SSCL-N-712
AS-CY-002

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84 K NITROGEN SYSTEM FOR THE SSC.

1. System requirements

The Nitrogen system will be designed to meet the following requirements:

1.1. Provide the "84°K shield" refrigeration at a nominal temperature of 84.0 °K. The temperature range should be between 77.3°K to 88.5°K. An optimum design will result in the minimum cost to obtain the lowest temperatures and smallest temperature variations along the rings.

1.2 Provide heat transport medium for the 84°K cryostat shields. After absorbing the heat from the cryostat the "warm" liquid nitrogen will be recooled and the vapor nitrogen will be removed from the system. To increase the system efficiency the vapor should be returned to the adjacent helium plant. The optimum design will result in minimum cost to obtain maximum vapor recovery and the least amount of pressure drop in the vapor return lines.

1.3 Provide a distribution system for the nitrogen in the tunnel. A promising design is based on two LN generation plants located at sites E1 and E6. Ten (10) reservoirs located at the E sites will be required to supply the nitrogen in case of plant malfunction. The distribution of the nitrogen from the plants and/or from the reservoirs to the rings will be through the nitrogen lines in the cryostats (the 84°K shield lines). An other possible design is based on 10 LN plants, one at each of the E site, along the collider rings. The optimum design will result in fewer installations and lower operating cost.

1.3 Provide make up nitrogen liquid to the reservoirs. It is desirable that the make up liquid be supplied by the main LN plants through the refrigeration piping system however, in case of emergency, liquid distribution to the reservoirs may be furnished by vehicular transportation.

1.4 *Provide fluid for the helium precooling system in the helium plants.* The nitrogen vapor return line will be used for this purpose.

1.5 Cooldown of the cold mass from 300°K to 90°K. The initial cooldown of the system using nitrogen vapor is required in order to speed up the cooldown process and to reduce the cooldown cost.

1.6 Provide refrigeration during each operational mode of the plant .
Whenever there is vacuum in the cryostat the 84°K shield should be refrigerated.

2. Design requirements

2.1 Provide refrigeration for the following configurations:

a - Simultaneous operation of both rings.
b - Independent operation of each ring.
c - A single section is disconnected in a ring.
d - Two parallel sections are disconnected in both rings.
e - Any combinations of disconnected strings.
f - Only one nitrogen plant is operating.
g - Both plants are shut down. This will be an emergency situation. The nitrogen supply will be from the local sector reservoirs.

2.2 The pressure in the nitrogen lines in the cryostats should be as low as possible.

a - During normal operation the desired upper limit is 0.5 MPa.
b - During cooldown, fill up, and warm up, the pressure may rise up to 1.0 MPa.

2.3 The cross sectional area of the lines in the cryostat are constant.

2.4 The inventory of the nitrogen in the tunnel should be minimized. The inventory depends on the line diameter and on the fluid quality.

2.5 The control loops in this system will be designed to keep the temperature in the operational range by controlling the circulation flows and/or the upstream and downstream pressures.

3. Design parameters and recooling schemes

The temperature of the nitrogen in the 84°K shield line and the temperature variations along this line depend on the following parameters:

a - the heat load
b - local mass flow
c - number of recoolers
d - pressure in the shield side of the recoolers
e - pressure in the feed line
f - diameter of the feed line
g - diameter of the vapor return line
h - relative altitude and slope of the line

Once the diameters of the lines have been determined, for a given geometry of the rings, the temperature will depend on the number of recoolers and on the operation pressures. It is easy to demonstrate that for a one phase liquid flow the downstream temperature gradient is positive. For two phase flow the temperature gradient is negative. This behavior, in addition to drastic difference in the flow rate parameters, makes the two phase flow more advantageous. The disadvantage of the two phase flow configuration is the need for the vapor return line. The design proposal considers the possibility of installing two lines of equal diameter in the cryostat. This will enable the system to operate in different modes and flow schemes. The building blocks of the ring ie., the sections (1080 m long) and the strings (4320 m long) enable the installation of recoolers and vapor separators according to the following different schemes:

a - A recooler every 8640 m (at the E sites)
b - A recooler every 4320 m (at the E and F sites)
c - A recooler every 1080 m (at the end of each section)
d - A recooler every 2160 m (every other section)

3.1 Recooler scheme "a" (See drawing 1)

In this case the recoolers are located at the E sites and the vapor generated there is removed directly to the helium plant. There is no need for a vapor return line. To keep the temperature in the design range the flow rates everywhere in the ring should be higher than 1600 g/s. The pressure required to drive this flow is high for liquid flow in a small diameter line. If the downstream pressure is kept low enough, the last part of the line will have two phase flow. This may increase the pressure drop and decrease the flow rate below the required value. An additional increase in the driving pressure and downstream pressure will be needed to solve the problem.

3.2 Recooler scheme "b" (See drawing 2, 3, 4, and 5)

In this case two lines are required in the cryostat: one for the liquid and for the two phase flow the other for vapor return. Because the vapor return lines are long, the pressure drop may be as high as 0.03MPa. for a 2.5" line. This will increase the temperature (in the recooler of site F) to 79°K. To solve this problem, a cold compressor can be added at every F site.

3.3 Recooler scheme "c" (See drawing 6)

In this case assuming that the boiling rate in the recoolers is a constant m (=20g/s) than the vapor flow in the four sections in each string will start with m/2 in the F site and increase steadily towards the E site (10 g/s, 30g/s, 50g/s, 70g/s). For a reasonable diameter of vapor return line in the cryostat the pressure drop will cause different pressures in the recoolers and different recooling temperatures. To solve this problem a cold compressor may be required.

4. Preliminary data

4.1 Consumption and storage

The expected heat load of the 84°K system is 65,000 watts per sector. To keep the temperature in the required range a certain amount of fluid has to be evaporated in each recooler. For an average latent heat of 200 J/g the boil off rate is 325 g/s/sector (= 82 g/s/string = 1,170 kg/h/sector = 28,080 kg/day/sector)

If the local storage is designed for a 2 day supply without LN generation then the volume should be 28,080 * 2 = 56,160 kg (18,300 gallons)

For 6 days supply, the volume should be 28,080 * 6 = 168,480 kg (55,000 gallons)

4.2 LN generation plants and locations

The two plants will be located in sites E1 and E6 . The surface level and the tunnel level of each E and F site are as follows:

site	surface	tunnel	
E1	233.2 (h)	156.7	LN plant 1
F1	216.4	161.8	
E2	198.1	162.2 (h)	
F2	207.2	157.0	
E3	209.4	148.7	
F3	160.9	136.6	
E4	158.5	122.2	
F4	150.9	109.1	
E5	141.7	96.9	
F5	137.2	88.4	
E6	150.9	82.3	LN plant 2
F6	138.7	82.3 (l)	
E7	139.6	84.7	
F7	144.8	90.8	
E8	128.6 (l)	100.6	
F8	155.4	112.2	
E9	156.1	124.4	
F9	164.6	134.1	
E10	169.2	141.7	
F10	205.7	149.4	

(l) - lowest point
(h) - highest point
altitude differences: (E3-E4)=26.5m, (E4 - E5)=25.3m,
(E8-E9)=23.8m, (E9-E10)=17.3m

5. Flow schemes

To provide transport media for 65,000 watts per sector an approximate boiling rate of nitrogen of 82g/s per string is required. An additional amount of liquid of 50 g/s is needed for make-up to each stand-by reservoirs (see schemes in Fig 1).

5.1 Liquid flow (recooler scheme "a", see drawing 1)

A system with two LN generation plants having recoolers only at the E sites, will fulfill the requirements as described above. This will require a minimum flow in each line of 1600 g/s. To this amount there will need to be added the transport requirement of 920 g/s. A maximal amount of 2,500 g/s may be required to operate this system. A system with 10 LN plants may require a maximum flow rate of 1600 g/s. (see drawing 7)

5.2 Two phase flow (recooler scheme "a")

The pressure drop for this scheme is very high and the resulting temperatures are not acceptable. Detailed calculations for this scheme are not part of this presentation.

5.3 Two phase flow (recooler schemes 'b', see drawings 2, 3, 4, and 5)

For normal operation mode the maximum flow required in a line is 542 g/s. However, the system has to be designed for different failure conditions as described in paragraph 2.1. A failure may cause a major change in the flow scheme (if only one plant and one ring is operational the maximum flow may rise to 920g/s) or only a local change in the flow rate (disconnection of one section may cause an increase in the flow rate of the parallel section).

6. The pressure in the recoolers and the recooling temperature

A design according to scheme 'b' and 'c' will require a second line installed in the cryostat for the vapor return.

For scheme "b":

The vapor flow rate through the 4 km vapor return lines (from the F sites to the E sites) will be 41 g/s .
For a 2 1/2 inch line the pressure drop will be 19,500 Pa . This means that the pressure in the recooler is higher than 0.1195MPa. and the saturation temperature is higher than $78.7^{\circ}K$.

For scheme "c" :

The vapor return flows in the four 1km sections will be 10.25, 30.75, 51.25, and 71.75 g/s. For a 2 1/2 inch line the pressure drop along each section will be 900, 1,900, 7,150, and 14,500 Pa. If the suction pressure at the E sites is 0.1 MPa, the absolute pressure in the recoolers will be: 0.1145, 0.12165, 0.12455 and 0.12545 MPa. The recooling temperatures will be : 78.38, 78.9, 79.14 and 79.2 ^{o}K respectively, with the highest temperature at the F location.

This increase in recooling temperatures will cause, in some cases violation of the high temperature limits permitted for the "84^{o}K shield". (The resulting value will be higher than 88.5^{o}K.) A cold compressor installed an the F sites will reduce the pressure in the vapor return line and reduce the recooling temperature.

7. The computer program

The computer program used for the N2 system analysis was 'TWOPHS'. The program simultaneously solves the continuity, momentum and energy equations for piping networks. The N2 piping geometry and elevation details are input to the program. The heat load used was based on nominal cryostat characteristics. Recoolers were simulated as heat removed at appropriate locations along the strings.
The program uses several empirical correlations to represent the real properties. The Swamee-Jain and Colebrook friction factor correlations were used based on local conditions. A National Bureau of Standards modified Martinelli correlation was used for two phase friction factors. A highly detailed table of nitrogen properties was used for fluid properties.

8. Results

8.1 Presentation
The results presented here are shown on pressure-temperature diagrams and are related to the different recooling schemes and the different flow schemes:

8.1.1 Liquid flow- recooling scheme "a"
A graphical description of this scheme is shown in drawing 1. The flow rates required to maintain the string temperatures within given limits are shown in figure 1 and the p-t diagram is shown in figure 4.

In order to maintain the f low rate, a back pressure higher than 0.3 MPa should be maintained. A lower back pressure will enable the two phase flow to be established in the ring. This in turn will cause a fast increase in the pressure drop and a decrease in the flow rate. A lower flow rate will cause a increase in temperature at a location where the flow rate is minimum.

Figure 4 shows a comparison between the results obtained for a 2.5" line and a 3.0" line carrying liquid nitrogen. It also shows for comparison the result obtained for two phase flow at the same location.

For the 2.5" line the maximum pressure is 1.26 MPa.
For the 3.0" line the maximum pressure is 0.82 MPa.

8.1.2 Two phase flow - recooling scheme "b"

A graphical description of this scheme is shown in drawing 2, 3, 4, and 5. The flow rates required to maintain the string temperature within given limits for two different flow schemes are shown in figure 2 and 3.

The p-t diagrams for the uphill maximal flow conditions in a 2.5" line are shown in figure 5, 6, 7, 8, and 9.

Figure 10 shows the comparison between the results obtained for a 2.5" line and a 3.0" line carrying two phase flow.

The p-t diagram for the downhill maximal flow conditions in a 2.5" line are shown in figure 11, 12, 13, 14, and 15.

The p-t diagram for the optimal flow scheme is shown in figure 16 and 17.

Scheme "b" is flexible and enables the system to operate in a normal or emergency modes without major changes in flows, pressures, or temperatures. The maximum required flows may reach the value of 920 g/s, however it is possible to operate the system with flows lower than 460 g/s.

8.1.3 Two phase flow - recooling scheme "c"

A graphical description of this scheme is shown in drawing 6. The p-t diagrams are shown in figures 18 and 19.

The resulting temperature for this scheme has the lowest range compared to the other schemes. Neglecting the pressure drop in the vapor return line, the temperature of the nitrogen line does not change more than 84K.

8.2 Summary of results

8.2.1 The following are the maximum required flow rates to keep the temperature in rages:

scheme "a"	2300 g/s
scheme "b", maximum flow	920 g/s
scheme "b", equal generation	460 g/s
scheme "b", non-equal generation	378 g/s uphill
	542 g/s downhill

8.2.2 Maximum pressure in a 2.5' line

scheme "a"	1.26 MPa
scheme "b" maximum flow	0.52 MPa

8.2.3 Maximum temperature

scheme "a"	89 K
scheme "b"	90 - 91 K
scheme "c"	84 K

8.2.4 Basic equipment requirements

scheme "a"	A recooler and cold pump in every E service site.
scheme "b"	A recooler and cold pump in every E severce site, plus two recoolers in the F sites and vapor return lines in the cryostat.
scheme "c"	The same as "b" plus six (6) recoolers per string.

9. Discussion

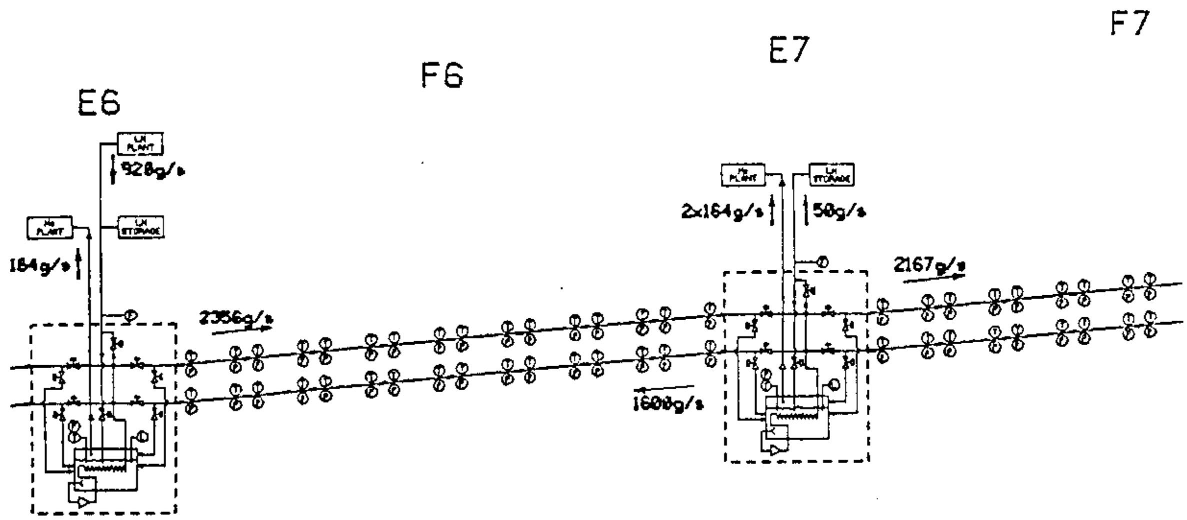
The recooler scheme "b" may result in a temperature change a little higher than required, however the flow rates may be adjusted to correct this condition.

The following additions may be considered to optimise the operation of the system:

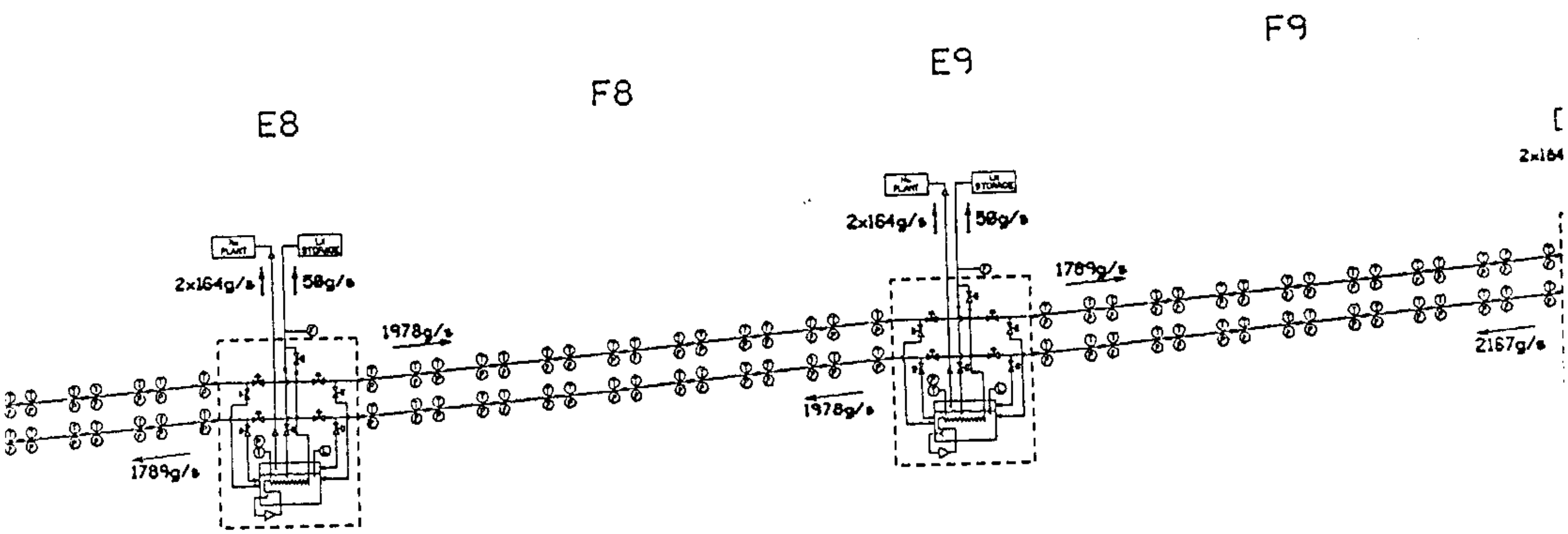
a. Add a liquid circulating pump at every "F" site.
b. Add a compressor for the vapor return line at the "F" sites.
c. Add a recooler every 2000 m.

The transfer line in the injection region maybe be install in the injection tunnels, or maybe merged with the cryostat of the injection line magnets. If this concept is used, than the computations for the pressure and temperature for lines E10 to E1 have to take into account the relative altitude of these tunnels. (see drawing 8)

After a detailed design of the cryostats, the updated numbers of the bends, the specific shapes of the U tubes, the number of valves and their characteristics have to be taken into account.



DRAWING 1: LIQUID FLOW- RECOOLING SCHEME 'a'



E8
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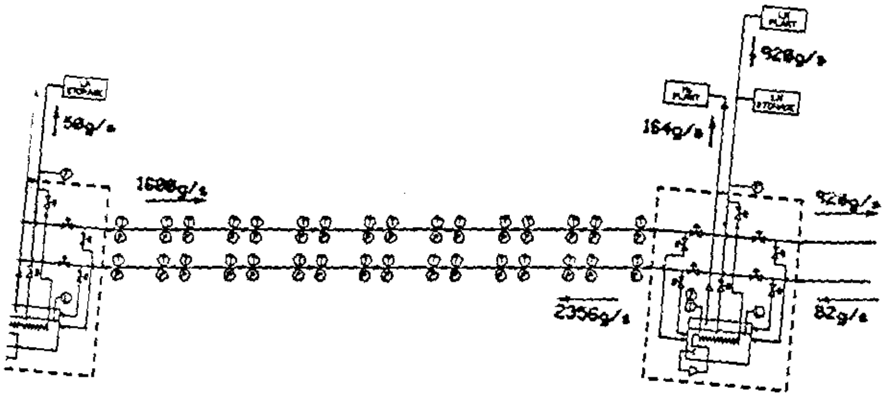
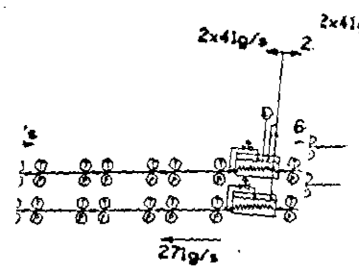
1Ø F1Ø E1



F7



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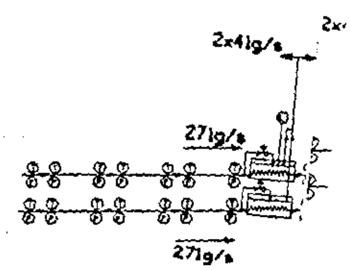
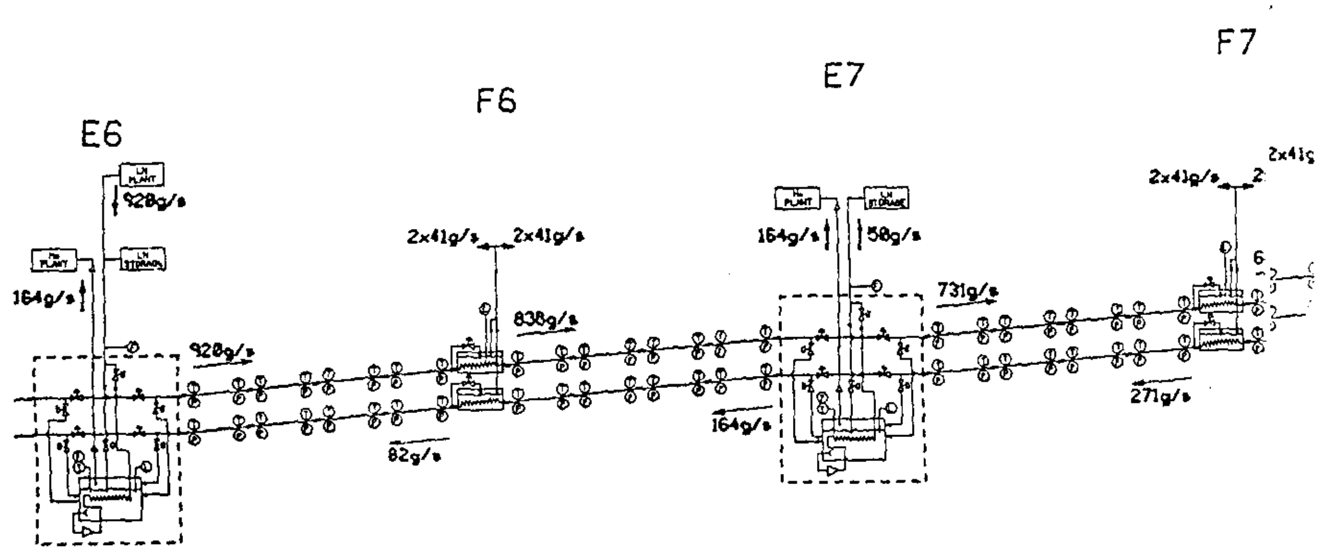
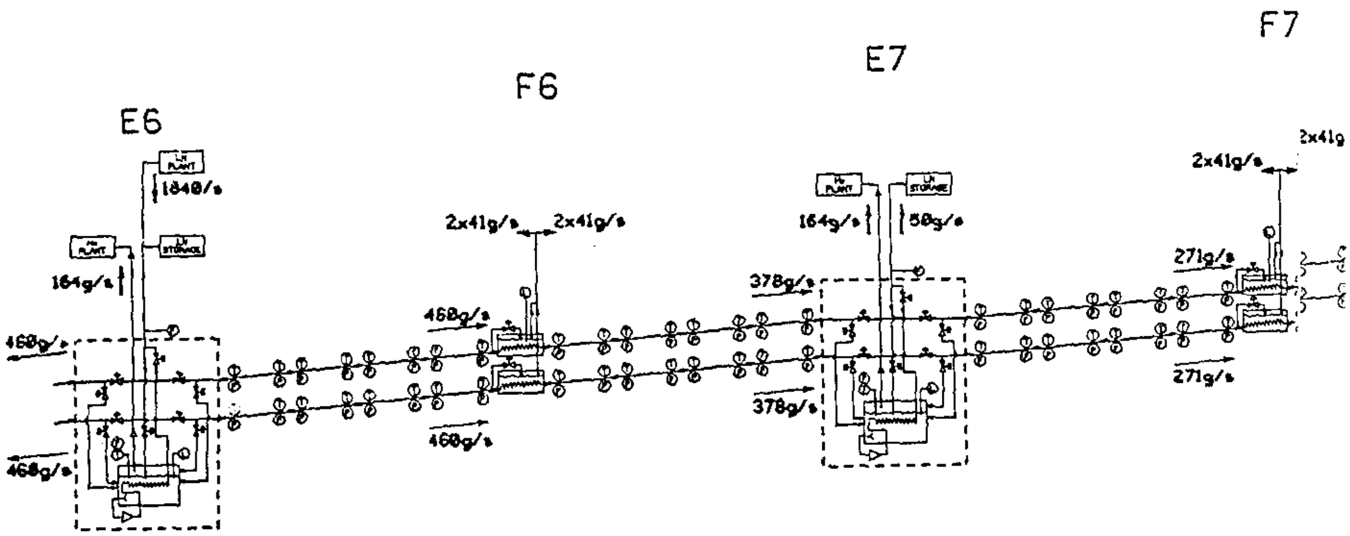
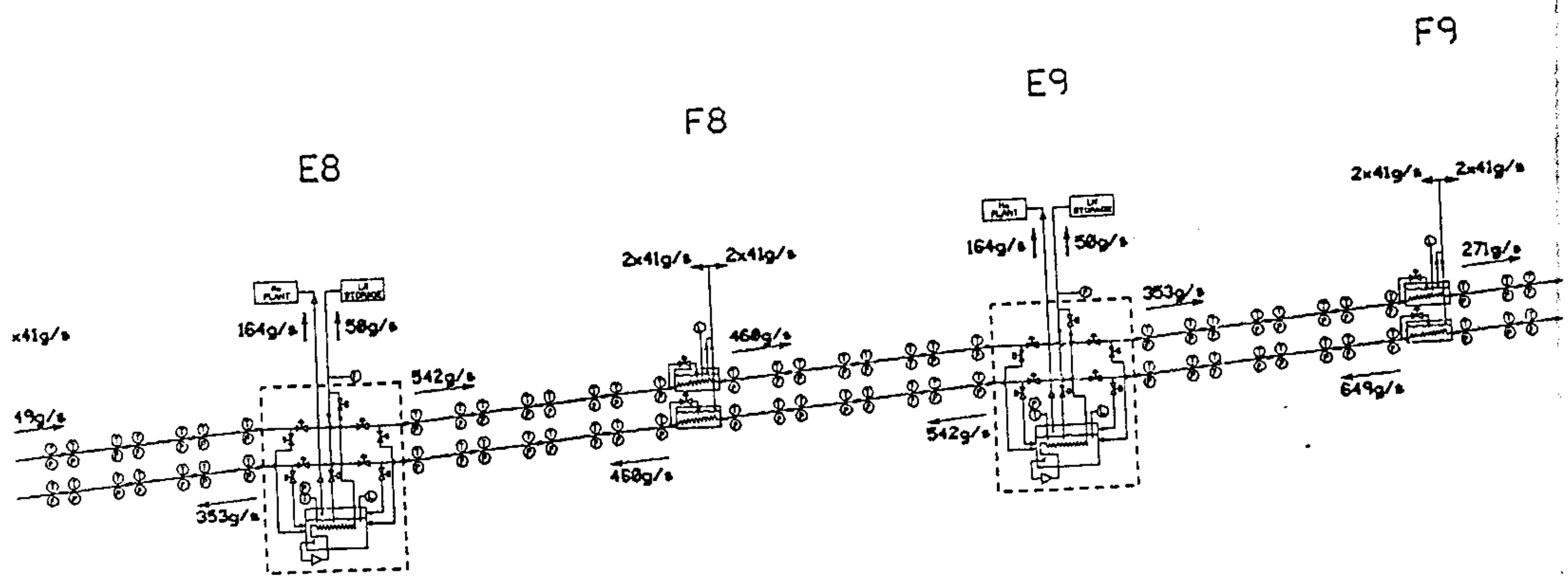




DRAWING 2: TWO PHASE FLOW - RECOOLING SCHEME 'b'
MAXIMAL FLOW



DRAWING 3: TWO PHASE FLOW - RECOOLING SCHEME 'b'
EQUAL GENERATION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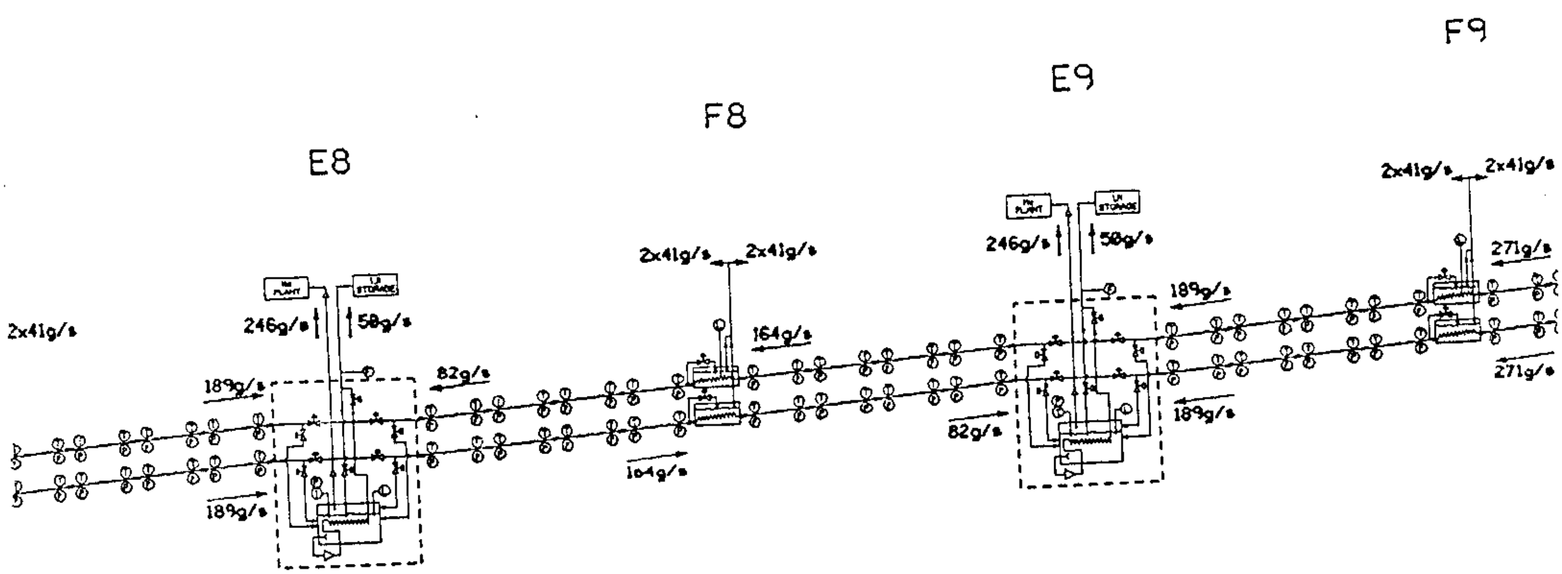
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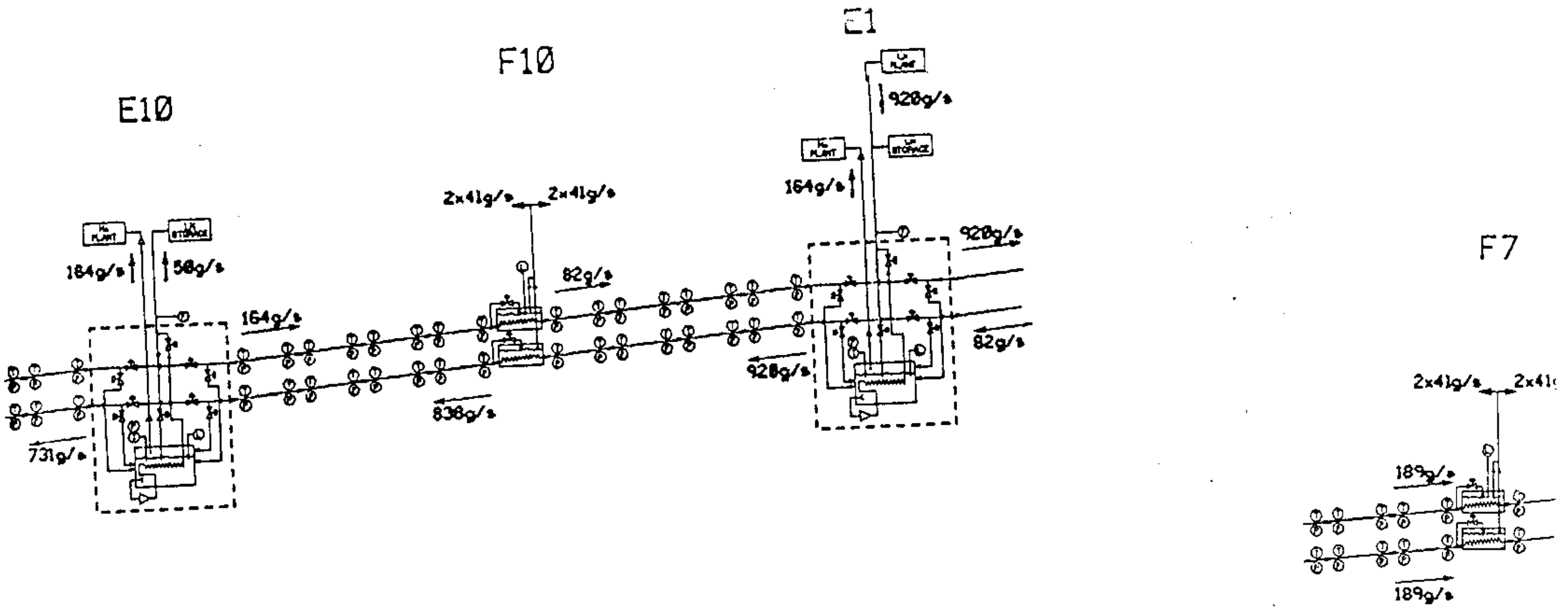
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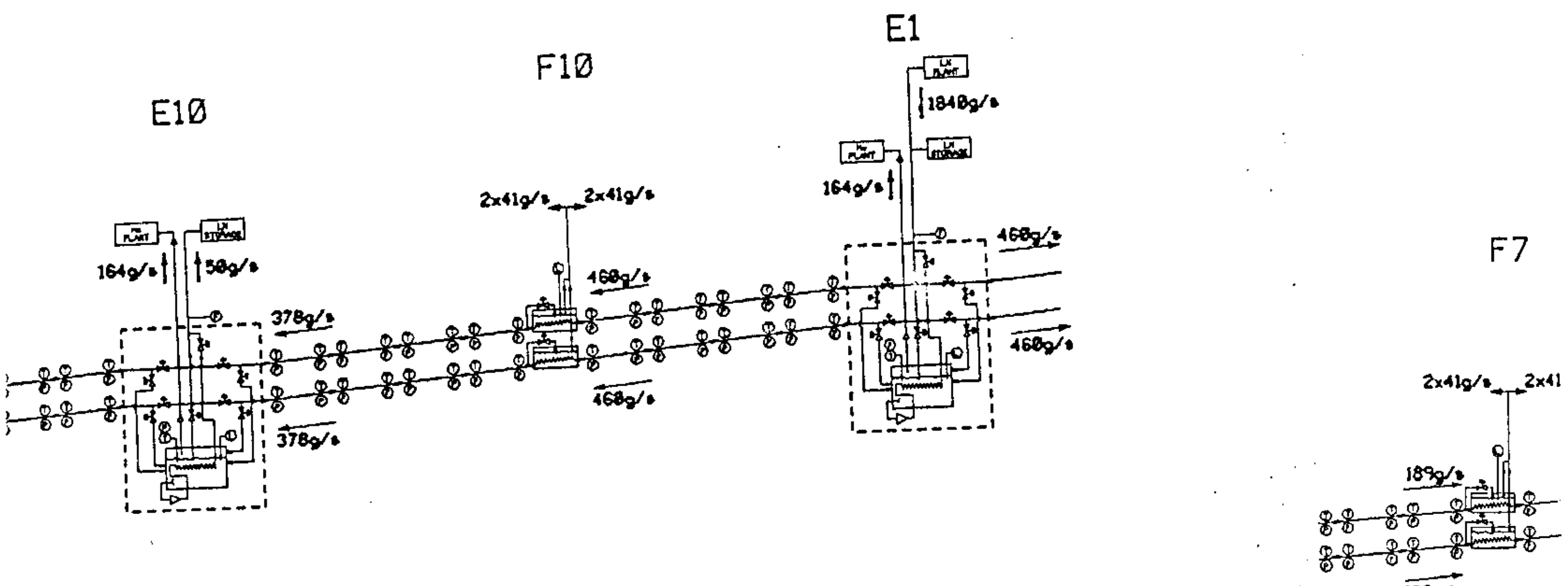
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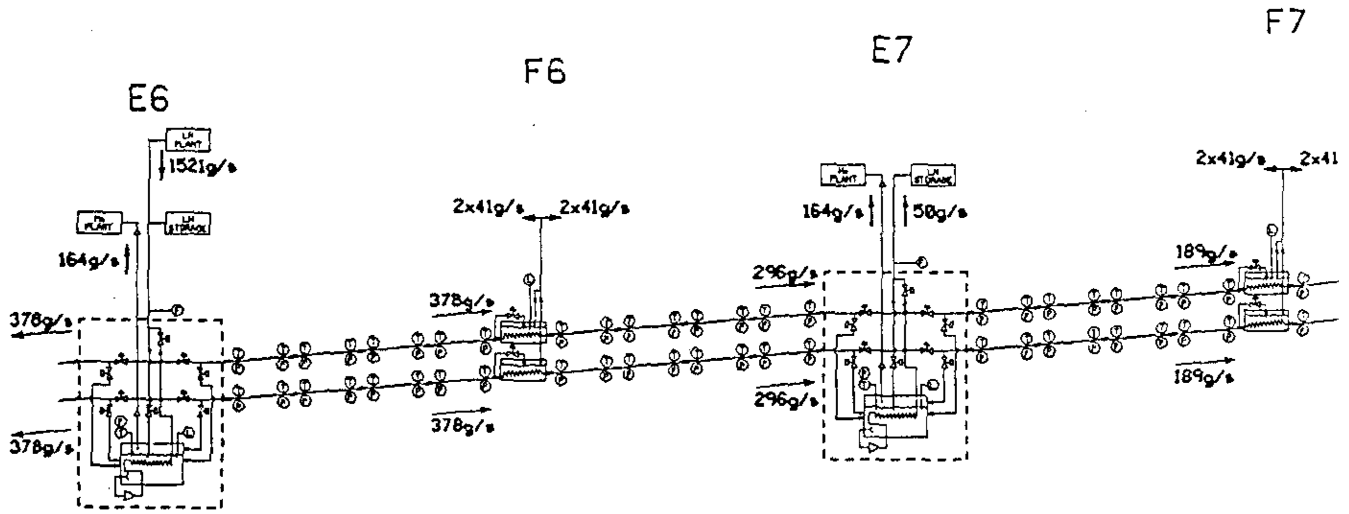
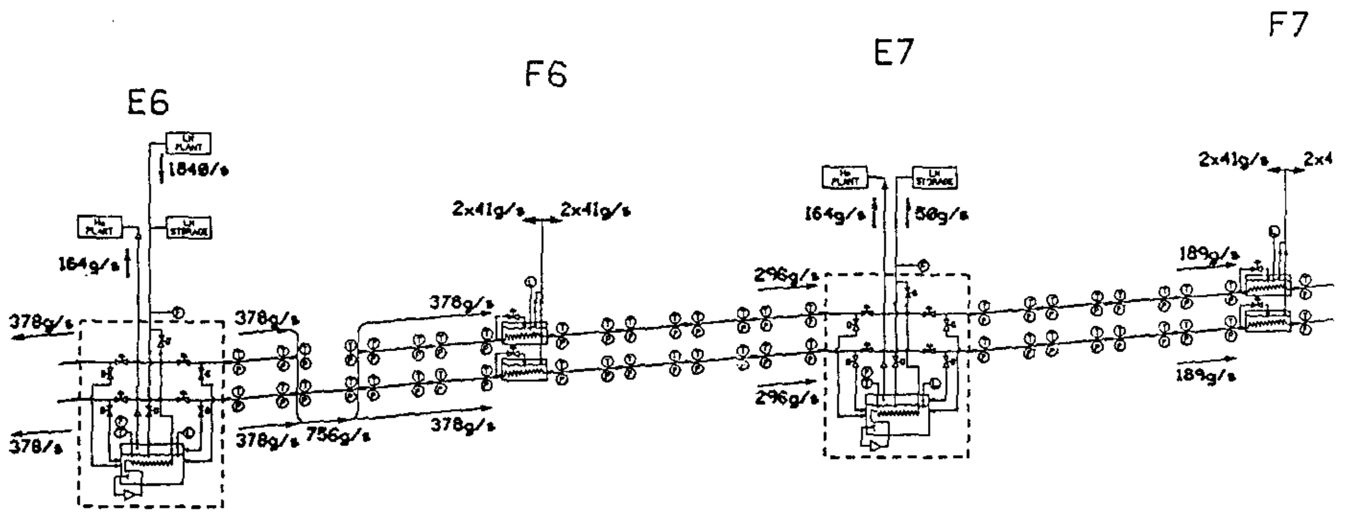
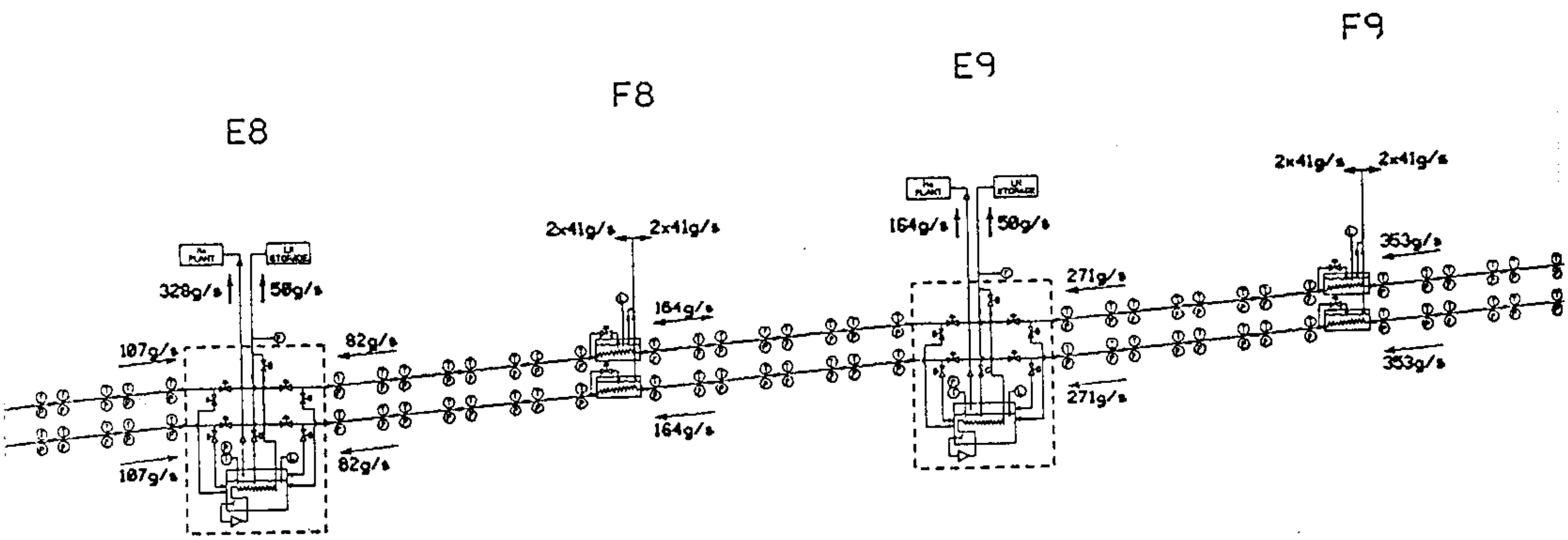


DRAWING 4: TWO PHASE FLOW - RECOOLING SCHEME 'b' NONEQUAL GENERATION



DRAWING 5: TWO PHASE FLOW - RECOOLING SCHEME 'b' FLOW DURING EMERGENCY DISCONNECTION.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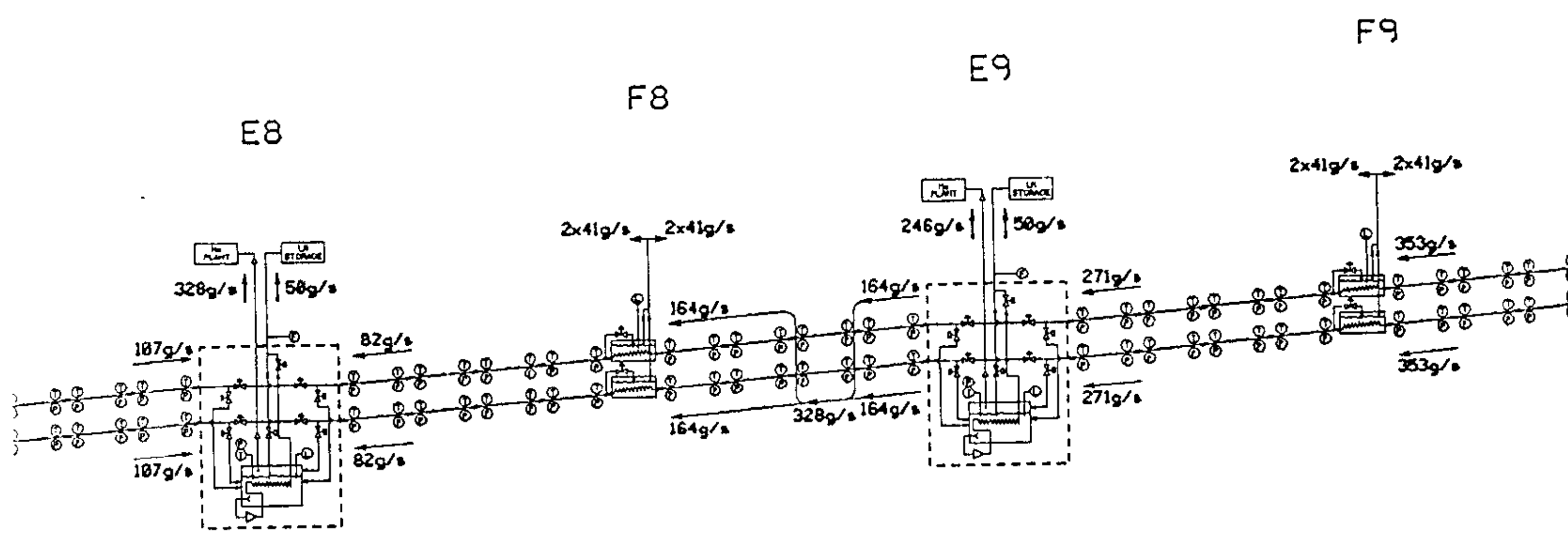
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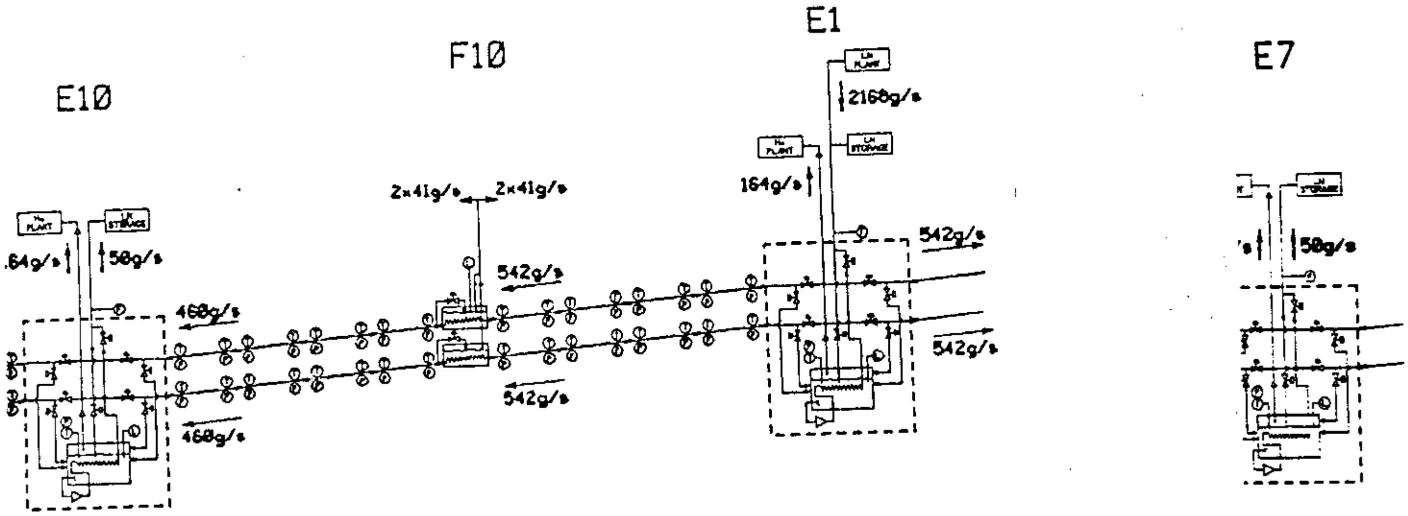
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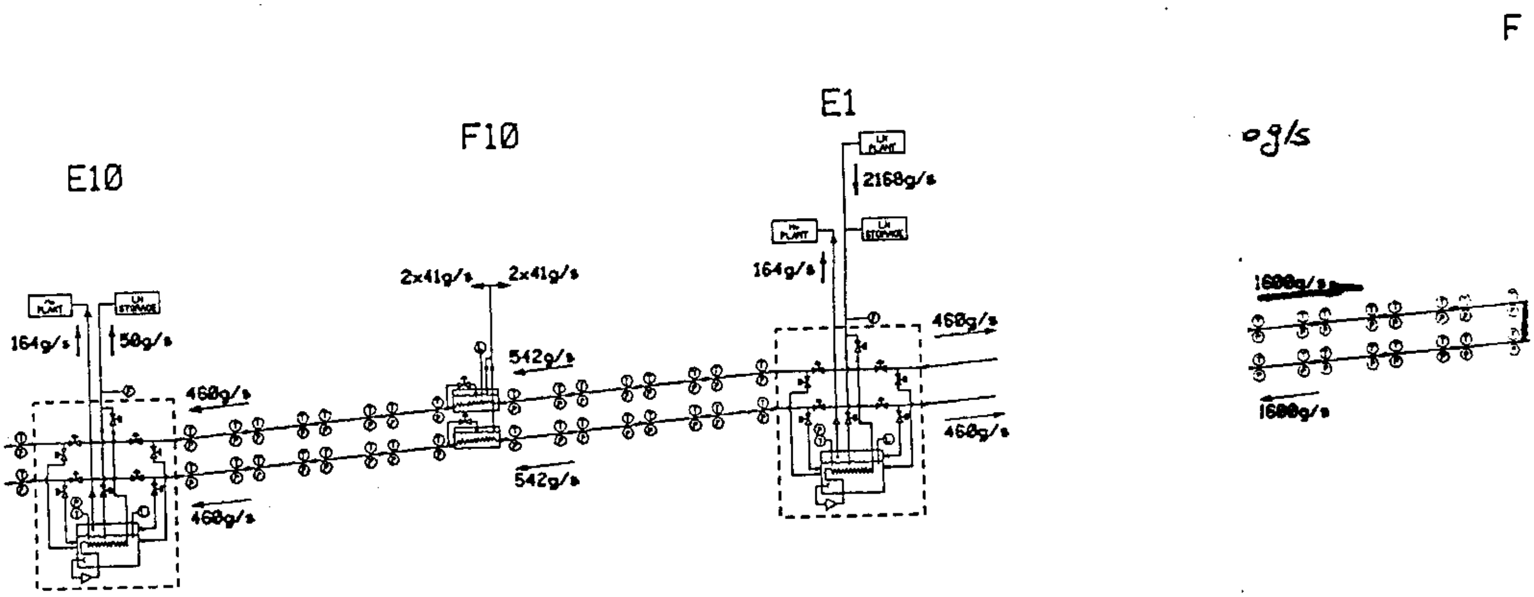
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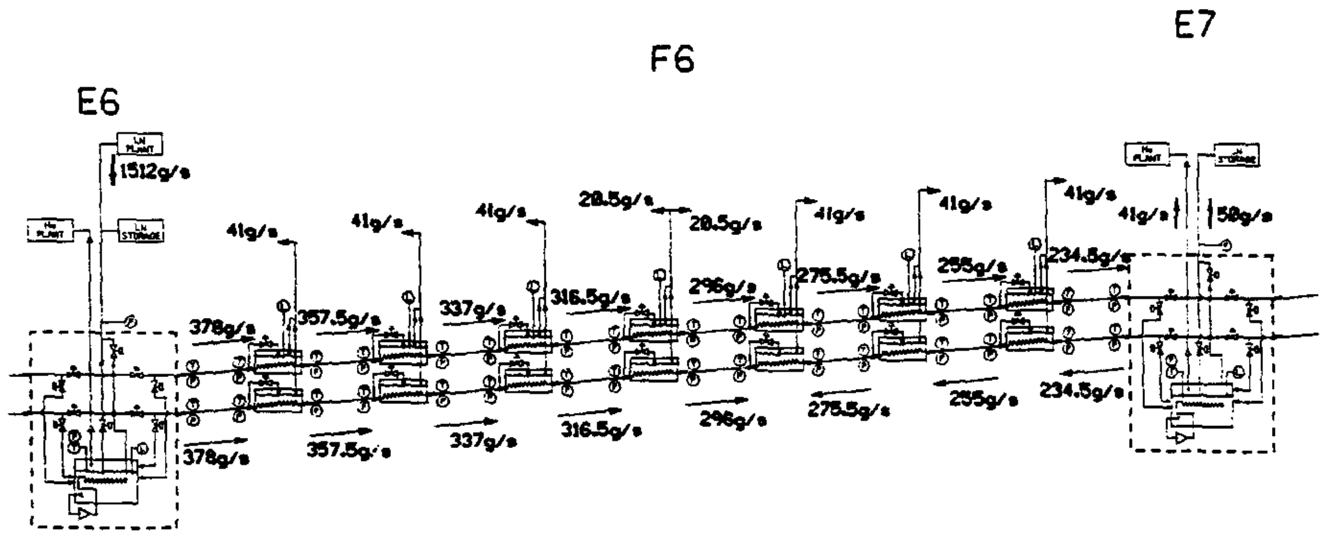
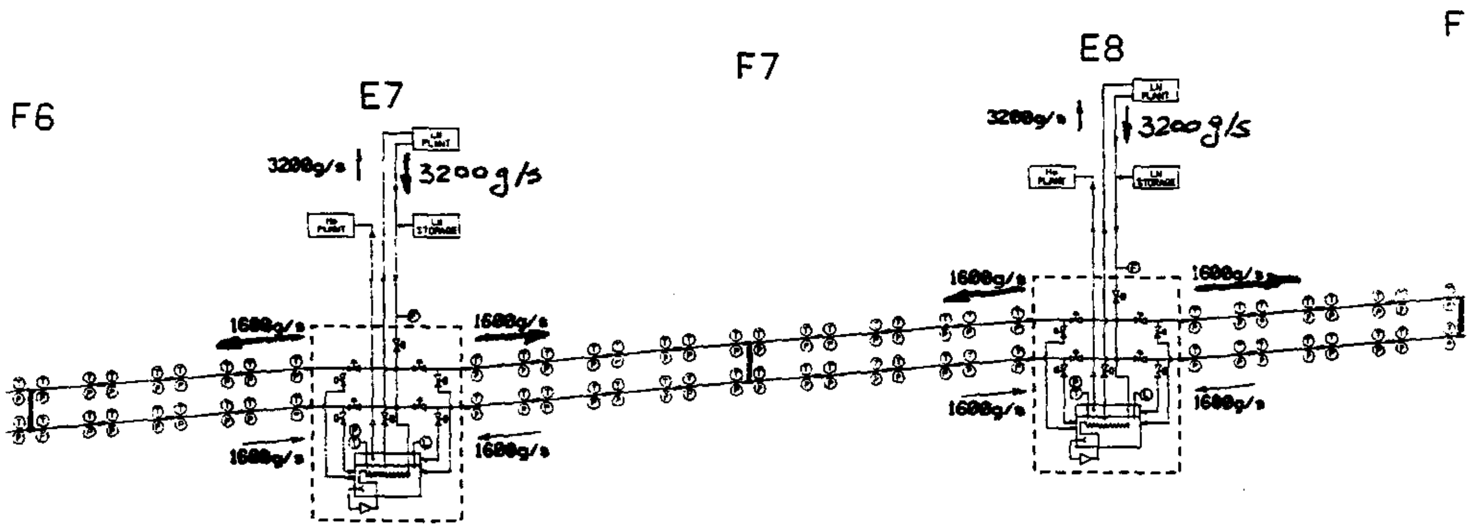


DRAWING 6: TWO PHASE FLOW - RECOOLING SCHEME 'c'



DRAWING 7: FLOW SCHEME FOR TEN LN GENERATION PLANTS

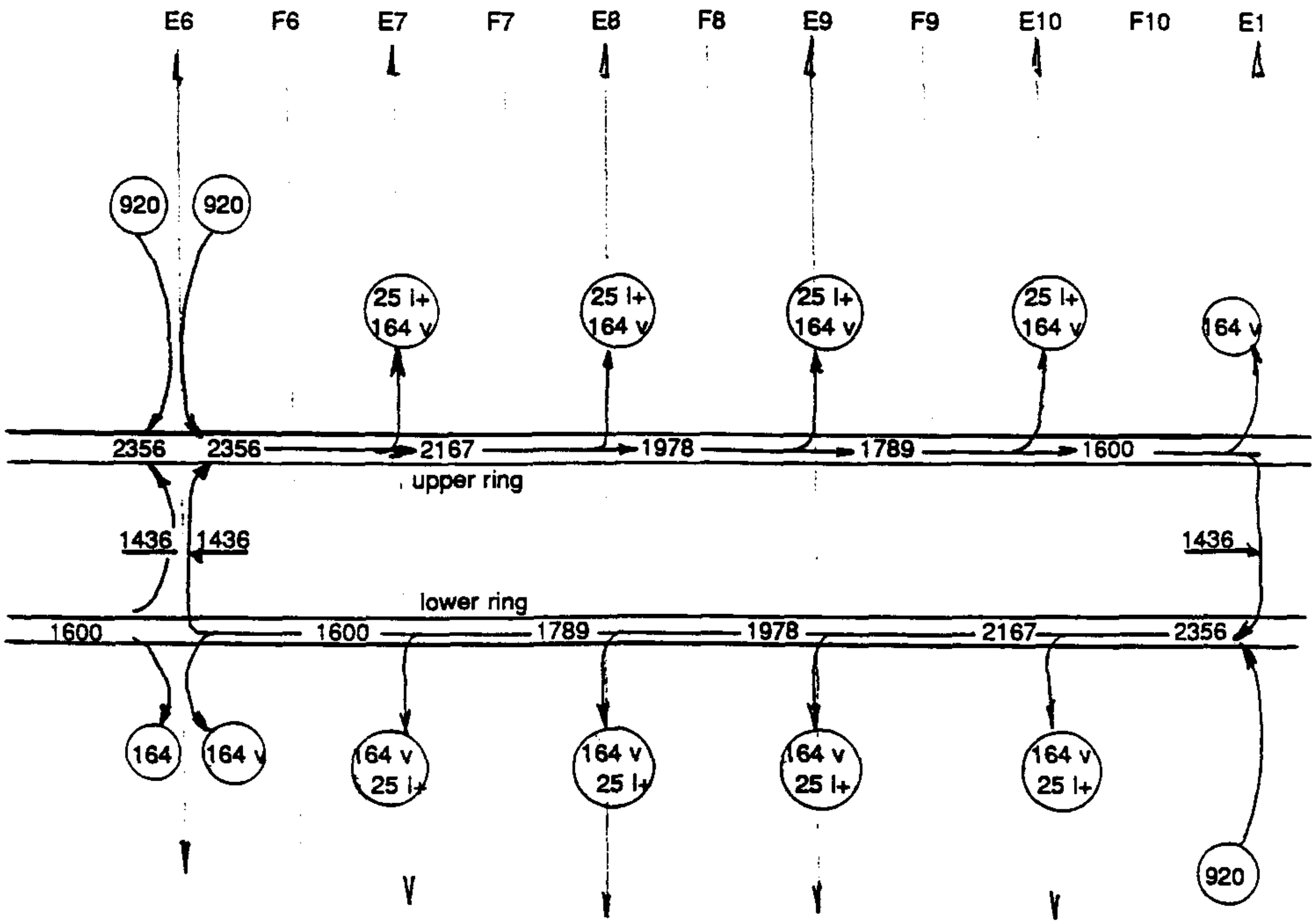


Fig 1: **Liquid flow in g/s in different locations.**
Recooling scheme - 'a'
Recoolers installed in every 'E' site.
The flow in one line is uphill, in the second downhill.

l = liquid flow , v = vapor flow

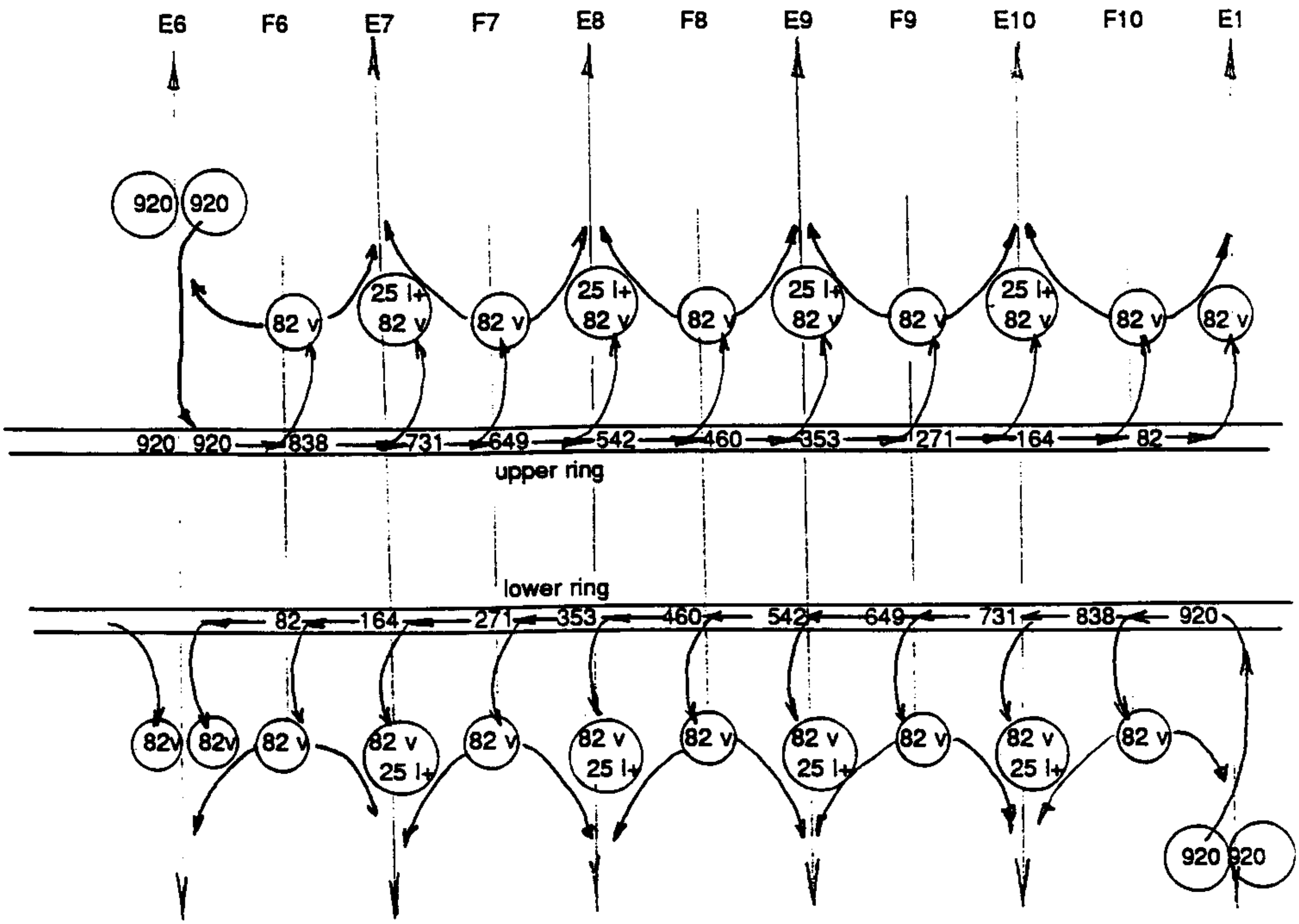


Fig 2: The maximal two phase flows in different locations.
Recooling scheme - 'b'.
Recoolers installed every 4360 m.
The flow in one line is uphill , in the second downhill.

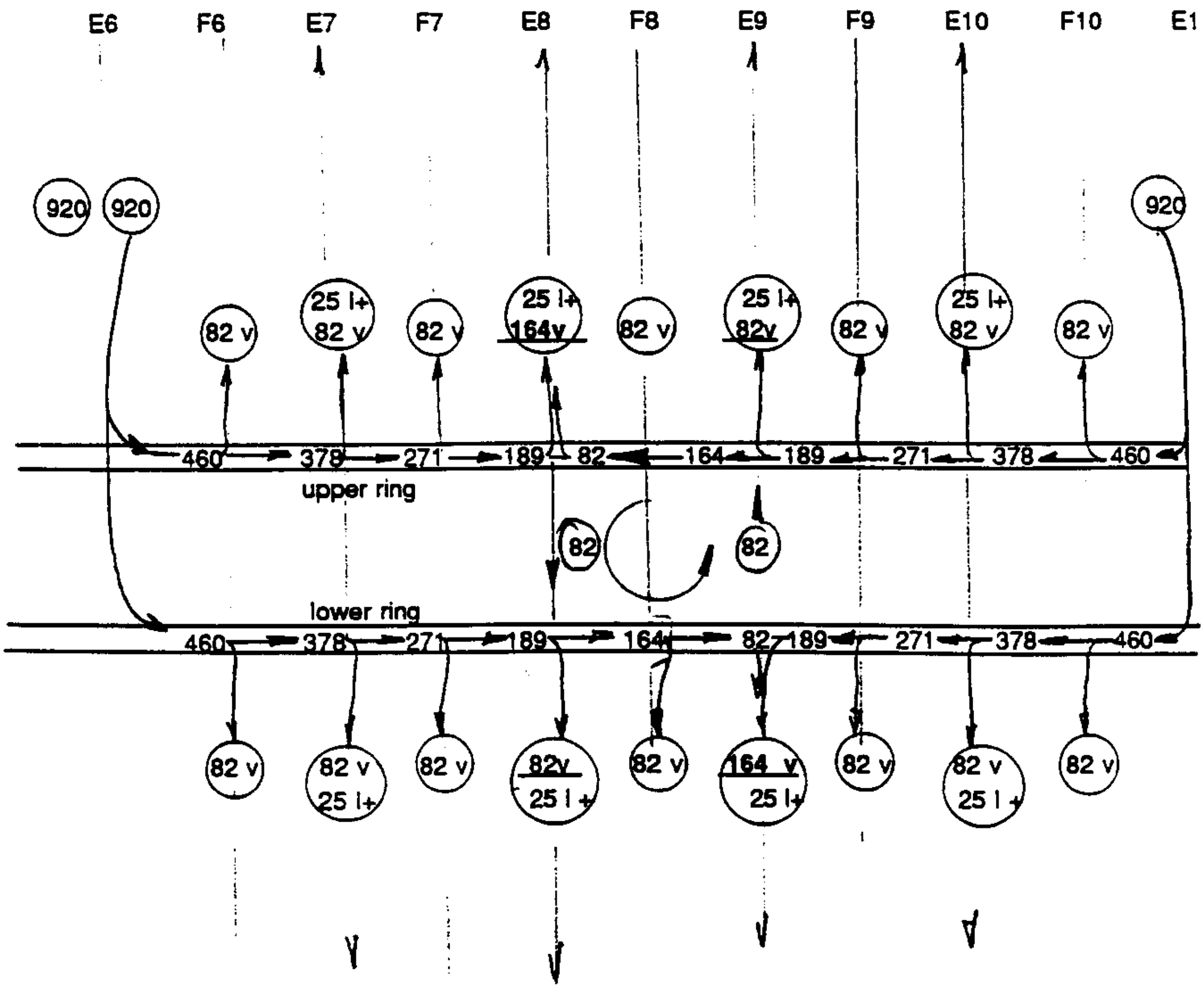


Fig 3 : The minimal two phase flows in different locations. Recooling scheme -'b'.
Each plant supplies Nitrogen to both rings in parallel (equal flow rates) to both sides of the collider.

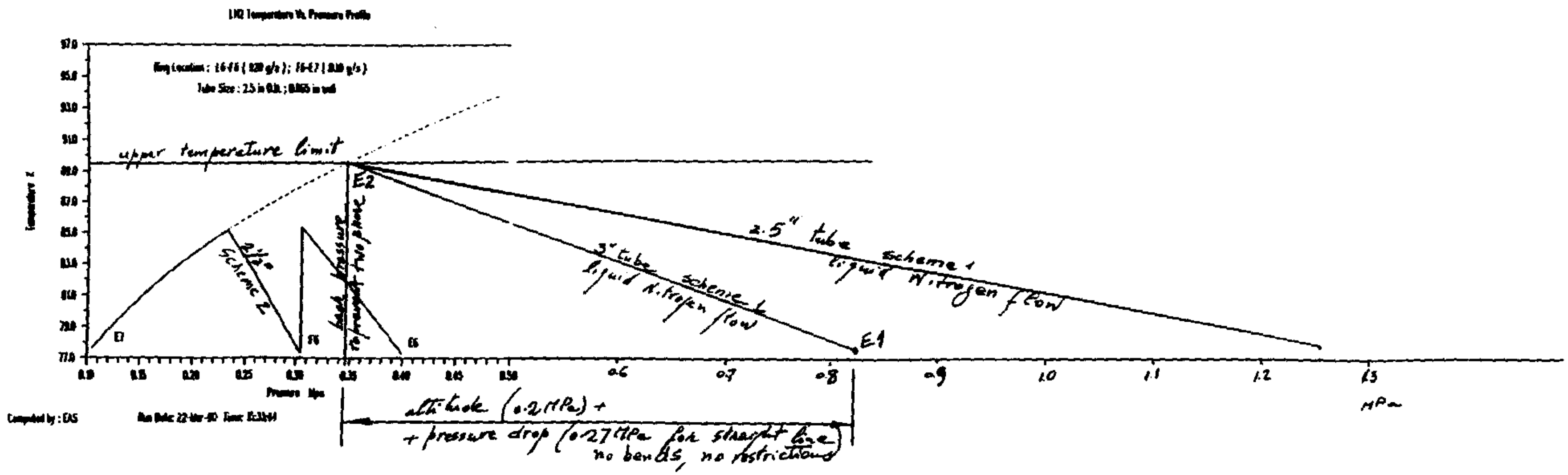
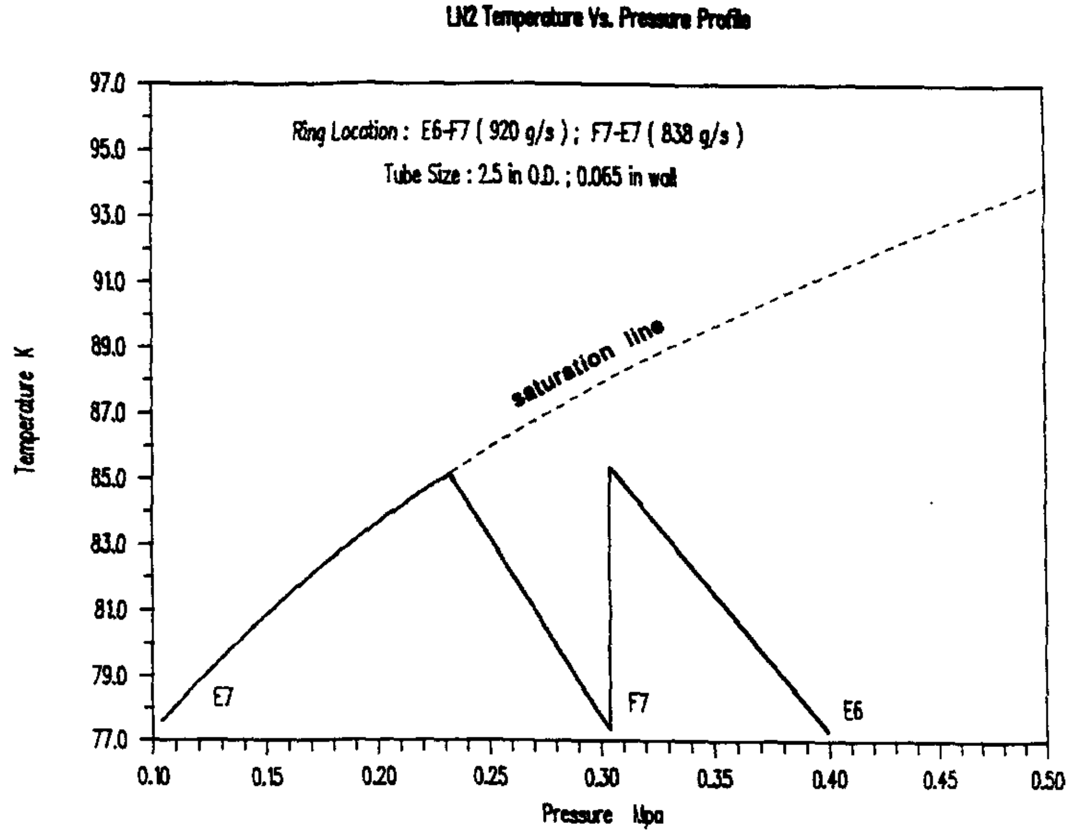
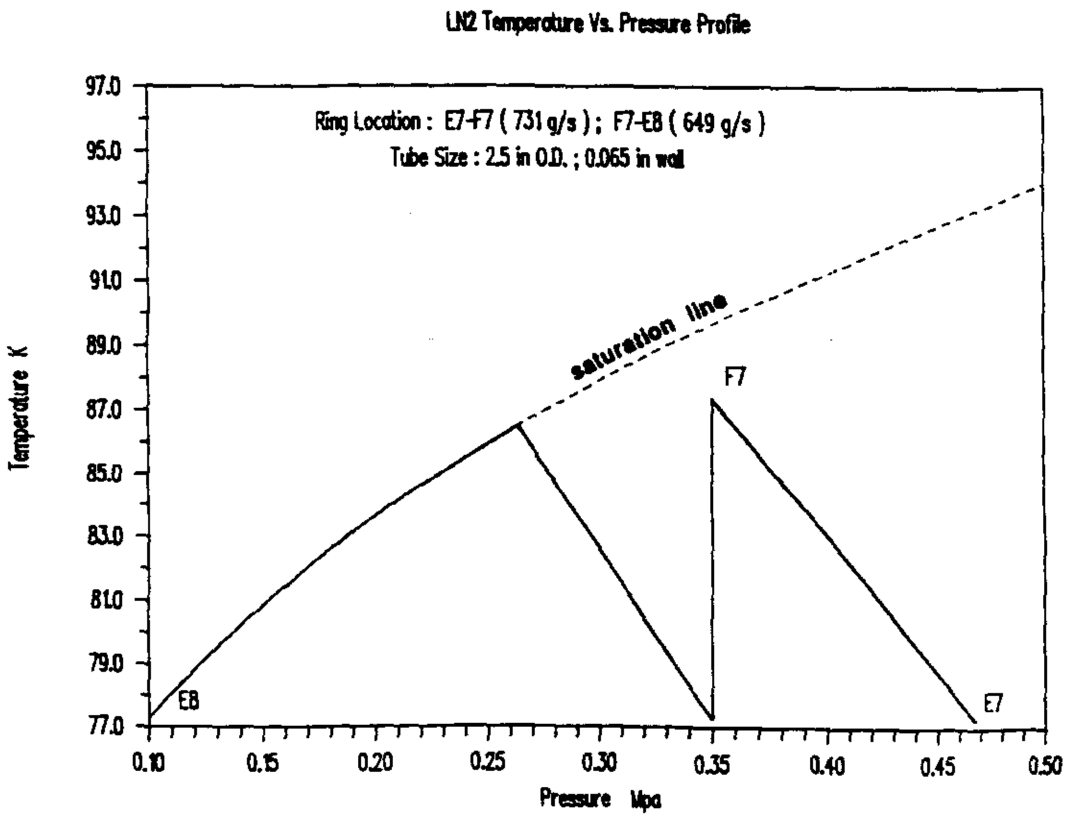


Fig 4 : p-t diagram for 8 km line
recooling scheme 1 - liquid Nitrogen flow in 2.5" line
" " " " " " " 3.0" "
" " 2 - two phase flow in 2.5" line.



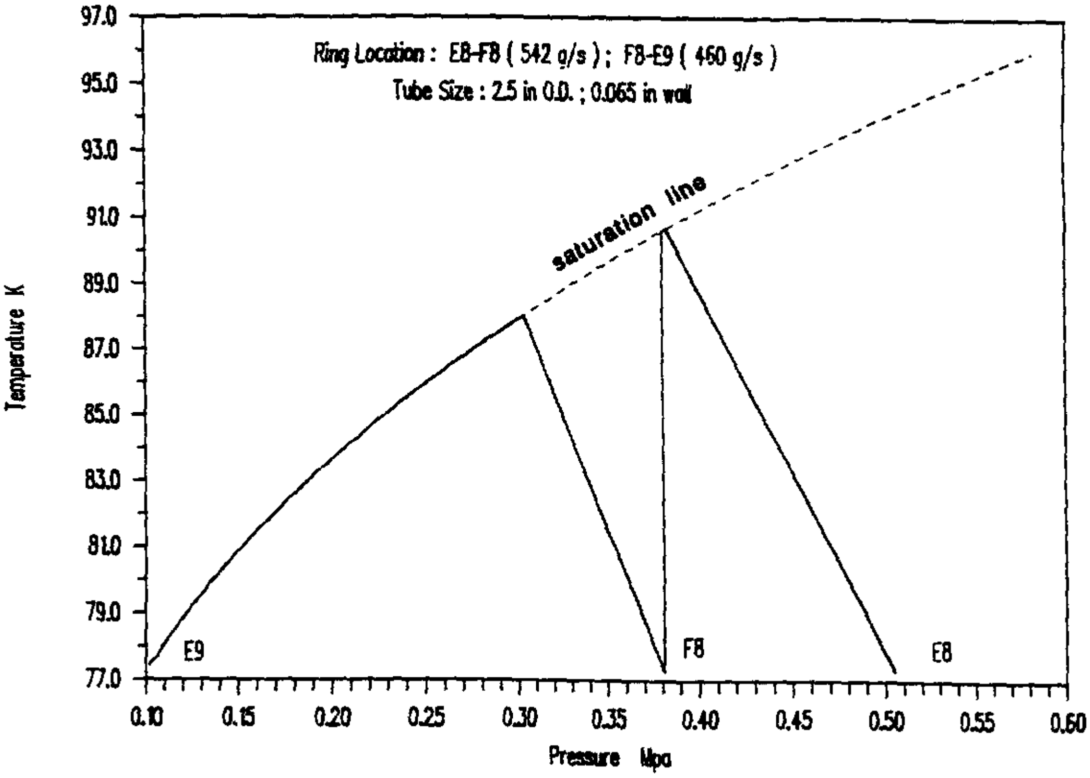
Computed by : EAS   Run Date: 22-Mar-90 Time: 15:33:44

Fig 5: p-t diagram for 8 km 2.5" line
between sites E6 and E7 (uphill)
recooling scheme 2 - maximal flow



Computed by : EAS   Run Date: 22-Mar-90 Time: 12:41:41

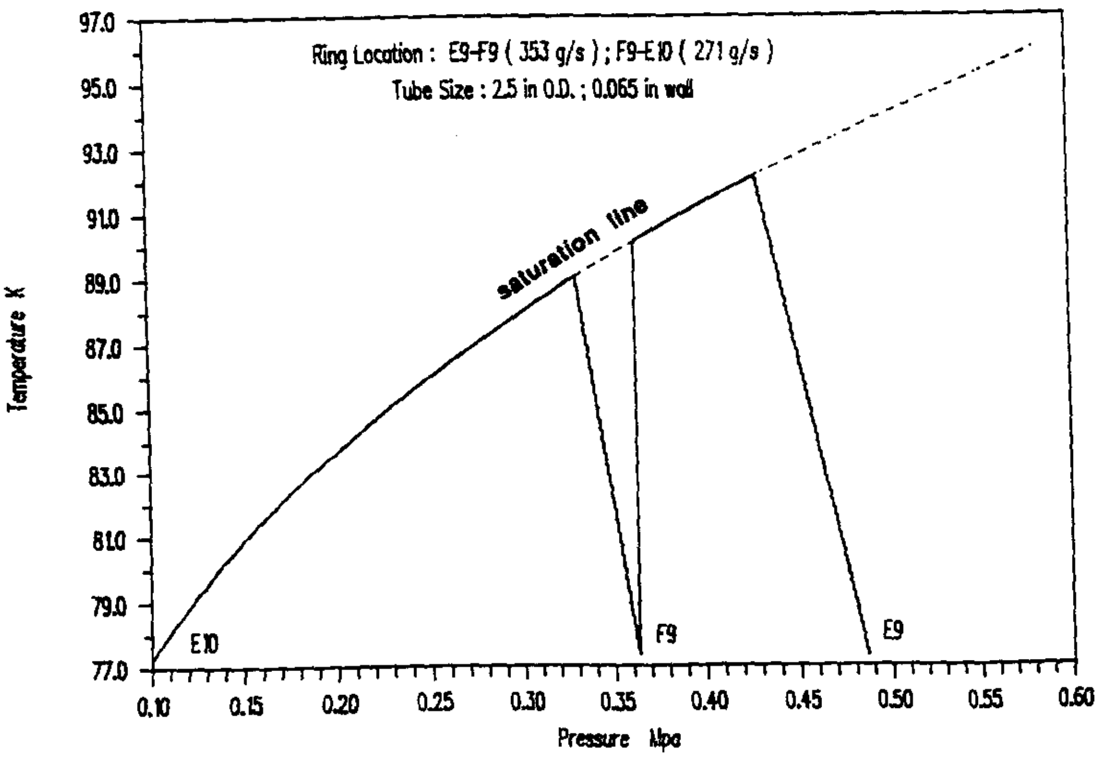
Fig 6: p-t diagram for 8 km 2.5" line
between sites E7 and E8 (uphill)



Computed by : EAS Run Date: 21-Mar-90 Time: 16:27:53

Fig 7: p-t diagram for 8 km 2.5" line
between sites E8 and E9 (uphill)
recooling scheme 2 - maximal flow

LN2 Temperature Vs. Pressure Profile



Computed by : EAS Run Date: 22-Mar-90 Time: 15:48:30

Fig 8: p-t diagram for 8 km 2.5"line
between sites E9 and E10 (uphill)

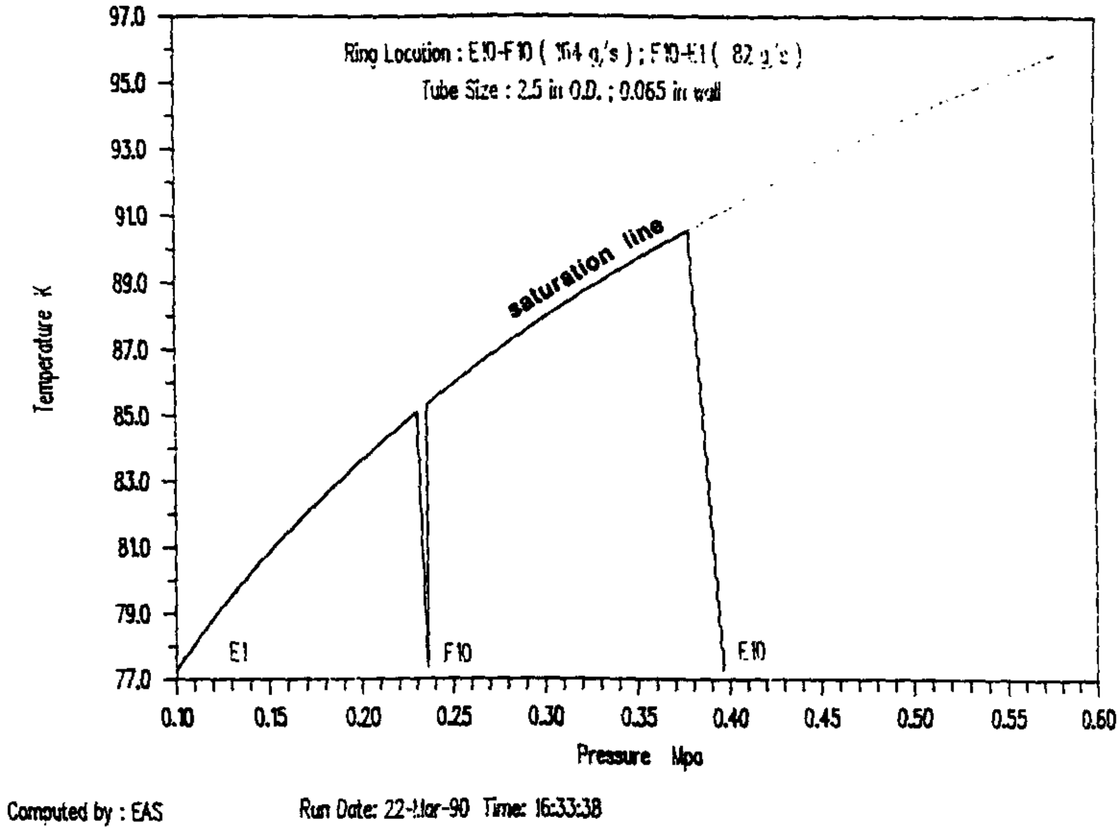


Fig 9: p-t diagram for 8 km 2.5"line between sites E10 and E1 (uphill) recooling diagram 2 - maximal flow

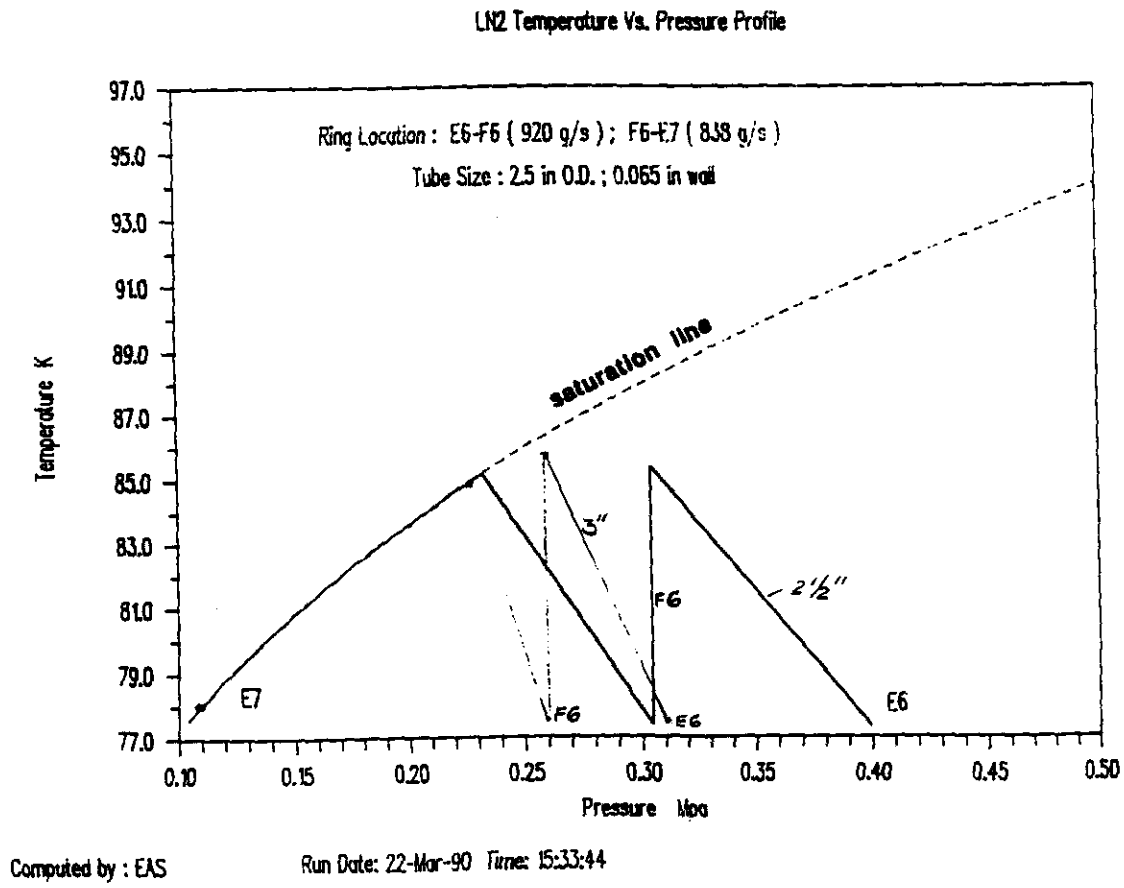


Fig 10 : Comparison between 2.5" and 3" lines

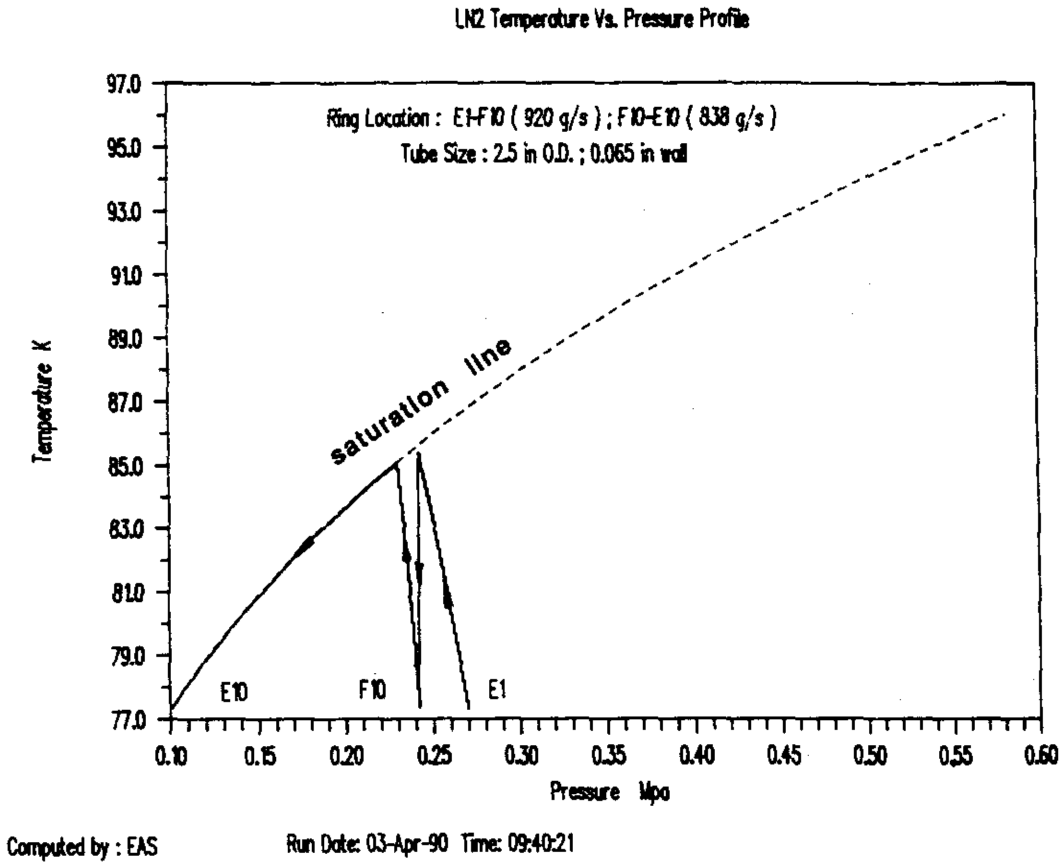


Fig 11: p-t diagram for 8km 2.5" line between sites E1 and *E10* (downhill) recooling scheme b - maximal flow (drawing-2)

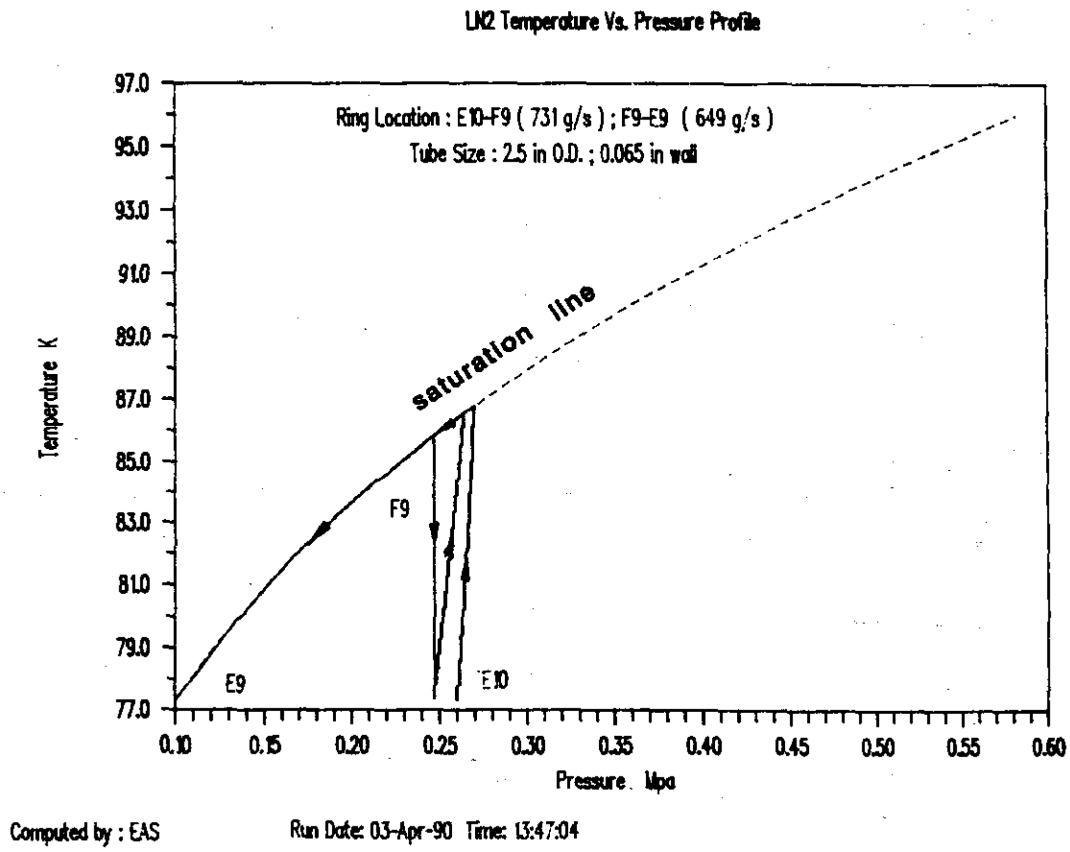


Fig 12: p-t diagram for 8km 2.5" line between sites E10 and E9 (downhill) recooling scheme b - maximal flow (drawing-2)

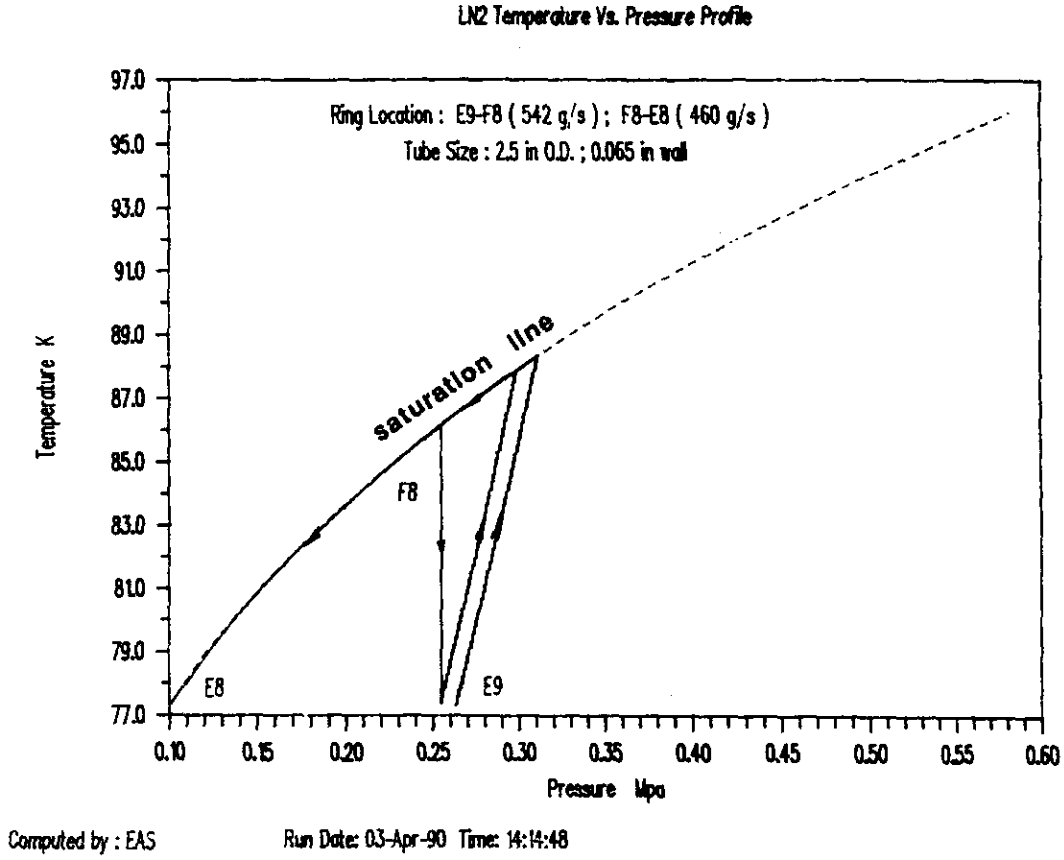


Fig 13: p-t diagram for 8km 2.5" line between sites E9 and E8 (downhill) recooling scheme b - maximal flow (drawing-2)

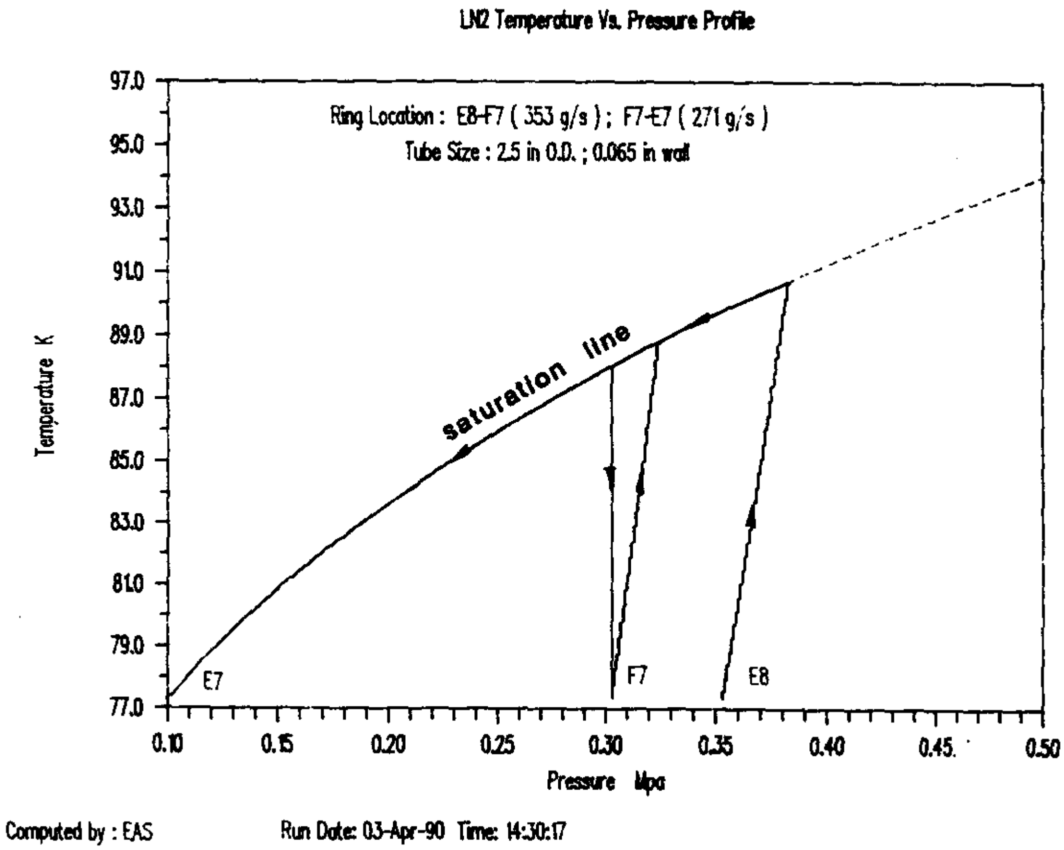


Fig 14: p-t diagram for 8km 2.5" line between sites E8 and E7 (downhill) recooling scheme b - maximal flow (drawing-2)

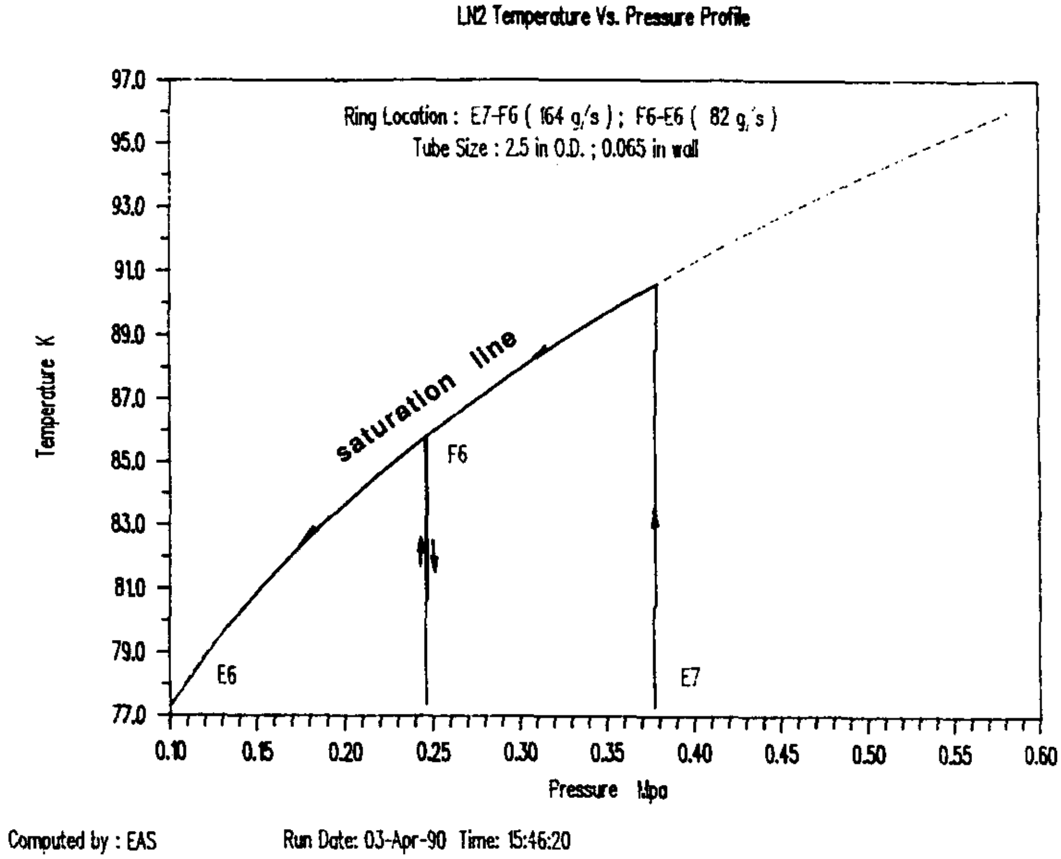


Fig 15: p-t diagram for 8km 2.5" line between sites E7 and E6 (downhill) recooling scheme b - maximal flow (drawing-2)

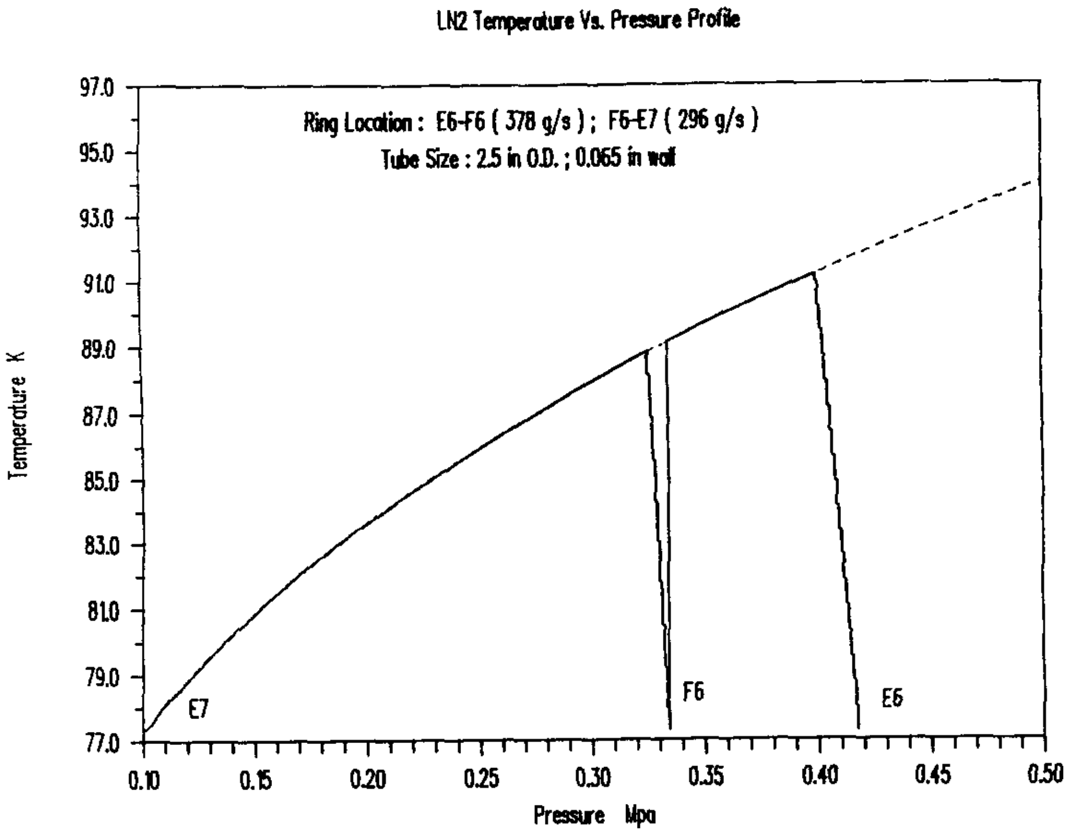


Fig 16: p-t diagram for 8km 2.5" line between sites E6 and E7 (uphill) recooling scheme b - equal generation (drawing-3)

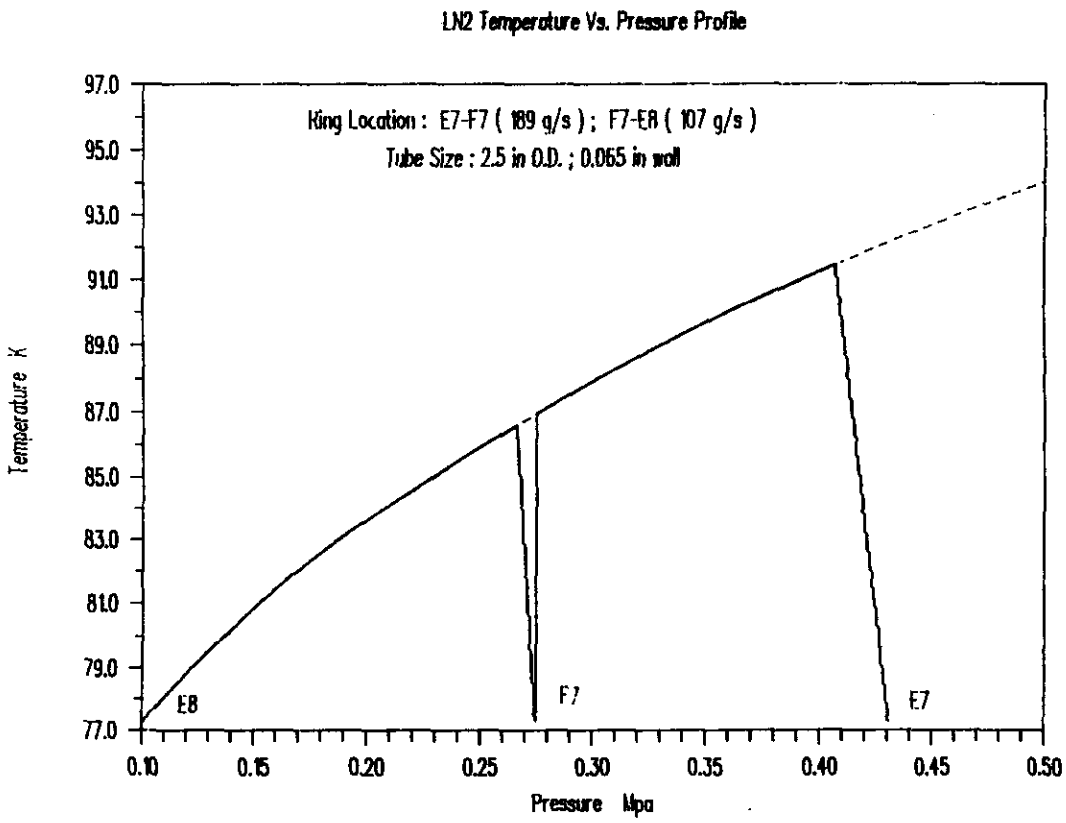


Fig 17: p-t diagram for 8km 2.5" line between sites E7 and E8 (uphill) *recooling scheme b* - equal generation (drawing-3)

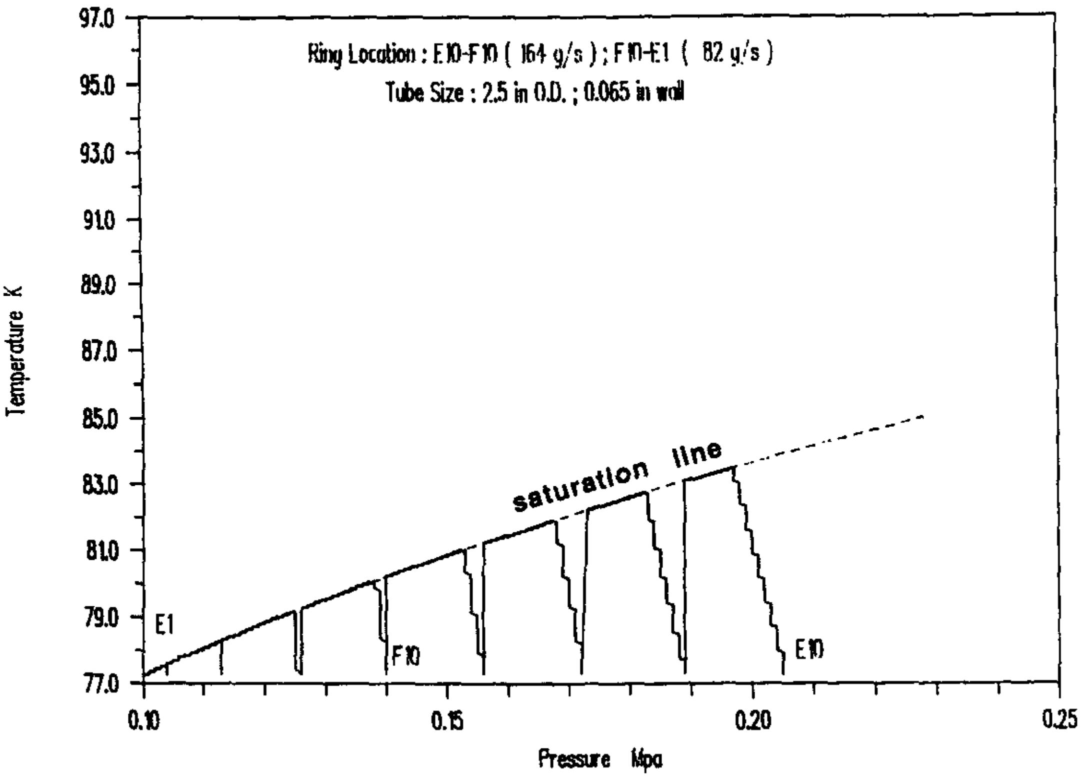


Fig 18: p-t diagram for 8km 2.5" line between sites E10 and E1 (uphill) recooling scheme c - maximal flow (drawing-6)

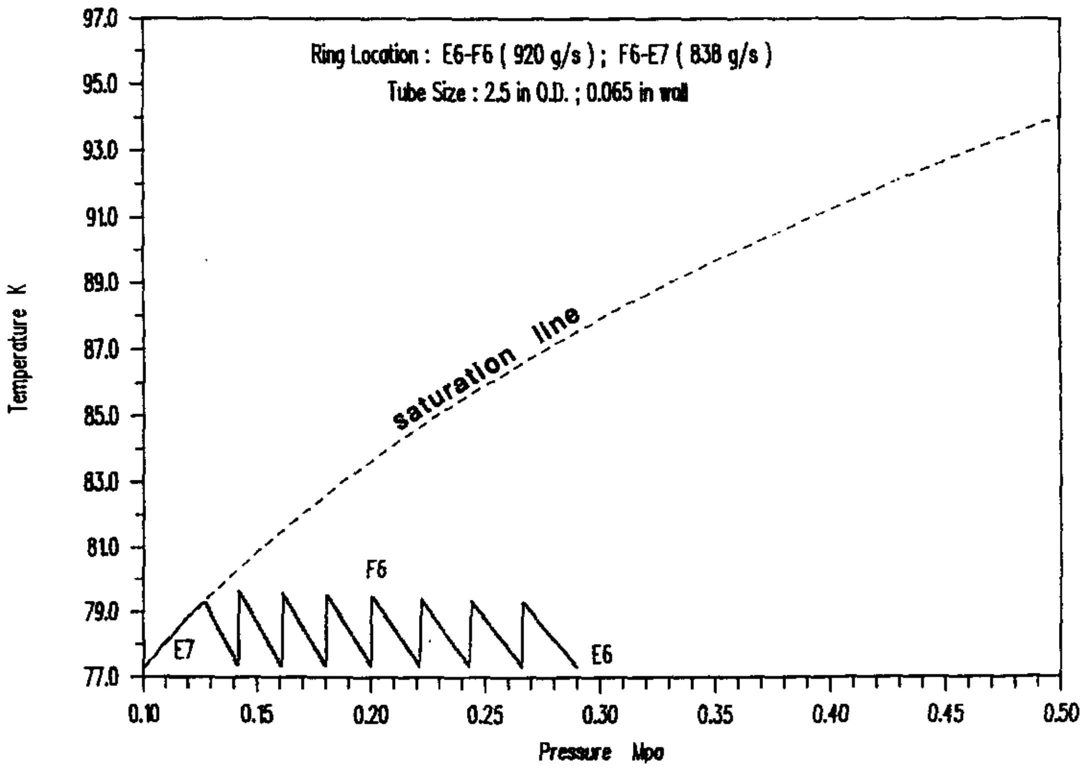
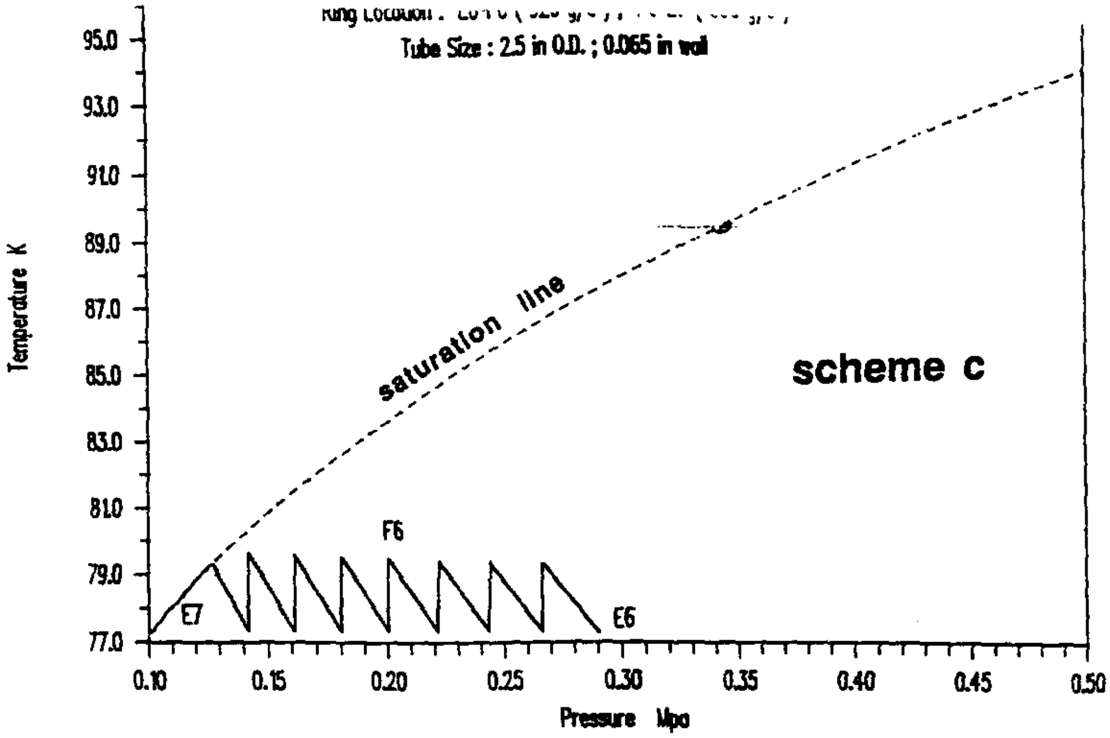


Fig 19: p-t diagram for 8km 2.5" line between sites E6 and E7 (uphill) recooling scheme c - maximal flow (drawing-6)



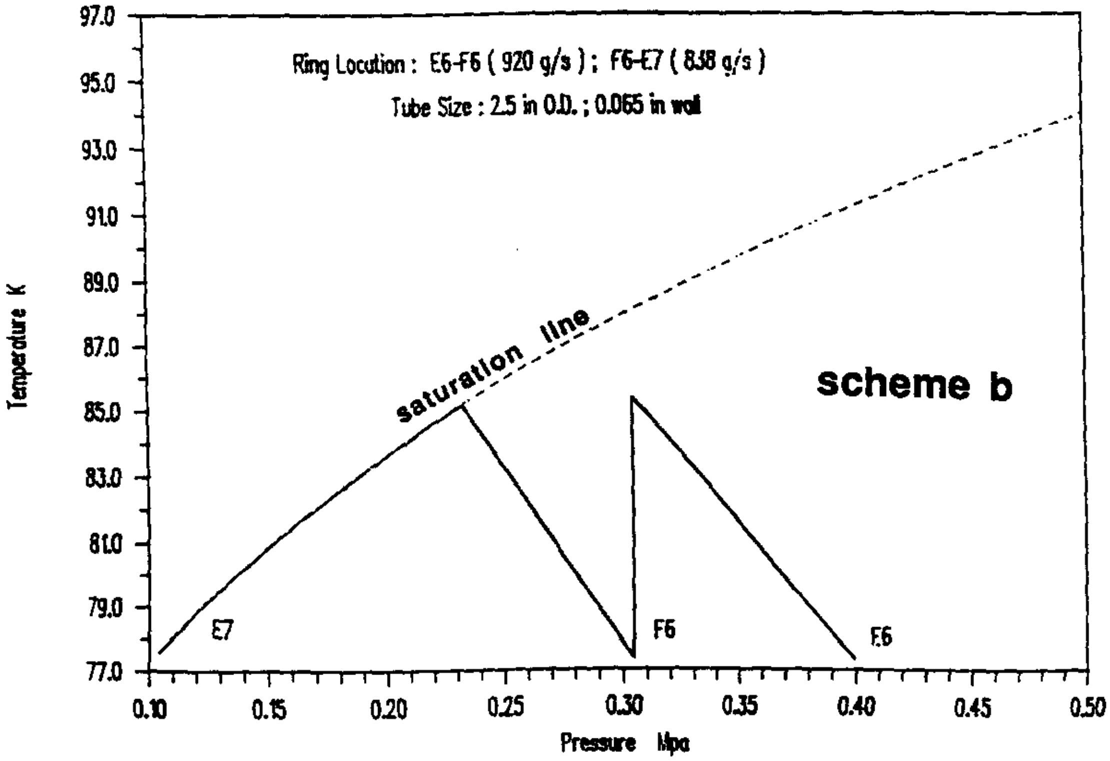
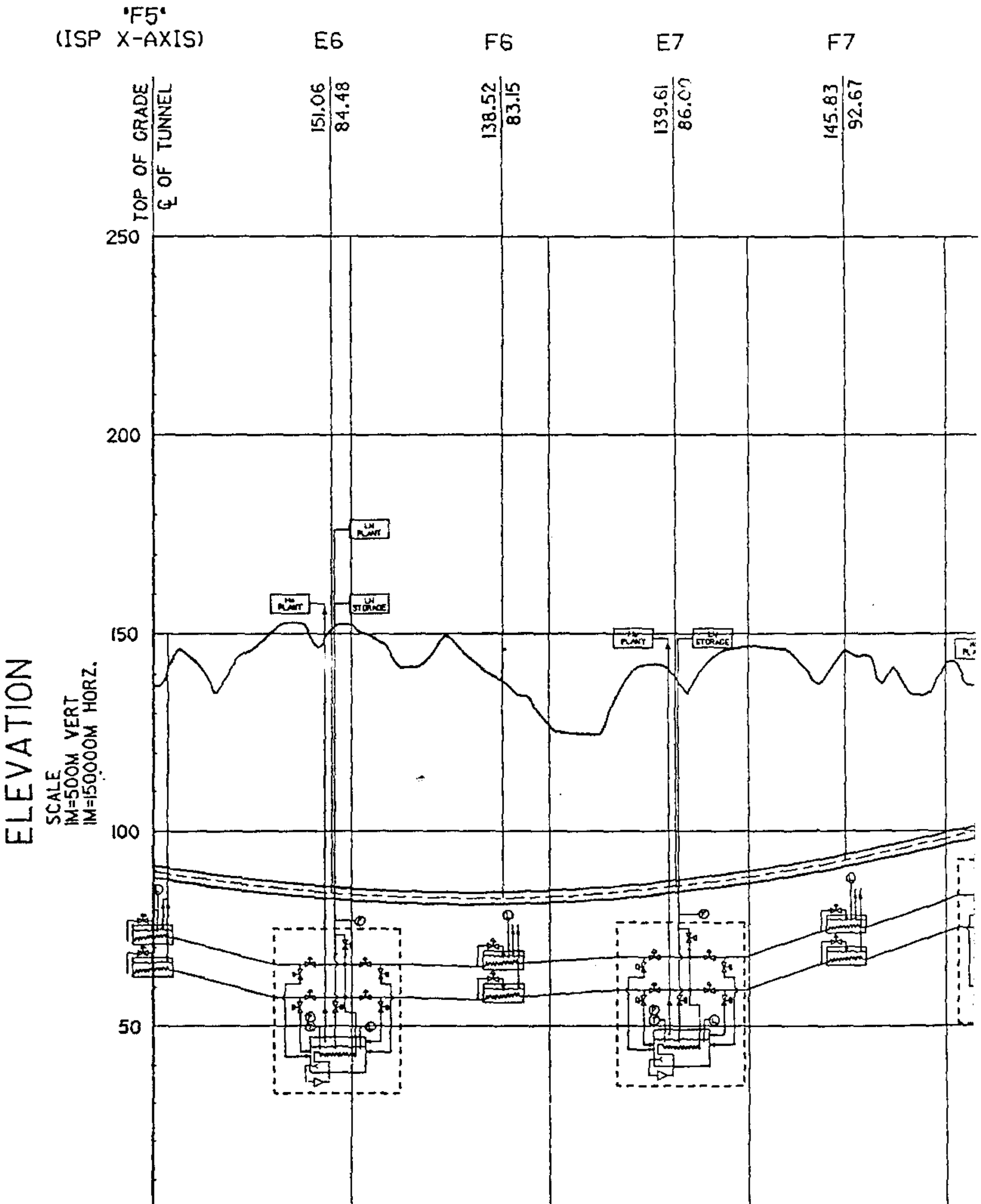
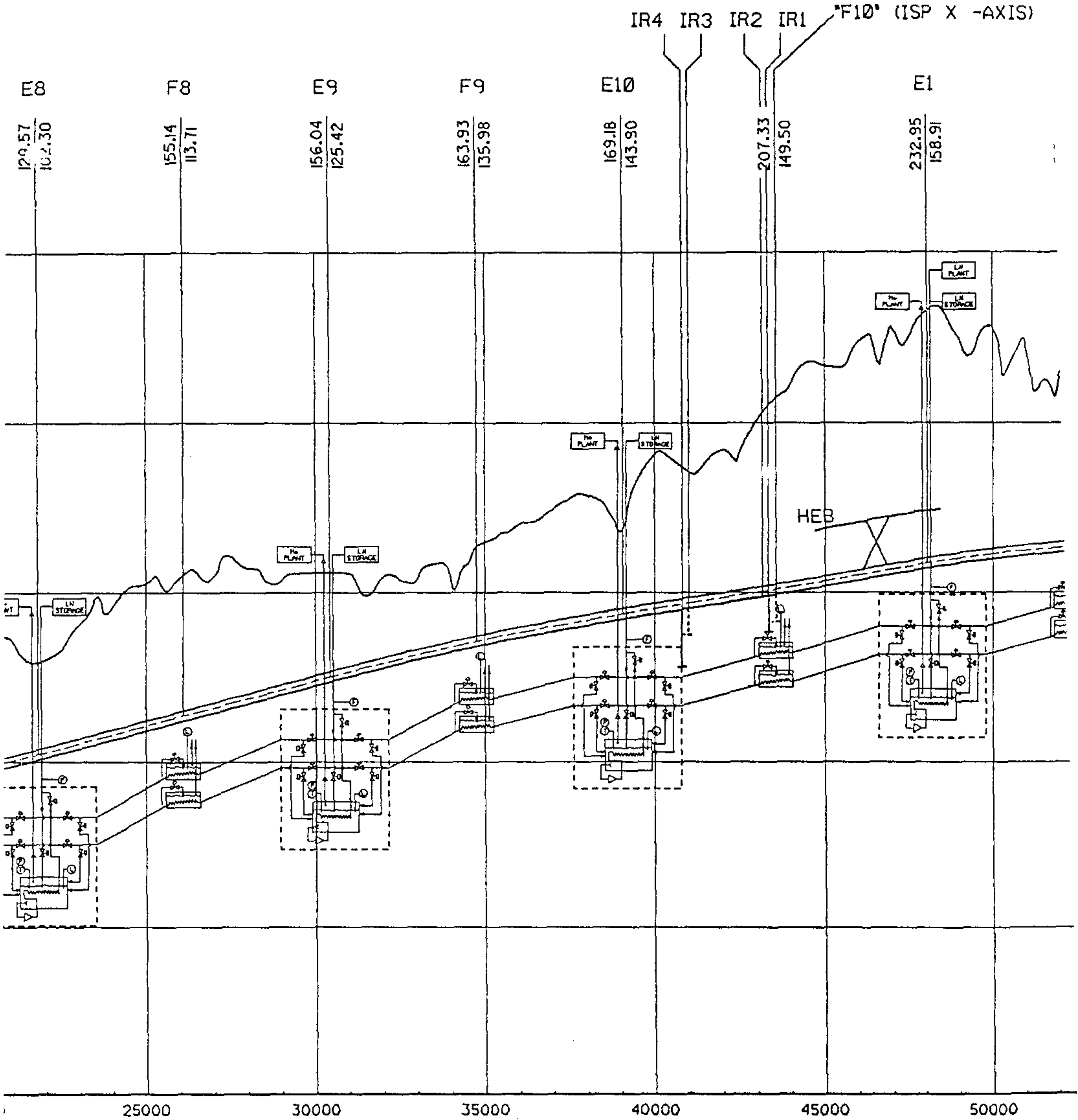


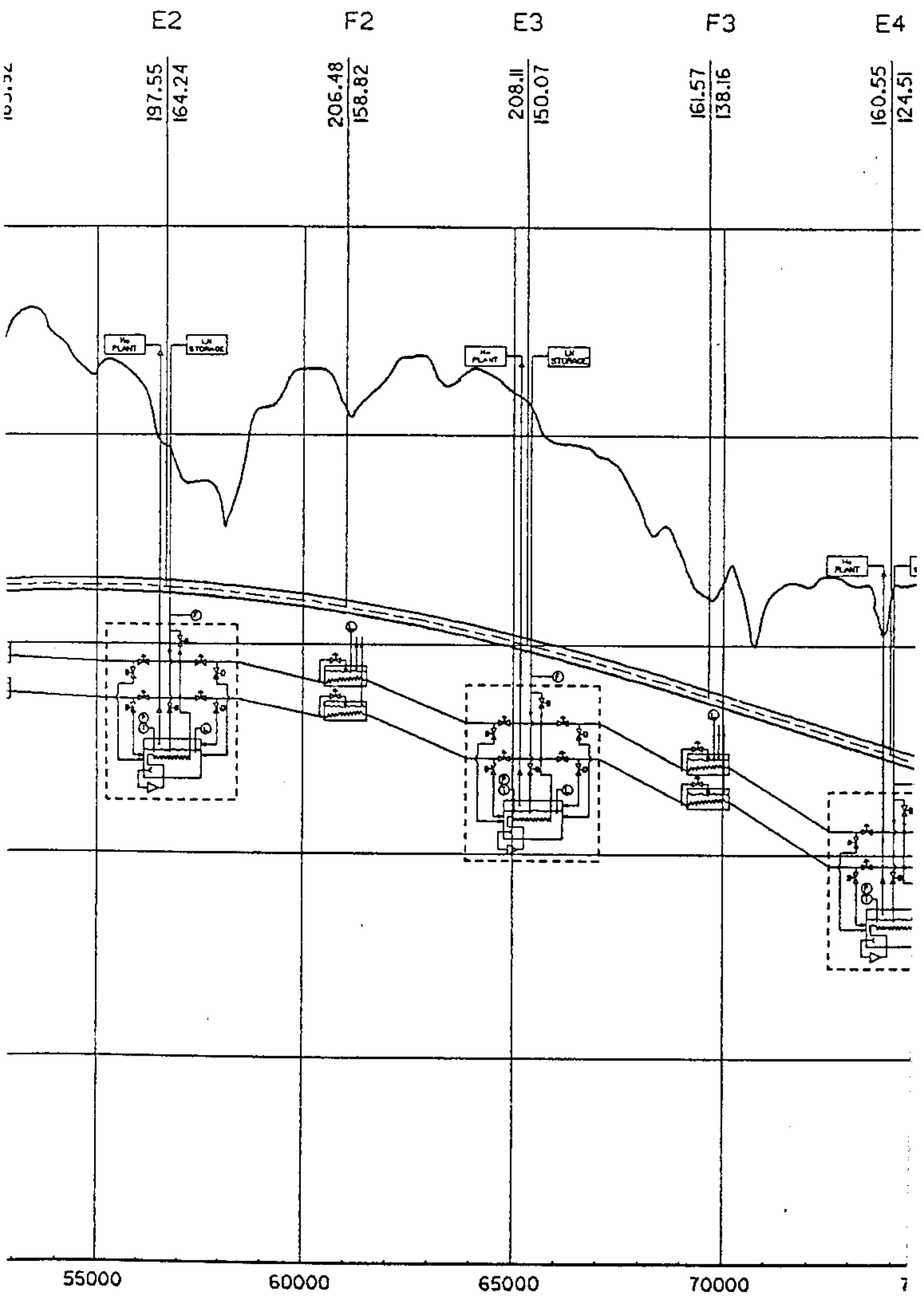
Fig 20: p-t diagram for 8km 2.5" line between sites E6 and E7 (uphill) comparison between recooling schemes b and c

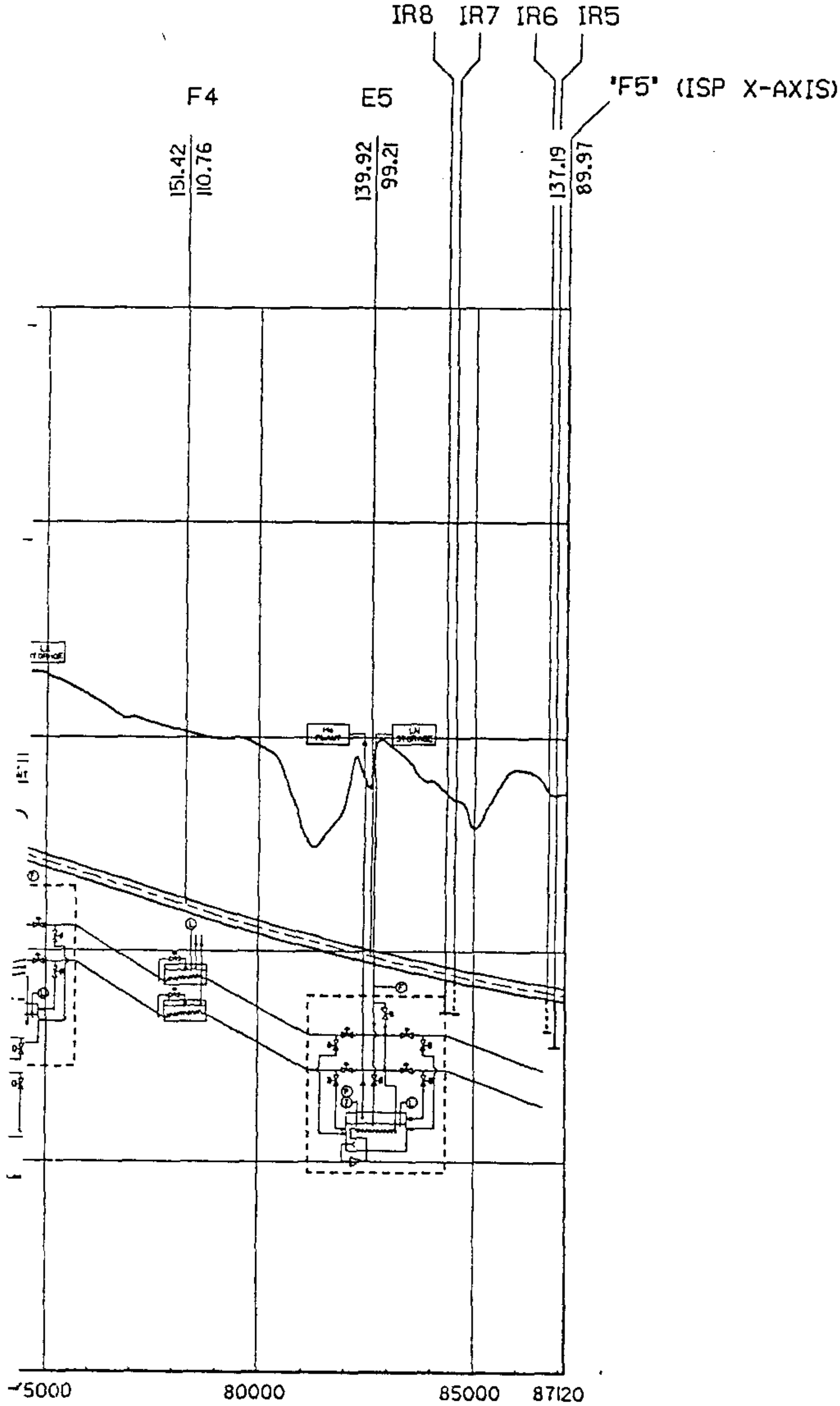


'F5'
(ISP X-AXIS)
E6
F6
E7
F7
TOP OF GRADE
℄ OF TUNNEL
151.06
84.48
138.52
83.15
139.61
145.83
92.67
250
200
150
100
50
0
0 METERS
5000
10000
15000
ELEVATION
SCALE
1M=500M VERT
1M=150000M HORZ.



IR4 IR3 IR2 IR1 "F10" (ISP X -AXIS)
E8
129.57
102.30
F8
155.14
113.71
E9
156.04
125.42
F9
163.93
135.98
E10
169.18
143.90
207.33
149.50
E1
232.95
158.91
He PLANT
LN STORAGE
LN PLANT
HEB
25000
30000
35000
40000
45000
50000


E2
F2
E3
F3
E4
197.55
164.24
206.48
158.82
208.11
150.07
161.57
138.16
160.55
124.51
55000
60000
65000
70000



IR8 IR7 IR6 IR5
'F5' (ISP X-AXIS)
F4
E5
151.42
110.76
139.92
99.21
137.19
89.97
-5000
80000
85000
87120