form the SSC network.

  3. Steady state simulation of the network

  4. Dynamic simulation of the basic scenarios

  5. Proposing how to use the simulator to devlop control
       strategies .

  Tasks 1 thru 3 were accomplished , but task 4 could not be completed as the dynamic model was found to have an index exceeding unity and the present algorithm in SPEEDUP cannot handle such problems. As a result, task 5 could not be taken up. Further research is needed to understand and reformulate the models to avoid the index problem.

While the SPEEDUP environment does provide extreme flexibility in specifications, work was hampered to a great extent because the (academic university) version provided to us could not deal with the large dimension problem presented by SSC. It was also found that steady-state convergence does not take place for all specifications (There are theoretical and practical reasons why this is the case). Generally, one has to first converge on a slightly different set of specifications and then, using the results just obtained, converge on the desired set of specifications. Often, this turned out to be a complex and difficult detective work because of the large dimension of the problem.

Our work complements the earlier work done at Air Products and Chemicals, Inc (APCI) described in the following reports :

1. Hartzog, D.G. , V.G. Fox, P.M. Mathias and D.Nahmias :
   " Dynamic Models and Simulator Design ", SSC Dynamic
    Modeling and Simulation Contract   Task 2 Final Report,
    APCI , Allentown (March 1988) .

2. Hartzog, D.G. and V.G. Fox : " Dynamic Models and Simulator
    Development " , SSC Dynamic Modeling and Simulation Contract
    Task 3 Final Report,   APCI , Allentown (June 1988) .

3. Hartzog, D.G. and V.G. Fox : SSC Helium Cryogenic Network
    Dynamic Simulator User Manual, APCI , Allentown (July 1988) .

Accordingly, this report supplements the material contained in these reports and is meant primarily for those who will be involved in future developments. To give some idea of the project, we have included extracts from these reports in Appendix 1. Please turn to Appendix 1 and get familiar with the contents before resuming .

The Helium thermodynamic package developed at Air Products was made available to us. Everything else was built up from scratch here.

2. SPEEDUP

SPEEDUP is a program developed at the Imperial College, London for process engineering applications. Its present capabilities include steady-state simulation and design, dynamic simulation, optimization and parameter estimation. For the underlying mathematical ideas, see Pantelides (1988).

SPEEDUP has a modeling language tailored for process engineering applications. The system easily links to user-written procedures and subroutines.

SPEEDUP provides an interactive environment for creating, storing, retrieving and modifying problems and also allows the results of one problem to be used in the solution of another. The executive handles request for on-line help, diagnostic information, plotting ,storing and retrieving of results and manages various house-keeping and accounting tasks.

In Appendix 2, a listing of the dynamic model of the recooler written in SPEEDUP is included to give a flavour of the language and to show how conventional modeling can be done using SPEEDUP. This should be compared with the description of the recooler model described in Hartzog £lai (1988a) .

3. Helium Thermodynamics

The Helium thermodynamic package of APCI was incorporated into the SPEEDUP system as described in the SPEEDUP System Manual. For someone familiar with the setting up of thermodynamic data bases, this is not a difficult task.

There were no serious problems with Helium thermodynamics during our steady state simulation with temperature and pressure as input variables in the thermodynamic procedures. However, convergence could not be achieved to the desired tolerances when using density and internal energy as the input variables. Also , on small problems (about 50 variables/equations) , we did not observe

much difference in computation times when working with Model 1 (Rigourous NBS McCarty Model) or with Model 3 (Simplified model due to Paul Mathias of APCI) when temperature and pressure are used as input variables in the thermodynamic procedures.

4. Modelling of SSC network

The basic system was divided into the following 4 sub-systems :

1. 4K Feed system
2. 4K Refrigeration system
3. 20K Refrigeration system
4. Main sub-system (String 1) consisting of half_cells, recoolers, vapour return nodes , liquid return nodes and 20K shield nodes.

(In the SPEEDUP code , these appear as the corresponding MACROs FEED4K, REF4K, REF20K and S)

4.1. Thermodynamic Procedures :

Under stand-by conditions , except in the shell-side of the recoolers only a single-phase, either liquid or vapour exists in the nodes. Accordingly, the following thermodynamic procedures were created :

No.	Procedure Name	Input	Output
1.	LHURHO	Temperature, Pressure, Total flow rate of (liquid) stream	Enthalpy-flow, Molar internal energy and density
2.	VHURHO	Temperature, Pressure, Total flow rate of (vapour) stream	Enthalpy-flow, Molar internal energy and density

3.	HURHOS	Pressure, Total flow rate of vapour	Saturation temperature, molar internal energies and densities of saturated liquid and vapour , and enthalpy-flow

The data tabulated in Hartzog et al (1988a) was used to set up the bounds on temperatures and pressures on the nodes to ensure that liquid or vapour state obtains, as appropriate.

Because the molar densities and the internal energies appear as state (i.e differential) variables in the modelling equations, it seems reasonable to set these as input variables and the temperatures and pressures of the nodes as the corresponding output variables of the procedures (density - internal energy flash). It was not possible to achieve convergence to the desired tolerance in this case, although the experience at Air Products seems to be different.

4.2 Modelling of the liquefier pump PI

When the proton beam is brought to full power, the system becomes "warm" and the average density of helium within the rings decreases. This means that helium must be removed from the system. The opposite is true when the beam is turned off. This requires that the liquefier pump must remove/load helium from/into the system depending on the operating conditions, i.e., the pump must "reverse" the flow when required.

This situation was modelled as two different pumps (FDP1A and FDP1B) with only one of them running under dynamic conditions and

both remaining stationary under either of the steady-state conditions (i.e standby and full load) (see figure 1).

Thus, beginning with standby conditions, both the pumps will be off. When the beam is turned on , the pump FDP1B will remove helium from the system , while the pump FDP1A is off. As the new steady state is approached , the flow through FDP1B will diminish gradually and cease eventually . A similar situation obtains when the beam is turned off with the roles of FDP1A and FDP1B interchanged.

4.3 Specifications

With the version provided to us, it was not possible to use the SPECIFY sub-environment when incomplete or incorrect specifications were made. The set of valid specifications were determined for each subsystem and these were pieced together to get a valid set for the system as a whole.

After a very large number of attempts, only one set of specifications was found on which the convergence takes place smoothly in the first attempt. On all other set of specifications, the program failed in the first attempt. The case for which it converged was a used as a base case . All other cases could be solved only when using the converged results of the base case as the initial set of values for the simulation.

This base case differs from the simulation carried out at Air Products in setting up the following variables :

1. Upstream pressure of the liquid return valve
   (variable PRET in node S.LV)

2. Flowrate of stream leaving the condenser of 4K refrigerator .
   (variable SOUT(l) in node REF4K.R4CON)

3. Pressure of feed exit junction node of 20K shield node
   (variable P0UT1 in node REF20K.R2EX).

In the simulation at Air Products, the following equivalent set of variables were set :

1. Conductance of the liquid return valve
   (variable C of unit S.LV)

2. Lift of the Feed exit junction node control valve to String 1
   of Ring 1 (variable XVI of unit FEED4K.FDEX)

3. Conductance of the feed exit junction of 20K shield node
   (variable C of unit REF20K.R2EX)

The differences in the converged results are not significant
(often, they were identical to three or more decimals).

4.4 Dynamic Simulation :

As mentioned earlier, this could not be completed as the differential algebraic system (DAE) was found to have an index exceeding one (Gritsis alai (1988)). The present algorithm in SPEEDUP cannot handle this case. Further work is needed to understand and overcome this problem .

5. Experience using SPEEDUP

(**It** is possible that some of the difficulties mentioned below have
already been set right in subsequent versions of SPEEDUP)

5.1 _Computer usage

The mainframe VAX computers at CMU are quite powerful, but
there are far too many users. So, most of the work was done on a
Micro VAX dedicated exclusively for this project. This hardware is
about 7 times slower than VAX 8700.

It is somewhat meaningless to talk about CPU time usage in
SPEEDUP, because this program is primarily a development tool.
Anyway, here are some statistics to give some idea about the size of
the problem . (The code runs to nearly 5000 lines).

```
No.  of variables              :  2360
No.  of equations              :  1645
No.  of specifications         :   715

No.  of differential variables :  364
No.  of procedure invocations  :  152
```

Here are the times required on the Micro VAX (in minutes)

	CPU time	Elapsed time
1. Translation	22	70
2. Compiling Equation Fortran	5	15
3. Block decomposition	3	8
4. Compiling Jacobian Fortran	5	15
5. Miscellaneous compilations	2	4
6. Linking	2	3
7. Execution (base case)	3.5	10
8. Retranslation for a different set of specifications	4	10
9. Steps 3 thru 6 above	5	15
10. Execution	0.6	3

SPEEDUP reports the times only for steps 1 ,7, 8 and 10. The other times were estimated and sometimes timed .

5.2 The Text Processor :

Undoubtedly, the text processor is one of the most powerful features of SPEEDUP . It leads to economy of thought and conciseness and clarity in coding . Naturally, it was used extensively because of the large number of repetitive units in the network. Unfortunately, its use in the PRESET sub-section of the OPERATION section was beset with problems .

For example, consider the following :

   ?Repeat

   Within ^{rf}S.HC(?(2*M))^{ff}

   POUT = 3. 85 - 0.01 * ?(I)

   ?WithI= < 1:18 >

  The use of the text processor prevented the setting of lower and upper bounds on POUT. For example, our version did not accept

   POUT = 3.85 - 0.01 * ?(I) : 3.55 : 3.95

(One could, of course ,   get around this somewhat by some programming gimmick   like introducing a new variable , say POUT1 , introducing a new equation POUT1 = POUT and finally, entering POUT1 = 3.76 : 3.55 : 3.95 in the PRESET subsection) .

Now, trouble arose when convergence did not take place and when diagnostic information was printed about the block on which these variables are present.

Since POUT was declared to be a variable of the type PRESSURE and in the DECLARE section the type PRESSURE appears as :

PRESSURE   = 1.0 : 0.5 : 18.0   Unit = "atm"

(i.e the nominal value for the variable of the type PRESSURE is 1.0 and the lower and upper bounds are 0.5 and 18.0, respectively),

the diagnostic information printed on the variable POUT will have that the initial value of POUT was 1.0 and the lower and upper bounds are 0.5 and 18.0, respectively. This was clearly incorrect , because had the initial value been 1.0 , during PRECALL , the thermodynamic program would have detected this, because the phase of the stream would not be what it was expected to be.

5.3 Precalling :

The PRECALL facility of the PROCEDUREs is also an excellent feature of SPEEDUP , but here again incorrect diagnostic information is printed.

For example, if

(H, U, RHO) LHURHO (T , P, SIN)   INPUT

is the PROCEDURE statement and the initial values of T , P and SIN are entered for the unit, only the nominal values of the variables types of H , U and RHO are printed in the diagnostics.

5.4 Use of Stream Variables in Connections :

The baffling inconsistency of allowing this sometimes and disallowing at other times has been eliminated in the recent version of SPEEDUP.

6. Conclusion

This report has described our experience in using SPEEDUP for solving a fairly large and complex problem. We believe that SPEEDUP is an excellent development tool , but its numerical performance on large problems certainly seems to require strengthening. Overall, our opinion about it is favourable and we have found it to be a valuable learning experience.

7. References

1. Hartzog, D.G. , V.G. Fox, P.M. Mathias and D.Nahmias :
   " Dynamic Models and Simulator Design ", SSC Dynamic
   Modeling and Simulation Contract   Task 2 Final Report,
   APCI , Allentown (March 1988) .

2. Hartzog, D.G. and V.G. Fox :   " Dynamic Models and Simulator
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   Task 3 Final Report,   APCI , Allentown (June 1988) .

3. Hartzog, D.G. and V.G. Fox : SSC Helium Cryogenic Network
   Dynamic Simulator User Manual, APCI , Allentown (July   1988) .

4. Pantelides, C.C.:   " SPEEDUP — Recent Advances in Process
    Simulation " , Computers and Chem. Engg., 7 , 745-755 (1988).

5. Gritsis, D. , C.C. Pantelides and R.W.H. Sargent : " The Dynamic
    Simulation of Transient systems described by Index two
    Differential-Algebraic Equations " , Third International
    Symposium on Process Systems Engineering, Sydney
    (September 1988) .

To storage

FDP1B

Connection

From **storage**

FDP1A

Condenser of 4K refrigerator

Suction node of pump P2

To pump P2

To feed recooler

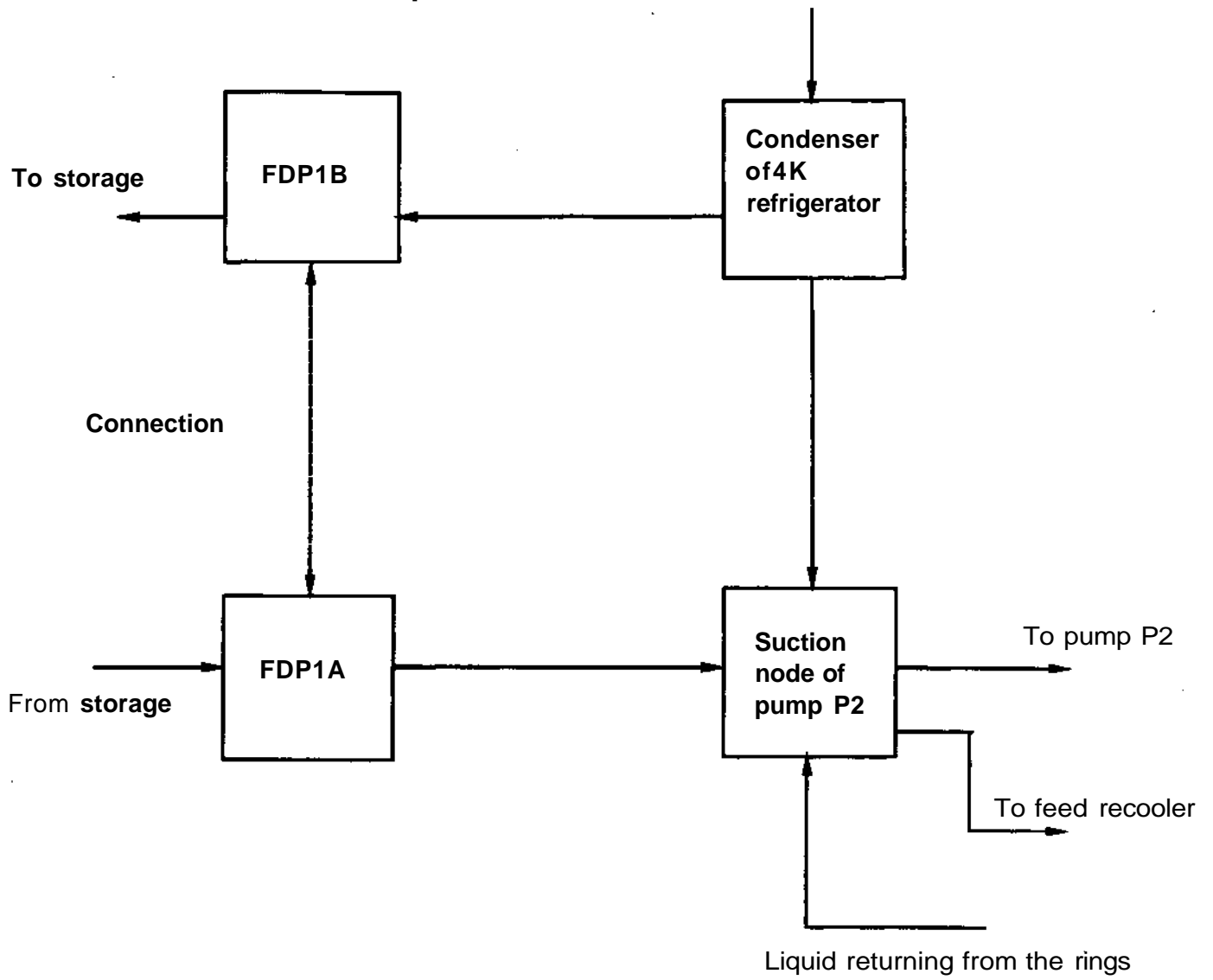Liquid returning from the rings

Figure 1. Logic diagram for Liquefier pumps

Appendix   1

**Extracts from "Dynamic Models and Simulator Design"
SSC Dynamic Modeling and Simulation Contract
Task 2 Final Report**

1.0 Introduction

This document constitutes the report due upon the completion of Task 2, Dynamic Models and Simulator Design, of the SSC Dynamic Modeling and Simulation Contract between the Regents of the University of California and Air Products and Chemicals, Inc.

As stipulated in the contract, this report includes the process flow diagrams of the helium refrigeration circuits, the dynamic models to be used to simulate the process, an explanation of the nomenclature :o be used in the software, and a list of the operating events to be simulated.

Also included as Appendices are (1) a report describing two simplified thenuodynamic models which predict helium properties very close to those predicted by the NBS standard helium model, but which execute several times faster; and (2) a report describing an analysis to obtain a reasonable estimate of the VAX 3700 CPU resources required to simulate the operating scenarios discussed in section 4 for each of the theraodynamic models*

2.0 Process Description

The proposed 20-TEV superconducting super collider requires an extensive cryogenic system to maintain the superconducting magnets at or beicw ..35 :< and to provide for transient conditions such as cooldown and magnet $z^{er}.ch$. The current conceptual design of the magnet cooling and refngera:.·re-distribution system is illustrated in Figure 1 for one-quarter of an ar: sector. Liquid helium from the 4 K refrigerator is mixed with reeve.ei liquid helium at essentially the same temperature and pumped at - a:r. through a recooler to remove the heat added by the pump and then into each ring of magnets both upstream and downstream of the refrigeration ::r.- for a distance of 4 km. The supercritical helium flows through :.-e -a^-.ets in series and is recooled periodically against boiling helium in :::~ •: maintain the magnets at or below 4.35 K. Helium inventory in this · ..: is governed by a.pair of flow controllers located at the beginn;-^ .:·-e.c of each string. Each magnet string consists of either 13 sets cr· -- magnet half-cells plus one recooler in series or 17 sets of two -<*£-e- half-cells plus one recooler in series plus two magnet half-cells \: -> -r.e 17th recooler- Along the 4 K liquid return line, small flows are -.--irivn and expanded into pool-boiling recoolers spaced at intervals of :re - . Tlie saturated gas from the recoolers is collected and returned :c - - • •: refrigerator in the cold vapor return line. At the end of each :•?.. •.:•? two valves which are normally closed. One is a safety relief vale -- it 20 atm, which vents to ambient. The other is a cooldown valve :r.s- connects the 4 K helium stream with the warm vapor return header.

RING 1

END OF SECTOR

TWO HALF CELLS + RECOOLER REPEAT 18 TIMES

WARM VAPOR RETURN
COLD VAPOR RETURN

20 ATM SAFETY

20K SHIELD

HALF CELL

HALF CELL

RECOOLER

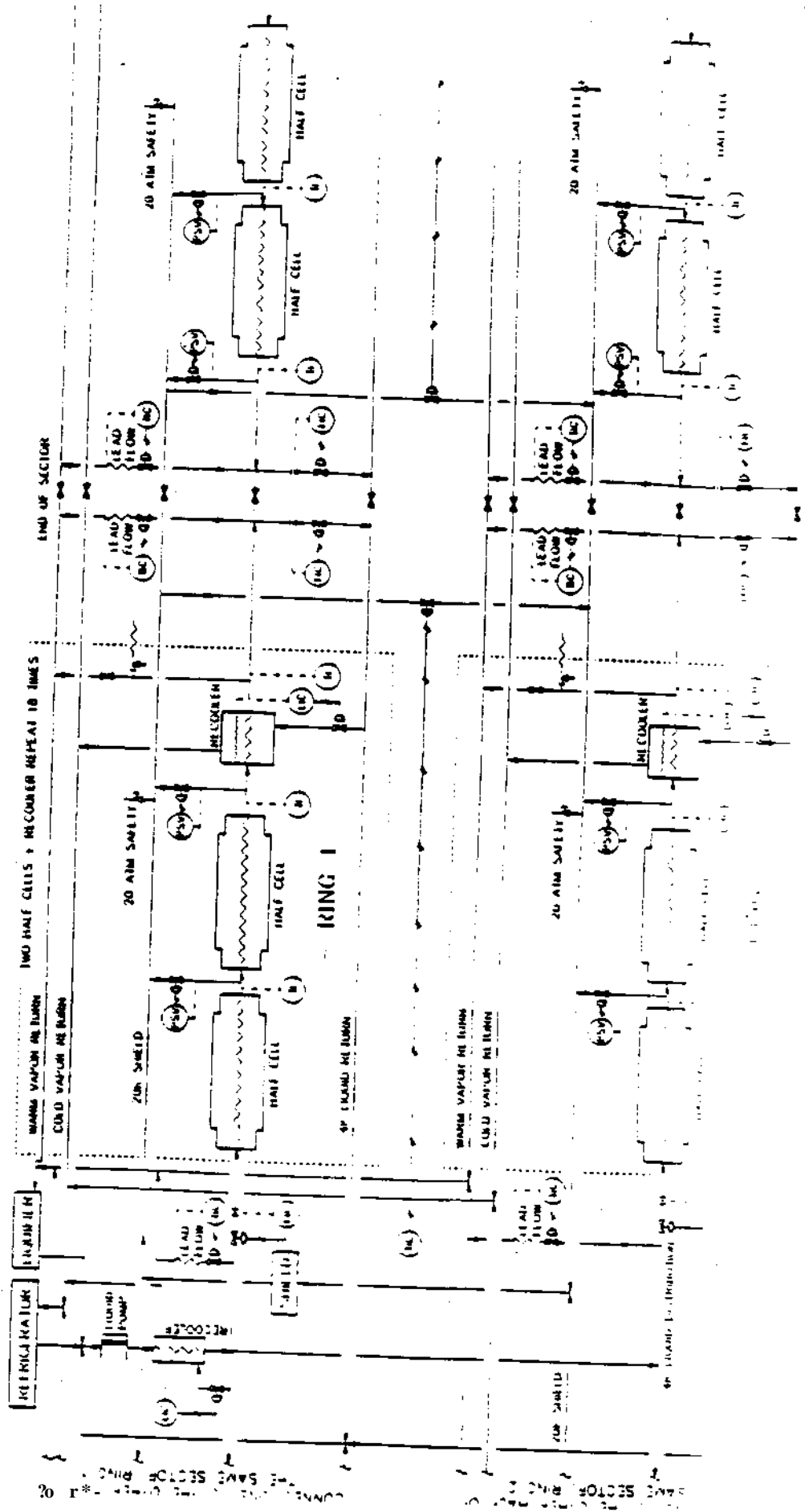LEAD FLOW

WARM VAPOR RETURN
COLD VAPOR RETURN

Figure 1

Acceleration Helium Circuit P&I Diagram

Tbt * K helium circuits of each ring are enclosed in separate,
vacuum-insulated cryostats containing shields at 20 K (helium) and 54 :<
(nitrogen) with multilayer insulation. (The nitrogen shield is not shown
in Figure i.) The helium gas which cools the 20 K shield passes from the
local refrigerator into one ring and is returned to the refrigerator in the
other ring. The return flow is governed by a temperature-indicating
controller (TIC). At the end of each half-cell is a quench relief valve
which connects the <* K supercritical helium circuit with the 20 :< shield
circuit. The operation of this relief valve is governed by a pressure
controller. At intervals of roughly one cell in the 20 K shield circuit is
a safety relief (20-atm) valve, which vents to ambient.

At the beginning and end of each string, helium is removed from the - :<
supercritical stream to cool the power leads. The amount removed is
governed by a TIC. The heated helium is returned to the refrigeration
plant through the warm vapor return line, which is located outside of the
magnet cryostats.

At the boundary between each sector, the circuits in each string of a
sector are connected by valving with the corresponding circuit :n :he
string of the adjacent sector. Under normal operating conditions.
these valves are open and thus flow between the sectors can occur
unless the circuits exactly balance.

3.0 Dynamic Models

3.1 Introduction

The most rigorous dynamic simulation of the SSC helium cryogenic ~e-·ᶜᵣᵡ
would be based on the solution of the partial differential equa:.:~ ·ᵗᵗᵋ
representation of the basic laws of mass, momentum and energy cor.se: ᵣ·.:n.
Unfortunately, a simulation model consisting of coded PDE's is ·ᵉʳ·
expensive to set up and to run, and is typically ouch store deta:.-:
that required for systems engineering tasks such as invest igat::.-. ·
failure response and propagation or determination of oeasuremer.: ᵢ .
control strategies. A simulation model based on the application -
engineering judgement and lumped parameter representation is gene- .
adequate for such analysis.

3.2 Basic Modeling Assumptions

In order to develop a workable mathematical model of the helium :.•
network, simplifying assumptions must be made. The basic assume*,   ᵊ
that the helium is always in thermodynamic equilibrium and tha: •-•*
"lumped-parameter" approach is adequate. A lump represents the :   ·:ᵉ
or volume of an individual process vessel or group of vessels p..;
interconnecting piping, or simply sections of piping over which --•>
spatial variations of density, pressure and temperature are ass,-·:
always be small. Obviously the more lumps incorporated within :-e ·   ·
the more rigorous the model becomes. However, as the rigor inc:ᵉ₃ ·

does the computational difficulty. The lumping proposed for the SSC helium network is shown schematically in Figure 2_f which represents one-quarter of an arc sector and its associated helium refrigerators.

Each rectangle or block in Figure 2 represents a "lump" or node. Each circle represents a stream or link between two nodes. Mass, energy and pressure are associated with the nodes. Flow is associated with the streams, which have no volume. As indicated in Figure 2, a half-cell is assumed to be a node. The boiling helium in each recooler is also considered to be a node. The helium flowing through the heat exchanger in the recooler is, however, not modeled as a node, since the holdup is quite small. Each 4 K vapor return header is modeled as 17 or is nodes corresponding to the number of recoolers in a string. The vapor return headers are interconnected by a junction node so that flow aay be passed directly among them. Likewise a junction node is used to distribute the 4 K supercritical helium to each string and a suction node is used to collect the 4 K liquid helium feed to pump P2. The 4 K liquid return header in each string is treated as a series of 17 or 18 nodes, corresponding to the number of recoolers in the string. Similarly, the 20 K shield in each string is treated as a series of 18 nodes corresponding to the :3 pairs of half-cells.

Since a high-fidelity model of a helium refrigeration plant is not required at this time, the refrigerator simulation, model has been greatly simplified. The liquefier is ignored completely. Liquid from storage is always available to meet the demand of pump PI, whose speed is manipulated by a pressure controller on the suction node of pump P2. All of the heat exchangers in the 4 K and 20 K refrigerators are ignored. Their capacities (volumes) are lumped into the respective compressor suction and discharge nodes, which are also assumed to be isothermal. Any excess flow through the 4 K refrigerator compressors (W4 and VS) is shunted to gas storage /ia a pressure controller on the discharge of V4. The suction pressure :r the 4 R refrigerator compressor is controlled by manipulating the scee; :r the compressor. Interconnections between gas storage and the suet.:- :.s:.-.arge of compressor W7 are maintained by pressure controllers.
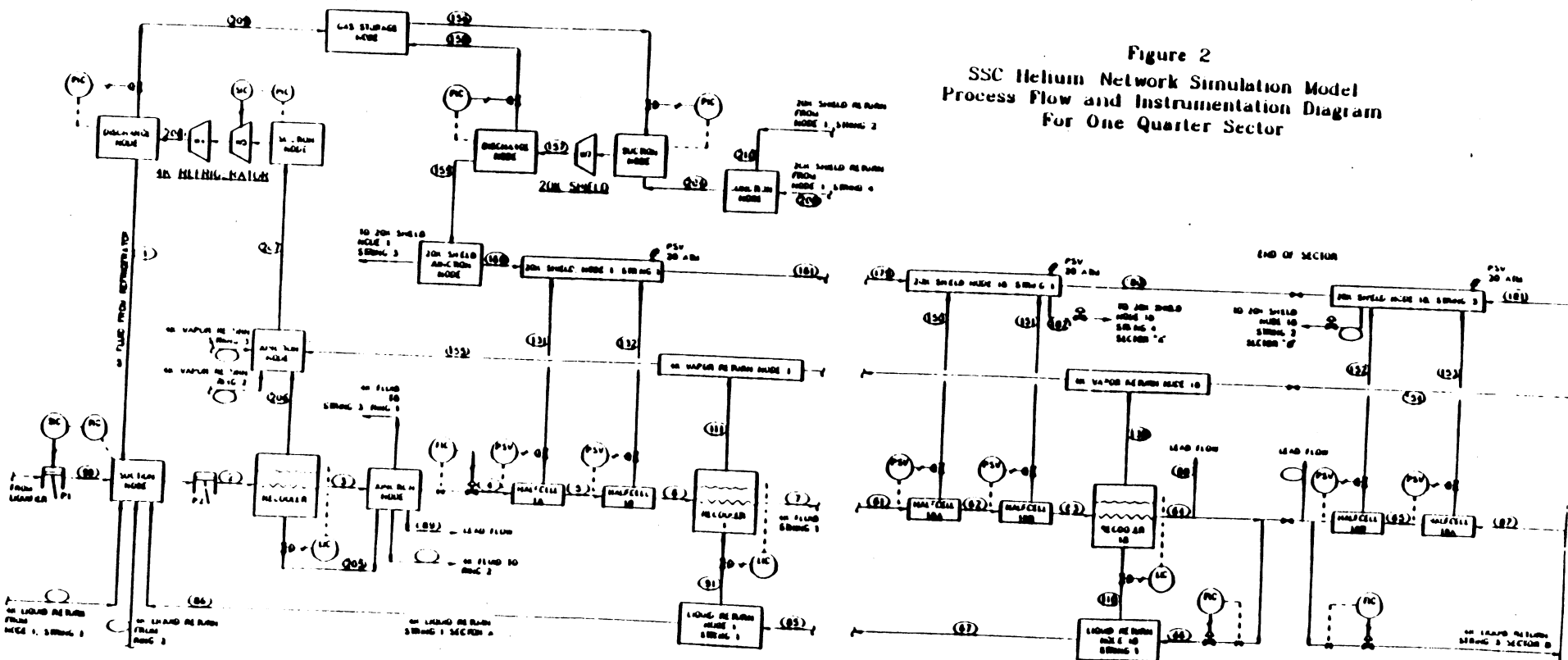
Figure 2
SSC Helium Network Simulation Model
Process Flow and Instrumentation Diagram
For One Quarter Sector

introduction

This document constitutes the report due upon the completion of Task 3, Dynamic Models and Simulator Development, of the SSC Dynamic Modeling and Simulation Contract between the Regents of the University of California and Air Products and Chemicals, Inc.

AS stipulated in the contract, the primary objective of this report is to present the results of the simulation of the three upset scenarios defined in the Task 2 report. By agreement made at the Task 2 Review meeting in February 1988, this report also includes discussion of the sensitivity of the simulation to integration parameters which originally was to have been presented in a separate report upon completion of Task 4. Also included is an updated simulation P&I diagram which reflects changes to the flowsheet requested by the CDG since the Task 2 review meeting and a control scheme for manipulating the speed of the primary coolant pump (P2).

Process Modifications

At the request of the CDG since the Task 2 Review meeting, four minor modifications to the flowsheet have been implemented: (1) the source or the feed stream to the shell of the recooler located immediately downstream of the primary coolant pump (P2) was changed from the ex;: junction node to the suction node of the pump; (2) the PIC controlling the 4K refrigerator compressor speed was changed to regulate the vapor return junction node rather than the compressor suction node pressure; (3) the PIC controlling the 4K compressor discharge pressure was inactivated by simply placing the controller in manual mode; and ⁴⁻⁾ ~~e liquefier transfer pump was allowed to run backwards in order to recur-. liquid helium to the storage tank as dictated by the PIC controlling •-•? suction node pressure.

In addition to the above modifications, we have added a PIC to con:re. the pressure in the 4K feed area junction node by manipulating the s:e ᴶ: of the primary coolant pump (P2). This modification was necessary :~ r:-r for the system to function stably when the FIC's controlling the fee• to the magnet strings would signal their respective control valves :• close. As the valves close, the pressure in the junction node increase* which then increases the flow through the valve and the contoller s:|~.J. : the valve to close even further. As a first attempt to rectify :h;s situation, we implemented the control scheme stated above and whicn -; shown on the updated simulation PSI diagram, Figure No. 1.
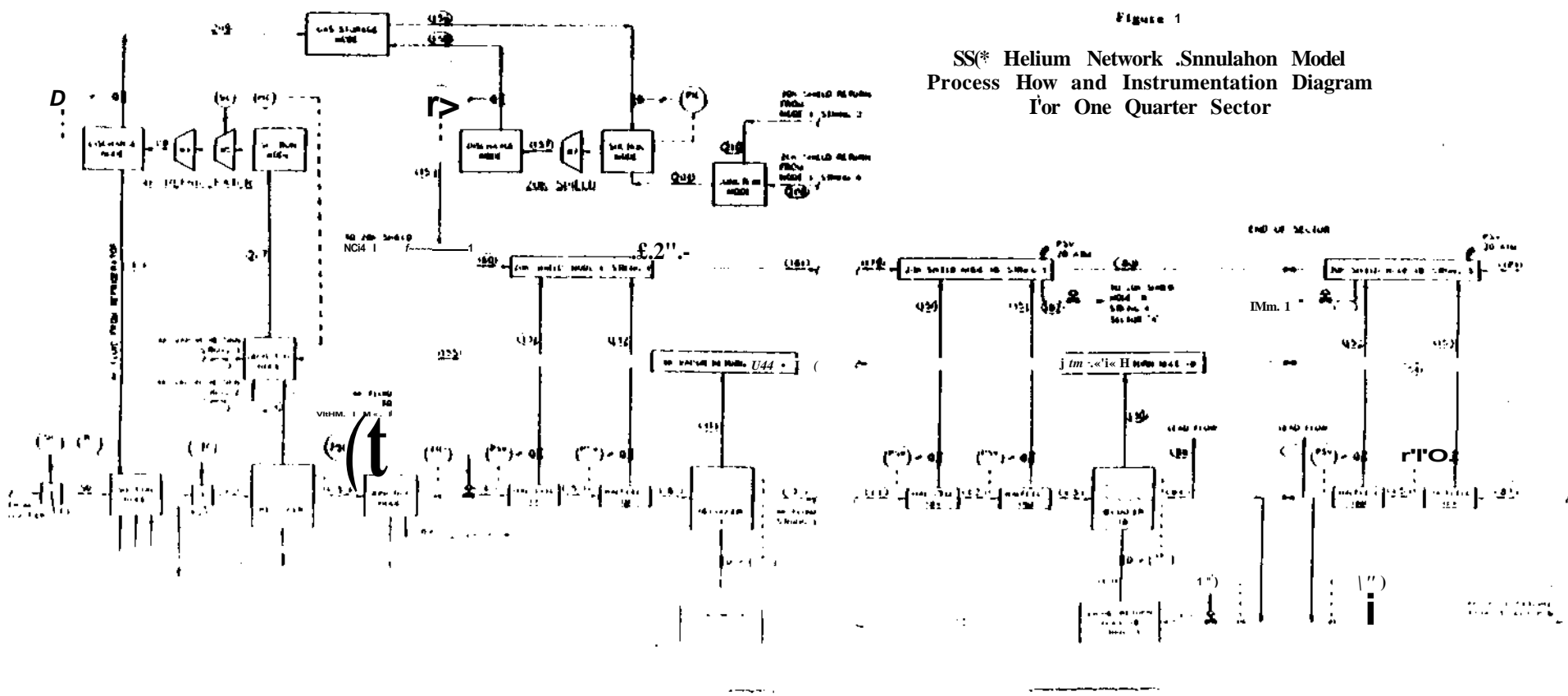
Figure 1

SS(* Helium Network .Snnulahon Model
Process How and Instrumentation Diagram
I'or One Quarter Sector

Appendix   2

Recooler   Model

MODEL RECOOLER

```
      # Dynamic model of the Recooler #*
      # See pp 7-10 of "SSC Dynamic Modeling and Simulation #
      # Contract   Task 2 Final Report        #
      # Dynamic Models and Simulator Design #
      #  March 1988 — DGH, VGF, PMM and DN of APCI   #


   SET

   NOCOMP,

   ESRE - *1.5 ,      # Exponent of mean temperature difference in recooler  #
                      # shell-side heat transfer coefficient expression #

   ETRE - *0.8 ,      # Exponent of flow rate in recooler   #

                      # tube-side heat transfer coefficient expression #
   QL  - *0.0,
                      #  Static heat leak to recooler          #
   LI  - *0.05 ,
                      # Recooler  normalized liquid level corresponding #
                      # to bottom of heat exchanger  #
   L2  - *0.68 ,      # Recooler  normalized liquid level corresponding #
                      # to top of heat exchanger  #

   LMAX  • *1.00,     #  Maximum recooler  normalized liquid level #



   BS - *60178.0 ,    # Proportionality factor in recooler  shell-side #
                      # heat transfer coefficient expression #


   VI  - *3.5 ,       # Recooler  shell-side volume corresponding #
                      # to bottom of heat exchanger   #
   V2  - *35.0 ,      # Recooler  shell-side volume corresponding #
                      # to top of heat exchanger   #

   VMAX - M5.0 ,      #  Maximum recooler  shell-side volume #

   AMAX - *1.525 ,    # Recooler maximum heat transfer area #

   BT  - *76.0306     # Proportionality factor in recooler  tube-side *
                      # heat transfer coefficient expression #

   TYPE


    WTIN , WTOUT,            # tube_side flowrates #

    WSIN , WSOUT     .       # shell_side flowrates #


                       AS        ARRAY(NOCOMP) OF FLOWRATE

   TTIN,TTOUT,TSIN,
   TSOUT                AS        TEMPERATURE # of respective str=:~ *
```

```
    PSIN ,                    # Pressure of return liquid upstream of control valve*

    PSOUT ,PSOUT1,            # Pressure of shell-side helium    #

    PRV,                        # Pressure of the return vapour header #

    PTIN ,                      # pressure of 'the tube-side fluid upstream #

    PTOUT                       # pressure of the tube-side fluid downstream #


                        AS      PRESSURE


    HSIN,                       # enth_flow of shell-side inlet fluid #

    HSOUT,                      # enth_flow of shell-side vapour        #

    HTIN,                       # enth_flow of tube-side inlet fluid #

    HTOUT,                       # enth_flow of tube-side outlet fluid #

    QR                          # Heat transfer between shell-side and  #
                                # tube-side fluids #

                        AS      ENTH_FLOW

    RHOSV,                      # Density of shell-side helium vapour #

    RHOSL,                      # Density of shell-side helium liquid #

    RHO                        # Density of shell-side helium mixture #

                        AS       DENSITY


    CSO,                        # Outlet shell side stream conductance  *

    ARE ,                        # Heat transfer Area #

    V,                          # Liquid volume on the shell side #

    DELTA1,                     # delta tl  #

    DELTA2,                     # delta t2  #

    LMTD,                       # log-mean temperature difference #

    UO,                         # Overall heat transfer co-efficient *

    HS,                         # Shell-side heat transfer co-efficier.-. '

    HT                          # Tube-side heat transfer co-efficient »


                        AS   POSITIVE


    L,                          # Normalized Liquid level on the she!.        *

    BETA                        # Vapour fraction #
```

```
                               AS   FRACTION

UL , UV , U                AS   INT_ENERGY

                        #  Internal energy of shell side liquid,*
                        #  vapour  and mixture #


   STREAM


   INPUT    1    WSIN,  TSIN , PSIN,  HSIN

   INPUT    2    WTIN,  TTIN , PTIN,  HTIN

   OUTPUT   1    WSOUT, TSOUT , PSOUT,  HSOUT

   OUTPUT   2    WTOUT, TTOUT , PTOUT, HTOUT


   CONNECTION  1   PRV      # Pressure of the return vapour header #

   CONNECTION  2   L        # Measured value of level to the controller #

   CONNECTION  3   PSOUT1    # To the upstream node on the shell side #


   EQUATION


   HS  - BS * LMTD ' ESRE     ;     # Shell-side heat transfer coefficient #

   HT  - BT * WTIN ' ETRE     ;     # Tube-side heat transfer coefficient #

   1/UO - 1/HS + 1/HT         ;     # Overall heat transfer coefficient *

   DELTA1 - (TTIN - TSOUT )      ;

   DELTA2 - (TTOUT - TSOUT )      ;


   LMTD -  2.0 *SQRT(DELTAl*DELTA2)/3  + (DELTA1+DELTA2) /6 ;

                              # Patterson approximation for LMTD *


   QR - U0 * ARE * LMTD

      - HTIN - HTOUT ;           # Heat exchanged  #



   # Volume - height relation  #
    IF  V < VI    THEN

    L  - (Ll/Vl)* V

    ELSE

       IF  V < V2 THEN

       L - (L2-L1)*(V-V1)/(V2-V1)  + LI
```

```
        ELSE

        L « (LMAX -L2)*(V-V2)/(VMAX-V2) + L2

        ENDIF

   ENDIF  ;


 # Volume - area relation  #

  IF  V < VI    THEN

  ARE - 0

  ELSE

        IF  V < V2 THEN

        ARE - AMAX * ( V - V1)/(V2-V1)

        ELSE

        ARE - AMAX

        ENDIF

  ENDIF  ;


   # Shell_side flow rate  #

   ( WSOUT(1)/CSO)'2   -   (RHOSV * ( PSOUT - PRV )) ;

   # Assume that tube_side hold-up is negligible #

    WTOUT(l) » WTIN(l)  ;

   # Assume that tube_side pressure drop is negligible #

     PTOUT - PTIN  ;

    # Vapour fraction #

    ( VMAX - V ) * RHOSV * (1 - BETA) - V * RHOSL * BETA - 0 ;

   # Density of the mixture  #

     VMAX * RHO - V * RHOSL + (VMAX - V) * RHOSV  ;

   # Internal energy of the mixture #

     VMAX * RHO * U - V * RHOSL * UL + (VMAX - V) * RHOSV * UV

   # Unsteady state mass balance (Shell side ) #

     VMAX * $RHO -  WSIN(l) - WSOUT(l) ;

   # Unsteady state energy balance (shell side) #

    VMAX* ( $RHO * U + $U * RHO )
```

```
    = HSIN - HSOUT  +  QL + QR  ;

    # Connection #

    PSOUT1 = PSOUT ;


    PROCEDURE


(TSOUT, HSOUT, UL, UV, RHOSL, RHOSV) HURHOS ( PSOUT, WSOUT)          INPUT

    ( HTOUT )              LIQENT    (TTOUT,PTOUT, WTOUT)    INPUT
```