Fermilab

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COMPUTER OPERATED CONTROL SYSTEM FOR THE ENERGY SAVER SATELLITE REFRIGERATORS

J.C.Gannon

INTRODUCTION

This paper will outline the hardware and software used to control each of the satellite refrigerators for the Energy Saver.

HISTORY

The refrigerator was initially designed for use with pneumatic control systems. Parameters in the refrigerator were measured using pressure to pneumatic converters, processed by pneumatic servo controllers, and controlled by valves to which pneumatic actuators were attached. Parameters obtained for control were either pressures (absolute, gauge, differential) or temperatures. These temperatures are measured using vapor pressure thermometers (VPT's) which give a varying output pressure over a limited temperature range depending on the charging gas.

Remote display of refrigerator parameters was not possible without installing additional transducers in parallel with existing ones and becomes expensive with 24 refrigerators. Remote control of set points, gains, time constants, valve position limits and other operating parameters becomes even more difficult and expensive with a pneumatic system.

Because of these considerations and others, it was decided to convert existing refrigerators and all new refrigerators to computer control so that they can be normally monitored and operated from one central point. It was also decided that each refrigerator should be able to function by itself without continuous intervention from the main computer system.

An individual refrigerator has many different operating conditions which require different settings, gains, and other parameters for the control loops. A microprocessor, therefore, became the logical choice for the basic control unit.

Electronic pressure transducers replace the pressure to pneumatic convertors, electric valve actuators replace the pneumatic valve actuators, and the microprocessor replaces the pneumatic servo controllers in the new system. In addition, the data logging facilities of the main computer system allows for long and short term monitoring of all system parameters and replaces many chart recorders that are always out of paper or ink or are attached to the wrong monitoring point.

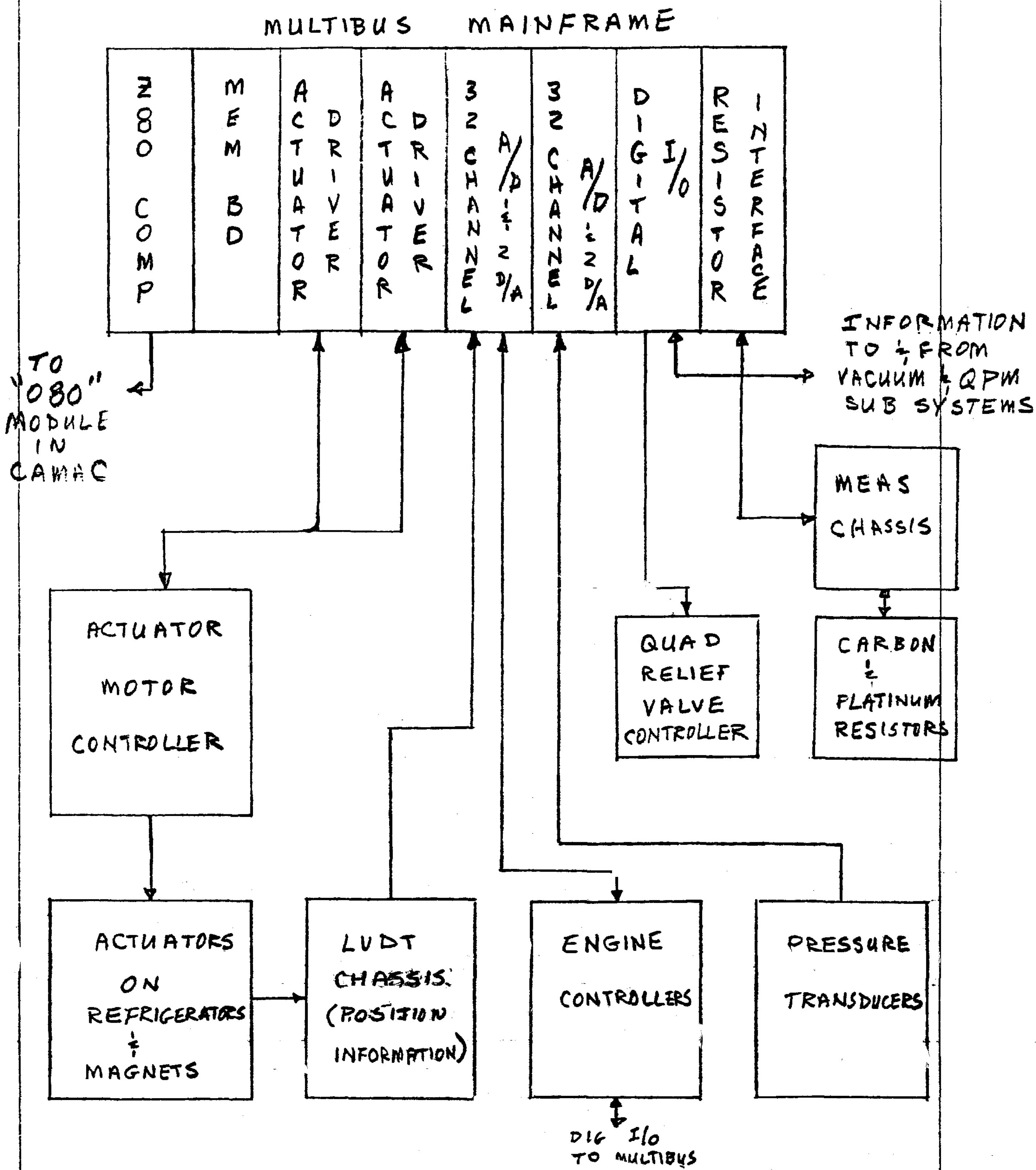
SYSTEM HARDWARE

The basic block diagram of the components used to control an individual refrigerator are shown in Fig. 1.

COMPUTER

Information is transferred to and from the μp through an "080" module in the Saver serial CAMAC system. This module was designed in-house by the Accelerator Division Controls Group.

The main frame for the μp, based on the "Multibus" standard, holds eight circuit cards and is expandable to twelve. The Z80 processor board, memory expansion board, analog to digital converter boards, and main frame are standard commercially available units.



REFRIGERATOR CONTROL SYSTEM
BLOCK DIAGRAM
FIGURE 1

The actuator driver boards, digital I/O boards, and the resistor interface board are in-house designs.

A/D CONVERTER BOARD

This board consists of a 32 channel, fully differential, multiplexed A/D converter and two D/A converter outputs. The resolution of the multiplier is eleven bits plus sign and has ±10V FS range. The D/A outputs can be configured to supply several output voltage ranges as well as 4-20 ma drive signals. It is manufactured by the ADAC Corp.

PROCESSOR BOARD

The processor board uses a Z80A CPU chip and has a 6K PROM and 4K RAM capacity. It is manufactured by Heurikon, Inc.

MEMORY EXPANSION BOARD

The memory expansion board, also made by Heurikon, has 8K PROM and 32K RAM capacity.

ACTUATOR DRIVER BOARD

Each driver board is capable of controlling eight actuators. Each channel has three outputs. One output is used to control the direction of actuator travel. The second output controls the length of time that the actuator is operated. This can be as short as 50 ms or as long as 10 seconds. The third output is a 50 ms square wave that appears while the actuator is operated. This could be used to control stepping motor type devices. The first two outputs are sent to the actuator motor controller unit where they are converted from TTL levels to driving signals to each actuator.

Each channel also has the local/remote status input which is sent from the motor controller. This input disables the actuator driver outputs to the motor controller and may also be read by the controls system.

DIGITAL I/O BOARD

The digital I/O board provides for 40 bits of input status and 24 bits of control output.

The input status comes from the refrigerator system- the QPM, and the vacuum system. The inputs are of two types, 24 are optically coupled inputs and 16 are TTL inputs.

The output bits are split into several groups. Eight bits are relay outputs for control of the dry and wet engine controllers. Ten bits will be used for control of quad relief valves during quench recovery and the others are either spares or are used for miscellaneous control functions.

RESISTOR TEMPERATURE MEASUREMENT SYSTEM

The magnets and refrigerator also use carbon and platinum resistors for temperature measurements. The platinum resistors are used in the range of 77 to 300K and the carbon resistors are used from 4 to 77K. Each quadrupole has a carbon resistor in the spool piece and the feedcan and turnaround boxes, and some locations in the refrigerator have platinum and/or carbon resistors.

The resistance of the sensor is obtained by measuring the dc voltage drop across the resistor using a four terminal measurement method. To reduce heating error effects in the cryogenic environment a 2.5 ma 50 μs pulse is sent through the resistor and the voltage is measured during the flat portion of the pulse. Resistances from 0 to 102.4 ohms can be measured using this system.

The measurement system contains two parts. These are a multibus resistor interface card and a NIM module which scans and measures the resistors.

The NIM module scans the resistors, upon command from the interface card, digitizes the voltage, and sends the data to the interface card. Twenty-four resistors can be measured by a module. Resistors are normally measured at a one second rate.

The interface card places the data from the measurement module into memory which can then be accessed by other parts of the μp or by the host computer. In addition, a single resistor may be measured at a different rate and the data is placed in a 232 word (one word per measurement) memory. When this memory is full a flag is raised so that the data can be transferred to the host and the memory refreshed. The measurement period for this function can be varied between 50 ms and 54 minutes per measurement.

The interface card can scan two modules (48 resistors) but only one module is needed at present.

ACTUATOR MOTOR CONTROLLER

The actuator motor controller is a 16 channel device for control of up to 16 actuators. Each channel has a p.c. card which converts the "TTL" level from the actuator driver card in the μp to the proper polarity of 24Vdc drive power for the valve actuator. The card also has switches for local control of the actuator position. Status is sent to the computer to indicate local control.

In addition the main chassis has a 24V, 28 amp hour battery to provide control of valves if the main power supply fails or during a power outage. Status is sent to the computer indicating battery or normal operation. The battery should last at least 4-8 hours.

ACTUATORS

Two types of linear actuators are used to control valves in the refrigerator. Both operate from 24Vdc and have similar current, speed, force, and stroke parameters. They both have a spring loading mechanism that provides 200 lbs of seating force when the actuator is de-energized. Microswitches shut off the actuator at the stroke or seating limits in each direction. Acme threads on the lead screw prevent valve creep between adjustments by the control system. A 50 ms pulse from the computer will move the valve 0.002" and a 7 sec pulse will move the actuator the full 9/16" travel. Both units have a Linear Variable Differential Transformer (LVDT) attached for position readout. These are ac devices and require a signal conditioning card and oscillator to convert the ac to dc for the control system.

The more compact and expensive actuator will be used in the tunnel for the JT and cooldown valves. The larger but less expensive actuator will be used in the rest of the system.

LVDT SIGNAL CONDITIONER

This unit supplies 3kHz ac to operate the LVDT and converts the returning signals from the LVDT to dc levels which are read by the A/D converter in the computer.

A common oscillator card provides a low distortion 3 VRMS sine wave at 3kHz to each of the LVDT's.

The conditioner card provides two channels of ac to dc conversion for the LVDT's. There are eight cards per unit.

A ±15Vdc power supply card completes the card cage for this unit.

ENGINE CONTROLLERS

Two types of dc motor/generator controllers are used to control the speed of the expansion engines. The larger 7.5 horsepower unit is used on the dry (gas) engine. The smaller two hp unit is used to control the wet (liquid) engine.

An internal feedback loop in the controller switches the device between the motor and generator mode to keep the speed constant at a given set point. Control of the set point is provided locally by a multi-turn pot or remotely by a computer D/A. Local or remote ON, OFF, and RESET control is also provided. Eleven bits of status are sent from each of the controllers to the computer.

PRESSURE TRANSDUCERS

Three types of pressure transducers are used on the refrigerator. They are: gauge pressure transducers, high line pressure differential pressure transducers, and low line pressure differential pressure transducers.

The gauge pressure transducers are used to measure pressures and temperatures. Three ranges will be used in the refrigerator. They are 0-25, 0-100, and 0-300 psig.

The high line pressure differential unit measures 0-5 psid and will be used to monitor the high pressure gas input flow.

The low pressure differential units will be used to measure liquid flows and levels, pressure drops across the magnet strings, and the superheat temperature of the two phase gas exiting the magnet string. The output ranges for these transducers are 0-1, 0-5, and 0-±5 psid.

Output voltages for all uni-directional transducers are 0-5Vdc and for bi-directional transducers ±2.5Vdc. At present all the tra ducers are variable capacitance type and operate from a 20-30Vdc power supply (24Vdc is the nominal value). The 24Vdc power supply that operates these transducers will be backed up by the actuator motor controller batteries.

QUAD RELIEF VALVE CONTROLLER

This chassis provides remote control of up to ten "Kautzky Relief Valves" for fast cooldown quench recovery. It converts "TTL" levels from the digital I/O board to 24Vdc at .5 amp signals to control solenoids near the valves in the tunnel at each quad. The computer decides which valves to open depending on quench location information sent to it by the QPM (Quench Protection Monitor).

SYSTEM SOFTWARE

The refrigerator has many operating modes which depend on the amount of output available from the Central Helium Liquefier, the number of cryoloops being cooled down at the same time, and the present efficiencies of the expanders (engines). There are also special conditions such as responses to and recovery from quenches, vacuum failures, and power failures. These modes and conditions are detailed in a document attached as Appendix A.

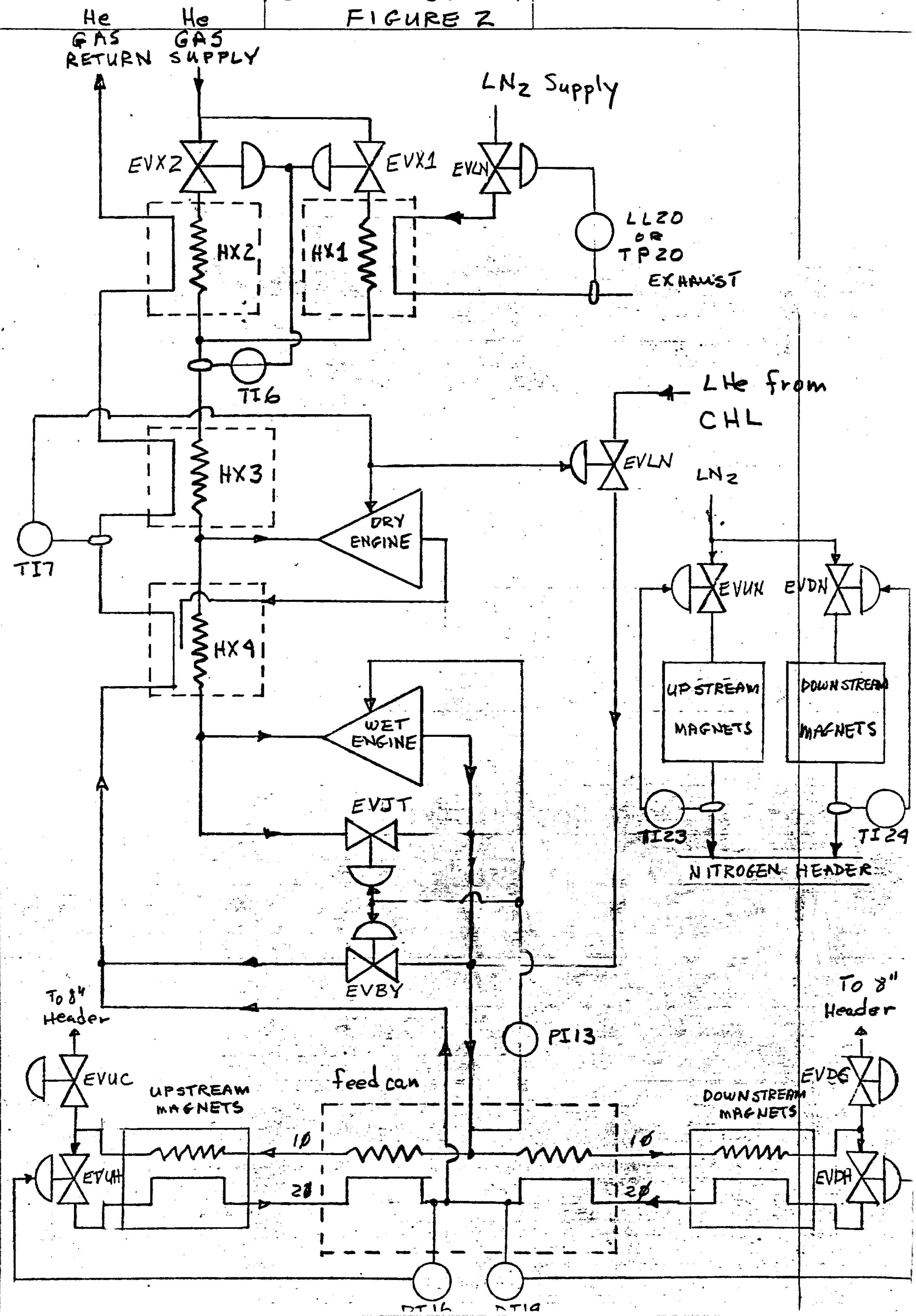
There are twelve valves and two engine controllers, which are run in proportional feedback loops by the computer. A simplified diagram of the refrigerator system which shows the magnets, heat exchangers, engines, valves, and servo points are shown in Fig. 2. The valves, EVUC and EVDC, are only used during cooldown.

The dry engine control loop only functions during cooldown or when the CHL is not working or at partial capacity. The cold box JT valve, EVJT, is only used when the wet engine is not operating. EVLN may be closed when CHL is at full capacity and the magnets are cold. Therefore, during normal operation when the magnets are cold, ten feedback loops will be operating at any one time.

CLOSED LOOP CONTROL PRINCIPLE

A typical closed loop is sampled and controlled at 1/10th of the normal system time constant. Each time the loop is serviced the control program does the following setps.

SYSTEM CONTROL POINTS
FIGURE 2



1. Reads the voltage of the controlled variable (pressure transducer, resistor, etc.) from the A/D converter, subtracts this voltage from the loop set point voltage, and generates an error voltage.
2. This error voltage is multiplied by the loop gain constant stored in the computer.
3. A derivative error is generated by subtracting the present and past values of the controlled variable.
4. This error is multiplied by a loop derivative gain.
5. The sum of these two calculations is multiplied by a third constant which converts this total error correction voltage to a valve position change which can be sent to the actuator drive card channel for that loop.
6. Before the output to the card is executed several checks are made:
    a. If the change is smaller than a minimum value no change is made.
    b. If the change will be larger than the maximum allowed value, the maximum value will be used.
    c. If the new correction will result in a valve position which is less than the minimum allowed valve position the output is modified to prevent this.
    d. A similar correction is made if the new position will exceed the maximum allowed valve position.

7. After these checks (and corrections, if necessary) have been made the output is sent to the actuator driver card and the loop sits idle until the next sample period.

A similar procedure is used to control the engines which have a D/A converter for control instead of a valve actuator.

There also are other loops used during cooldown, quenches, etc., which use a decision making process to control valves to fixed positions during different modes of operation. These loops do not require that the system gains and time constants be measured and used.

The loop programs can also be easily modified to allow for loops that have two time constants or require corrections based on the past history of the valve position.

OTHER SOFTWARE FEATURES

The software will also monitor selected channels and issue refrigerator "not ready" alarms to the Host and/or QPM when the parameters are out of tolerance and it is not safe to operate the ramp and beam.

The Controls Group is also providing a portable control unit called the RLI (Resident Local Intelligence) which will provide control of the refrigerator and other systems at the service building. This should prove invaluable for start-up and system debugging.

SUMMARY

This system is in a constant state of flux and I will try to keep this document up-to-date as major changes are made.

Appendix B contains a list of device names to be used on the computer system and several tables detailing A/D channel assignments and digital inputs and output designations.

TABLE I

REFRIGERATOR A/D CHANNEL ASSIGNMENTS

	NAME	DESCRIPTION
0	EVX1	EX#1 Helium Valve
1	EVX2	EX#2 Helium Valve
2	EVLN	EX#1 Nitrogen Valve
3	EVLH	Central Helium Liquefier Valve
4	EVJT	Cold Box JT Valve
5	EVBY	Cold Box Bypass Valve
6	EVUH	Upstream Helium JT Valve
7	EVDH	Downstream Helium JT Valve
8	EVUN	Upstream Nigrogen Valve
9	EVDN	Downstream Nitrogen Valve
10	EVUC	Upstream Cooldown Valve
11	EVDC	Downstream Cooldown Valve
12		
13		
14		
15		
16	TI3	EX#2 Shell Temperature
17	TI4	EX#1 Output Temperature
18	TI5	EX#3 Return Temperature
19	TI6	EX#3 Supply Temperature
20	TI7	EX#4 Return Temperature
21	TI8	EX#4 Supply Temperature
22	TI9	Dry Engine Output Temperature
23	TI11	Cold Box Return Temperature
24	TI12	Wet Engine Input Temperature
25	PI20	EX#1 Nitrogen Pressure
26	PI6	EX#3 Supply Pressure
27	PI8	EX#4 Supply Pressure
28	PI12	Wet Engine Supply Pressure
29	LL20	EX#1 Nitrogen Liquid Level
30		
31		
32	SPDE	Dry Engine Speed
33	PWDE	Dry Engine Power
34	SPWE	Wet Engine Speed
35	PWWE	Wet Engine Power
36	PI11	Cold Box Return Pressure
37	TI13	Feed Can Input Temperature
38	PI13	Feed Can Input Pressure
39	PI14	Upstream 1Ø Input Pressure
40	PI16	Upstream 2Ø Output Pressure
41	DP14	Upstream 1Ø Differential Pressure
42	DP16	Upstream 2Ø Differential Pressure
43	TI14	Upstream 1Ø Input Temperature
44	TI15	Upstream 1Ø Output Temperature
45	FIUH	Upstream Helium Flow
46	DT16	Upstream Output Superheat
47	PI21	Upstream Nitrogen Shield Pressure
48	TI23	Upstream Nitrogen Shield Output Temp
49	PI17	Downstream 1Ø Input Pressure
50	PI19	Downstream 2Ø Output Pressure
51	DP17	Downstream 1Ø Differential Pressure
52	DP19	Downstream 2Ø Differential Pressure
53	TI17	Downstream 1Ø Input Temperature
54	TI18	Downstream 1Ø Output Temperature
55	FIDH	Downstream Helium Flow
56	DT19	Downstream Output Superheat
57	PI22	Downstream Nitrogen Shield Pressure
58	TI24	Dnstream Nitrogen Shield Output Temp
59	FI4	Total Bldg Helium Gas Input Flow
60	TSV	Transducer Supply Voltage
61	ASV	Actuator Supply Voltage
62	RBT	Refrigerator Bldg Temp.
63		

TABLE II

DIGITAL OUTPUT

1.	Start Dry Engine N/O - 300 ms close	RELAY OUTPUTS
2.	Stop Dry Engine N/C - 300 ms open	RELAY OUTPUTS
3.	Reset Dry Engine N/O - 300 ms close	RELAY OUTPUTS
4.	Start Wet Engine N/O - 300 ms close	RELAY OUTPUTS
5.	Stop Wet Engine N/C - 300 ms open	RELAY OUTPUTS
6.	Reset Wet Engine N/O - 300 ms close	RELAY OUTPUTS
7.	OPEN/CLOSE Main Safety Gas Valve N/O	RELAY OUTPUTS
8.	Spare	
9.	Refrigerator Ready to QPM	
10.	Relief Valve Enable	
11.	Open Relief Valve #1	
12.	Open Relief Valve #2	
13.	Open Relief Valve #3	
14.	Open Relief Valve #4	
15.	Open Relief Valve #5	
16.	Open Relief Valve #6	
17	Open Relief Valve #7	
18.	Open Relief Valve #8	
19.	Open Relief Valve #9	
20.	Open Relief Valve #10	
21.	Spare	
22.	Spare	
23.	Spare	
24.	Spare	

TABLE III

DIGITAL STATUS

BIT

0. Quench has occurred
1. Quench in Cell Ø
2. Quench in Cell 1
3. Quench in Cell 2
4. Quench in Cell 3
5. Quench in Cell 4
6. Vacuum GOOD/BAD
7. Spare
8. Motor Controller NORMAL/BATTERY
9. Transducer Supply NORMAL/BATTERY
10. Main Safety Gas Valve OPEN/CLOSED
11. Dry Engine REMOTE/LOCAL
12. Dry Engine ON/OFF
13. Dry Engine OK/FAULT
14. Wet Engine REMOTE/LOCAL
15. Wet Engine ON/OFF
16. Wet Engine OK/FAULT
17. 8" Header Valve OPEN/CLOSED
18.
19.
20.
21.
22.
23.

BIT

24. Dry Engine Speed Normal/Over
25. Dry Engin Cont.Temp. OK/Over
26. Dry Engine Power OK/Reverse
27. Dry Engine Brake OFF/ON
28. Dry Engine Emergency Push Button OFF/ON
29. Spare
30. Spare
31. Spare
32. Wet Engine Speed Normal/Over
33. Wet Engine Cont.Temp. OK/Over
34. Wet Engine Power OK/Reverse
35. Wet Engine Brake OFF/ON
36. Wet Engine Emergency Push Button OFF/ON
37. Spare
38. Spare
39. Soare

APPENDIX A

Cooldown Mode

Both strings (upstream and downstream) are cooled independently. There are 4 steps to the cooldown procedure with transition between the states occurring in both directions and defined by the carbon resistor temperature sensors. Unless directly specified all control loops are active and running in their "normal" settings. In order to accommodate the inherent difference between cooling down only one cryoloop where the Central Helium Liquefier (CHL) can be used to overpower the string and other types of cooldown where this is not possible, the operator will choose a particular cooldown mode explicitly corresponding to case A, B or C as defined below:

Case A (single cryoloop)

The CHL is on (and running 100%) and only one cryoloop is being cooled down. In this case the dry engine is turned off and the central helium input loop is active.

Case B (multiple cryoloops)

The CHL is on and more than one cryoloop is being cooled simultaneously. In this situation the helium input loop is off but the input valve is open to 20%. The dry engine loop is active at its normal setting.

Case C (stand-alone)

The CHL is unavailable. The helium input valve is closed and the dry engine is active and running normally.

Once the operator has chosen a particular cooldown scenario the rest of the cooldown will proceed automatically through the various stages.

State 1

a. magnet JT loops off - JT valves closed

b. wet engine loop off - engine speed set to fixed valve (near max)

c. cooldown valves set to initial positions (~95%). At 10 minute intervals check carton resistor TR12 if this voltage $\leq$3.0 V close cooldown valves by 2%. If voltage $\geq$3.3 V open cooldown valves 2%. The valves stay within the range 95-55%.

In cases B and C when the cooldown carbon resistors (uS and DS independently) reach 3.0 volts make transition to State 2. The reverse transition is made at a voltage of 2.3 V.

In case A the transition is not made until an 8.0 V level and then the step is made directly to State 4 with no reverse transition.

State 2

a. cooldown valves closed

b. magnet JT's open to 100%.

When cooldown resistors reach 8.0 volts make transition to State 3. Reverse transition made at 7.0 volts.

State 3

a. magnet JT's open to 80%

b. If carbon resistor T17 gets $\geq$2.5 volts halt the CBJT loop and close the JT valve 2%. Check this voltage every 10 minutes and close the JT valve 2% each time the voltage >2.5 V.

When the differential pressure gauge reaches 3.0 volts make transition to State 4. There is no reverse transition.

State 4

This is the normal running condition, when both US and DS strings reach State 4. Then all loops are activated with "normal" set points. If the CHL is on then ask operator whether or not he wishes to turn off the dry engine.

Normal Mode

Dry engine off, all other loops active.

Stand-Alone Mode

CHL helium input valve closed, loop off. Dry engine loop active. r.b. in both normal and stand-alone mode when the ramp changes from on-to-off the magnet JT loops are halted in their current position for 5 minutes and then reactivated.

Vacuum Failure

Vacuum failure is regarded as a catastrophic failure from which the system will not attempt to recover without operator intervention.

a. The system will recheck failure bit to reject noise spikes.

b. Close cooldown valves if open.

c. Helium supply loop off - close valves EV4A, EV4B.

d. CHL loop off - close valve.

e. Main helium supply valve closed.

f. Nitrogen flow loops off - valves closed.

g. Wet and dry engines off.

h. Set system no-go bit.

Quench Recovery

a. See (a) above.

b. Decode the 5 bits to determine quench location and open the appropriate relief valves (time elapsed <50 msec.).

c. Set system no-go bit.

d. Magnet JT loop off - valve closed.

e. Wait 10 secs, check carbon resistor closest to the refrigeration, when it hits 5 volts. Close the relief valve. Wait 1 min and then repeat for the next closest valve until all valves are closed.

f. Default to the state 2 in cooldown mode without changing dry engine or CHL loop.

Power Recovery

a. Disable interrupts

b. Set system no-go flag

c. Default to stand-alone made (with or without HOST).

To return to normal operation the μP will require the HOST to issue a system RESET.

In order to minimize sudden pressure perturbationslarge step function changes in certain valves will not be allowed. The central helium input valve will always start from 0% open and creep (2% change max in 10 secs) to the set point. The other valves which operate in this mode are the 3 nitrogen supply valves.

The μP will also have the ability to protect the system from accepting catastrophic set points e.g. a 1Ø pressure point which is above the relief valve setting. The μP will reject obviously erroneous input valves.

APPENDIX B

Fermilab

December 19, 1980

TO: All Refrigerator Users

FROM: C. H. Rode, J. Gannon, M. Harrison, M. Hentges, J. Theilacker

SUBJECT: COMPUTER NAMES

This memo is a list of the names of all refrigerator devices with the exception of manual valves, check valves, safety valves, and relief valves. (These will be updated in the next several months, since there must be different lists for A1, A2, A4, and B1.) All devices have the format:

"XXYYZZ"

XX is building name A0, A1,...F4, and CL (central)
YY is device type:
- TI - VPT
- TR - carbon thermometer
- TP - platinum thermometer
- TC - thermocouple
- DT - differential temperature
- PI - pressure
- DP - differential pressure
- EV - electric valve
- HV - hydraulic valve
- PV - pneumatic valve
- SP - expander speed
- PW - power out
- WK - work out
- FI - flow indicator
- LL - liquid level
- MV - manual valve
- CV - check valve
- RV - relief valve
- SV - safety valve

ZZ is device number or name. Number 9 or less are written: 9,BLANK.

CHANGE "XX" PV"ZZ" NAMES

B0 PV1 → B0 EVLP	low pressure
B0 PV2 → B0 EVKI	kickback
PV3 → EVHP	high pressure
PV4A → EVX1	EXCH#1
PV4B → EVX2	EXCH#2
PV5 → EVLN	liquid N_2
PV6 → SPDE	dry engine
PV7 → EVLH	liquid He
PV8 → SPWE	wet engine
PV9 → EVJT	JT
PV10 → EVBY	bypass
PV11 → EVUH	upstream He

PV12 → EVDH	downstream He
PV13 → EVUN	upstream N_2
PV14 → EVDN	downstream N_2
PV15 → EVUC	upstream cooldown
PV16 → EVDC	downstream cooldown
PV17 → HV1L	COMP#1 low
PV18 → HV1H	COMP#1 high
PV19 → HV21	COMP#2 low
PV20 → HV2H	COMP#2 high
PV21 → HV3L	COMP#3 low
PV22 → HV3H	COMP#3 high
PV23 → HV4L	COMP#4 low
PV24 → HV4H	COMP#4 high

<u>NEW "XX" PV"ZZ" NAMES</u>

A1 PV8D	8" header remote valves (2 status bits per valve, no control)
A2 PV8U	
A2 PV8D	
A3 PV8U	
A3 PV8D	
A4 PV8U	

<u>ELIMINATE PIC, LLIC, TIC NAMES</u>

PIC1,2 → PI1	compressor building suction, low pressure
PIC3 → PI2	compressor building discharge, high pressure
??? → PI3	refrigerator building low pressure, guage only
??? → PI4	refrigerator building high pressure, guage only
TIC4 → TI3	

LLIC5 } TR20
TIC5

TIC6,7 → TI7 (H_2 charged)
TI7 eliminated (N_e charged)
PIC8, 9, 10 → PI13

<u>Note</u>: PI13, PI113, PI213 will be reduced to PI13. }
PI11, PI111 will be reduced to PI11. } located in feed can
TI13, TI113, TI213 will be reduced to TI13. }
TI11, TI111 will be reduced to TI11, located in exchanger can

DPIC11 → DT16
DPIC12 → DT19
TIC13 → TI23
TIC14 → TI24
TIC15 → TR12
TIC16 → TR12

"XX" TR"ZZ"

15 turnaround upstream string
Q1 only at 1 building at 11 location
Q2
Q3
Q4
Q5
14 feed can upstream string
17 feed can downstream string
Q6
Q7
Q8
Q9
Q0 only at 1 building at 21 location
18 turnaround downstream string
12 wet engine inlet (replaces diode in u-tube)

"XX" TP"ZZ"

15 upstream cooldown
14 feed can upstream lead
17 feed can downstream lead
18 downstream cooldown
4 high pressure
3 low pressure
TL top lead at turnaround box (11 and 49 locations)
BL bottom lead at turnaround box (11 and 49 locations)
20 EXCH#1 N_2 vent
23 upstream shield
24 downstream shield

"XX" PI"ZZ"

PI2 high pressure - compressor discharge
4 high pressure - refrigerator input, gauge only
6 high pressure - exchanger #3 input
8 high pressure - exchanger #4 input
12 high pressure - wet engine input
13 feed can input pressure
11 low pressure - cold box return
9 low pressure - dry engine output } obsolute
7 low pressure - exchanger #4 output, } obsolute
5 low pressure - exchanger #3 output } obsolute
3 low pressure - refrigerator output, gauge only
1 low pressure - compressor suction

PI14 upstream 1 Ø pressure
16 upstream 2 Ø pressure
17 downstream 1 Ø pressure
19 downstream 2 Ø pressure

PI20 exchanger #1 N_2 pressure
21 N_2 upstream shield pressure
22 N_2 downstream shield pressure

PI30, 40, 50, 60 COMP#1, 2, 3, 4 interstage pressure
PI31, 41, 51, 61 COMP#1, 2, 3, 4
etc.

"XX" DP"ZZ"

DP14 upstream 1 Ø differential pressure
16 upstream 2 Ø differential pressure
17 downstream 1 Ø differential pressure
19 downstream 2 Ø differential pressure

"XX" TI"ZZ"

TI4 high side temperature - EXCH#1 output
6 high side temperature - EXCH#3 input
8 high side temperature - EXCH#4 input
12 high side temperature - wet engine input
13 feed can input temperature
11 low side temperature - cold box return
9 low side temperature - dry engine output
7 low side temperature - EXCH#4 output
5 low side temperature - EXCH#3 output
3 low side temperature - EXCH#2 middle

TI14 upstream 1 Ø input
15 upstream 1 Ø output
17 downstream 1 Ø input
18 downstream 1 Ø output

TI23 upstream shield output
24 downstream shield output

"XX" DT"ZZ"

DT16 upstream string output superheat
19 downstream string output superheat

"XX" LL"ZZ"

LL20 N_2 liquid level

"XX" FI"ZZ"

FI2 compressor building output flow
FIBY compressor building bypass flow
FI4 refrigerator building total flow
FIX1 EXCH#1 flow, local gauge
FIUH upstream manget flow
FIDH downstream magnet flow
BO FICL He flow toward CHL

<u>"XX SP"ZZ"</u>

SPDE speed dry engine motor
SPWE speed wet engine motor

<u>"XX" WK"ZZ"</u>

WKDE work dry engine (power/speed) x α } cal. no.
WKWE work wet engine (power/speed)

<u>"XX" PW"ZZ"</u>

PWDE power dry engine
PWWE power wet engine

CHR
JG
MH :er
MH
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