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CONTROL SYSTEM OF THE 4 K AND 20 K REFRIGERATORS

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I. Introduction

The SSC cryogenic system requires a control system, which handles the simultaneous operation of 10 refrigerators in parallel. Each refrigerator provides three separate services. These are

(a) liquefaction of warm low pressure helium vapor

(b) Condensation of saturated helium vapor

(c) Refrigeration for the 20 K shields of the magnet system

Furthermore there are at least two steady state conditions of the 4 K refrigeration system. One of these is the standby mode, when there is no beam and consequently no synchrotron heatload. The other in operation at 20 TeV, where there is a major heatload due to synchrotron refrigeration. The control of the refrigerator - magnet system is discussed for the refrigerator model developed by the CDG. In this model, liquefaction has been separated from the 4 K refrigeration system, and by this action is essentially decoupled from the magnet system.

II. Discussion

Figure 1 represents the flow diagram of the refrigerator developed by the CDG. Figure 2 shows the flow diagram of the refrigerator equipped with control loops. Note that the liquefaction section of the refrigerator is not included. Figure 2 shows, that there are 4 lines connecting the refrigerator with the magnet system. Two of these lines connect to the 20 K shield system, and the other two to the 4 K vapor return header and the liquid helium distribution header of the magnet rings.

In order to study the control system, the following assumptions have been made:

SSC Refrigeration Plant

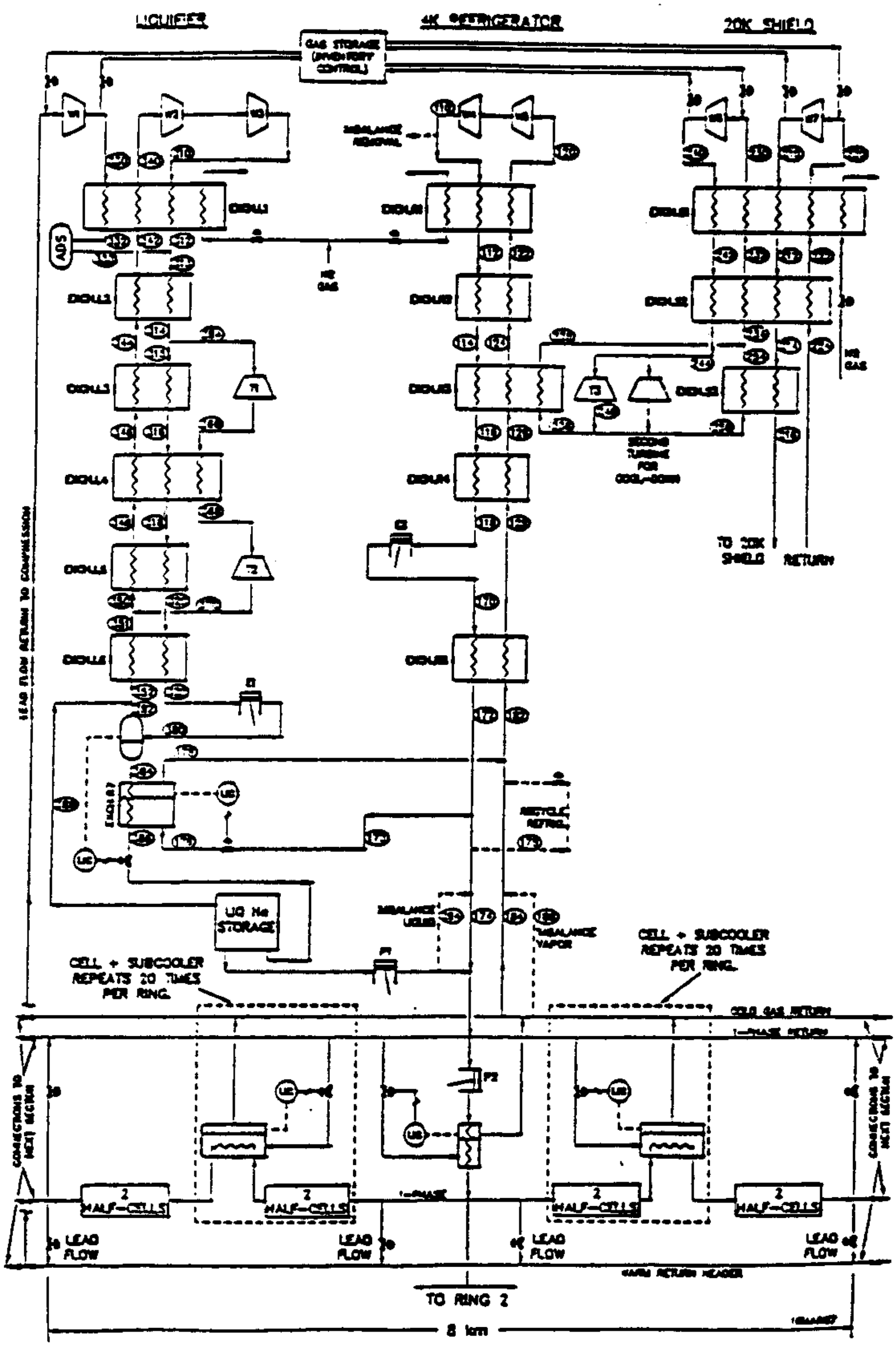

Fig. 1.

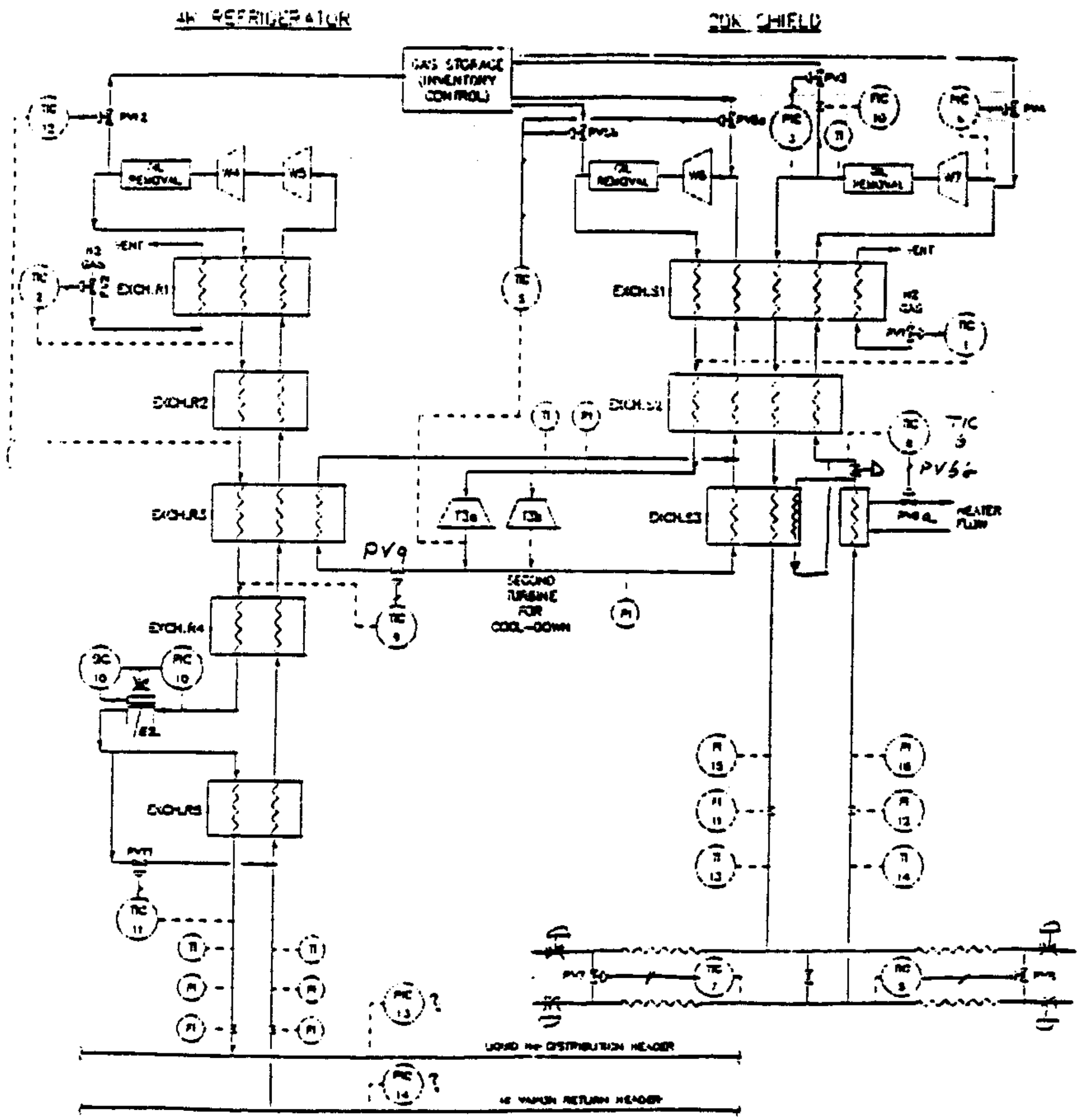
4K REFRIGERATOR
20K SHIELD
GAS STORAGE (INVENTORY CONTROL)
OIL REMOVAL
EXCH.R1
EXCH.R2
EXCH.R3
EXCH.R4
EXCH.R5
EXCH.S1
EXCH.S2
EXCH.S3
VENT
SECOND TURBINE FOR COOL-DOWN
HEATER FLOW
LIQUID He DISTRIBUTION HEADER
He VAPOR RETURN HEADER

Fig. 2.

(1) For each magnet ring the 4 K vapor return header and liquid helium distributor are continuous over 360°.

(2) At each refrigerator, the 4 K vapor return headers are in open connection with the low pressure circuit of the 4 K refrigerator (suction of compressor W5).

(3) At each refrigerator the liquid helium distributors are in open connection with the 4 K refrigerator (discharge from wet expander E_2).

(4) The 20 K shield lines of the magnet system are in open connection with the 20 K refrigerator.

(5) There are flow indicators in the 4 K vapor return lines and liquid helium distributors at the points where one magnet sector interfaces with the adjacent sectors.

(6) Compressors W6 and W7 of all refrigerators are in operation.

(7) As a minimum, one set of W4-W5 compressors per refrigerator is in operation.

There are a number of steady states of the system, as follows:

1. All of the magnets cold and maintained at the proper temperature.
2. Magnets operating at low field with beam circulating.
3. Magnets operating at full field with beam circulating at 20 TeV.

Conditions 1 and 2 are not much different from a standpoint of load on the refrigerators. The conditions are characterized by a small refrigeration load relative to maximum capacity of the refrigeration system. Condition 3 represents possibly 2/3 of the maximum capacity of the refrigeration system. Also, changing over from condition 2 to 3 requires a substantial increase in liquid helium consumption for the high current power leads.

Table I provides the basic purpose of each control loop shown in Fig. 2.

Tat'e I

Control loops of a 4 K - 20 K refrigerator

Control	System	Purpose
TIC1 - PV1	20 K	Maintain exchanger S1 cold end at 80-85 K.
TIC2-PV2	4 K	Maintain exchanger R1 cold end at 80-85K
PIC3-PV3	20 K	Allows removal of helium vented during a quench
PIC4-PV4	4-20 K	Allows supercharging of 20 K loop
TIC5-PV5a PV5b	20 K	Controls supply of refrigeration by T3
TIC6-PV6a PV6b		Controls temperature of gas returned after a quench
TIC7-PV7 TIC8-PV8	20 K 20 K	Allows flow distribution in 20 K shield loops.
TIC9-PV9	4 K	Controls supply of refrigeration to 4 K refrigerator
PIC10-SIC10	4 K	Controls expander E2 speed
TIC11-PV11	4 K	Controls subcooling of liquid flow to liquid He distribution header.
TIC12-PV12	4 K	Controls flow of vapor to gas storage in case of expander E2 being down.
PIC13-PIC10	4 K	Control of pressure in liquid helium distribution header, resets PIC10
PIC14	4 K	Control of pressure in 4 K vapor return, resets PIC10 (only as a check on PIC13)

III. Controls of the 20 K refrigeration systems

III.1 Steady state control system.

a) A pressure level is chosen which provides a circulation rate of gas through the 20 K magnet shield which produces about a 6° K temperature rise between entry and exit.

b) T3a turbine discharge temperature (TIC5) is controlled at 17 K $\pm$ 0.5 K. This is accomplished by varying the inventory of the turbine loop, which in turn controls the amount of refrigeration made with the turbine. Flow of gas in and out of the turbine loop is accomplished by valves PV5a and PV5b from a signal of TIC5.

It should be noted that a fixed turbine discharge temperature means a fixed inlet temperature.

c) Division of flow between the two loops of the 20 K shield flow system is controlled by either PV7 or PV8 operating from a differential signal between TIC7 and TIC8.

d) PV1 controls flow of cold nitrogen gas to maintain a point near the center of exchangers S1 at a constant temperature. This control determines the shape of the cooling curve of the exchanger S1 and as a result, controls cold end temperature differences of S2.

III.2 Quench and quench recovery. During a quench of a half cell, liquid and cold gaseous helium is ejected form the half cell and added to the 20 K shield line. As a result, the pressure in the 20 K shield will go up slightly and flowrate will increase proportionally. There is no other immediate effect on the 20 K shield system. During recooling of the quenched magnets, gas of approximately 25-30 K temperature is added to the 20 K shield system. This will increase the shield line pressure somewhat more. Total mass added to the shield may be of the order of 200,000 grams. This mass must be removed from the 20 K shield system and reliquefied. To minimize the effects of the 20 K shield, control value PV3 will be activated by switching its actual sensor from PIC3 to FIC10. This flow controller will discharge a constant mass flow rate. For instance, a flowrate of 20 g/sec would require a period of some three hours for removal of excess gas from the 20 K shield system. During the mass removal phase, heat exchangers S1 and S2 become imbalanced and there will be no need for cold nitrogen vapor. Valve PV1 will close.

When the cold bubble reaches the refrigerator, TIC6 will detect a large change in temperature. This will initiate heat addition in exchanger S4, which will stabilize the temperature at TIC6 within a narrow range. As a result refrigerator turbine T3a loop is only very slightly effected.

The heat addition to exchanger S4 may be electrical heat. It turns out, that this is not very costly in terms of power consumption (of the order of $100.00) and it takes care of a potentially massive upset of the turbine T3 loop.

When the hot bubble arrives, temperature of 20 K shield gas flowing to exchanger S2 may be as warm as 26 K.

In order to reduce this temperature to less than 24 K, TIC6 will actuate a control valve PV6b which directs some flow to the S3 exchanger. This will correct the temperature of the gas flowing from the 20 K shield to the cold end of exchanger S2. This is turn makes it possible to operate turbine T3 at nearly constant inlet and discharge temperature.

III.3 Interaction between 20 K refrigerators

By closing off the valves at the turn-around points halfway between refrigerators, each refrigerator becomes a stand alone unit not affected by its neighbors.

By opening up the valves at the halfway points, all refrigerators are coupled by means of 2 parallel headers, each 80 km long, with crossovers at 8 km intervals. The advantage of this is that a single quench will become a non event from the standpoint of pressure change in the loops. On the other hand, trying to balance flow and temperatures by means of valves PV7 and PV8 may become more complicated.

III.4 Operation of compressor W7

Under full load conditions compressor W7 is responsible for 6% of the total power load of the refrigeration system. For this reason, efficiency of W7 operation is not of prime importance. To provide the means for a quick increase of flowrates, compressor W7 could operate at less than 100% of full throughput. It should be realized, that an increase of flowrate through manipulation of the slide valve means a change of pressure drop in the flow circuit. When changing flowrates, pressure drop in the 20 K shield circuit changes. This will affect the section pressure of W7 and may partially reduce the desired effect of slide value adjustment.

A change of mass inventory of the 20 K shield system will nulify the effect of a mass flowrate change.

IV. Control of the 4 K refrigerator system

IV.1 Steady state

Control of the 4 K refrigerators will be governed by the behavior of pressure indicator controllers PIC 13 and PIC 14.

In addition to PIC13 and PIC14 in each sector, there will be flow indicators in both liquid helium distribution header and 4 K vapor return header at the connections between sectors. This means that it can be established that each refrigerator handles its load or that non-equal sharing of the load occurs. In principle an unbalance in refrigeration supplied by adjacent refrigerators is characterized by gasflow in the 4 K vapor return header in one direction and liquid helium in the liquid helium distribution header in the other direction. An overall unbalance in refrigeration supplied by 10 refrigerators and that required by the rings of magnets is characterized by a simultaneous increase and decrease of the pressures in the 4 K vapor return line and the liquid helium distribution header.

It is of interest to note, that due to the large inventory of both vapor and liquid headers, the changes in pressure are slow. For instance, an unbalance of 1 Kw (for 2 rings) results in a pressure rate of change in the liquid helium distribution headers of 0.51 ata per hour and 0.032 ata per hour for the 4 K vapor return lines. A change of 0.032 ata in the 4 K vapor return line results in a temperature change of 3.9 mK in the recoolers. It is obvious that the pressure of the liquid helium distribution headers will be used to adjust the refrigerators.

IV.2 Steady state at low level

At the lowest load steady state operation (roughly 20-25% of full capacity), it is possible to turn off 5 of the 10 refrigerators and load the operating refrigerators to approximately 40-50% of full capacity. Both 4 K vapor return line and liquid helium distribution header will then transport gas to and liquid from the operating refrigerators. Each operating refrigerator has one set of W4-W5 compressors in operation. Functioning controls are then TIC2 (valve PV2), TIC9 (valve PV9), PIC10-SIC10 (speed control of the wet engine) and TIC11 (PV11). At this operational level maximum refrigeration supplied is of the order of 14.0 KW. Excess may be of the order of 1-2 KW and adjustment may be made, by reducing compressors W4 - W5 throughput through use of the compressor W5 slide valve.

IV.3 Change from low level to load at 20 TeV

Figure 3 shows the refrigeration load as a function of time when the beam is brought to 20 TeV. The refrigeration system needs to be turned up and its supply of refrigeration to the magnet rings increased to roughly match the demand for refrigeration as shown in Fig. 3.

It is not necessary to provide the increase in refrigeration proportional to the demand curve of Fig. 3. The mismatch between refrigeration supplied and load results in a change of temperature of the recoolers (through increased or decreased boiling points). As shown, an unbalance of 1KW maintained during an hour, changes the recooler temperature by 3.9 mK. Another way of expressing this is to state that the addition of 923000 Joules to the 4 K vapor return line system changes recooler temperatures by 1mK. It is therefore permissible to bring the refrigeration supplied to the ring up linearly with time as shown by the straight line of Fig. 3. The maximum temperature increase or decrease of the 4 K vapor return line system is then of the order of 0.5 mK.

In order to accomplish the above, all 5 mon operating refrigerators have been turned on with at least one compressor W4-W5 system in operation. They will make refrigeration, and in standby condition this refrigeration will be supplied to a bypass between streams 172 and 182 of Fig. 1, with a heater taking up the refrigeration.

The second set of W4-W5 compressors of the 5 operating refrigerators will also have been turned on and will be put in service in parallel with the operating compressors. Refrigeration supplied will be brought up linearly

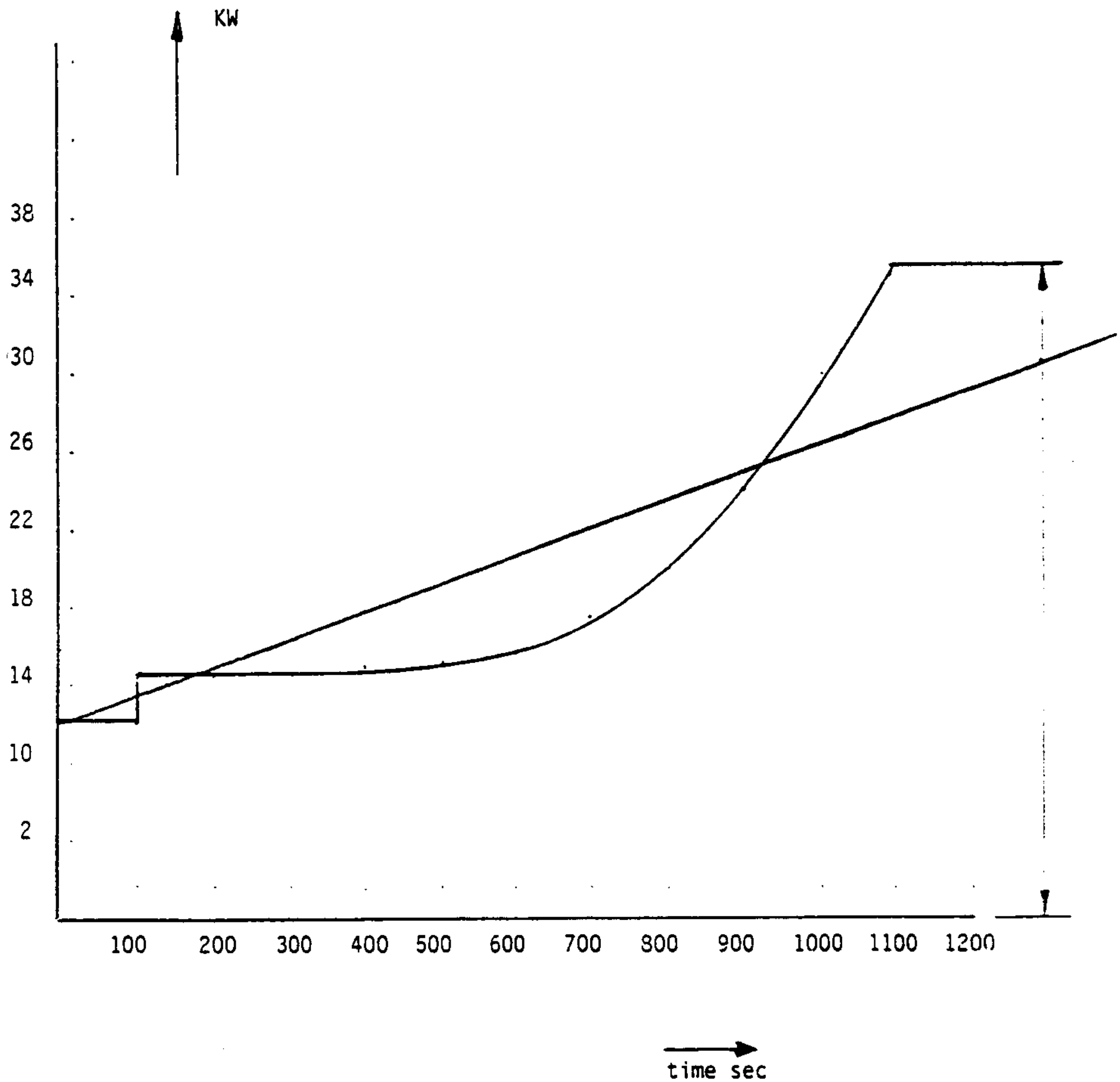

Fig. 3. Refrigeration load as a function of ramping to full energy level.

by increasing the pressure level in turbine T3 loop. All of this takes place over a period of some 1600 seconds.

Final matching of refrigeration supply and demand may be made in increments.

IV.4 Steady state at high level

From observation of mass transport between sectors, compressor W4-W5 flowrate adjustments will be made. At the same time, turbine T3 loop pressures will be adjusted and expander E2 speed changed to maintain a constant inlet pressure to the expander.

V. Controls of the helium liquefier

Figure 1 shows the helium liquefier to be coupled to the magnet systems by a warm vapor return line and a liquid line, which through pump P1 moves liquid helium form liquid storage to the liquid helium distributors.

In order to match the demand for liquid helium, pump P1 speed will be controlled by a flow meter in the warm vapor return line. Flow in the warm return line means that compressor W1 is operating. It does not necessarily mean, that the liquefier is operating. When operating, it may not produce liquid at the rate of warm gas return.

The overall system may be operating with one liquefier turned off altogether. In that case pump P1 and compressor W1 may be not operating at all and liquid helium and warm vapor will be dispensed and received by the other 9 liquefiers.

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