JOINT EUROPEAN TORUS

JET–P(85)14

R.L. Roberts, A. Jones, P. Kupschus, E. Kussel, C. Mayaux, M.J. Mead,
W. Obert, F. Spath, C.A. Steed and B.A. Wallender

The JET Cryogenic Supply System

The JET Cryogenic Supply System

R.L. Roberts, A. Jones, P. Kupschus, E. Kussel, C. Mayaux, M.J. Mead,
W. Obert, F. Spath[1], C.A. Steed and B.A. Wallender

JET-Joint Undertaking, Culham Science Centre, OX14 3DB, Abingdon, UK

[1]*Kernforschungszentrum, Karlsruhe, FRG.*

Preprint of paper presented at the Cryogenic Engineering Conference at Boston,
August 1985 and to be published in Advances in Cryogenic Engineering

ABSTRACT

The paper describes the build-up of cryogenic supply facilities for JET, the main loads being the neutral beam injector cryopumps. It deals with the LHe and LN_2 supply and distribution system and covers the work through design, manufacture, installation and testing. The cryosupply control employs an autonomous programmable controller operating in conjunction with the JET Central Computer. From the Central Computer the operator can initiate actions remotely, using touch panels and mimics, both for the cryosupply system and the cryopump loads. The cryosupply may be operated locally from local control panels. The cryosupply has been fully performance-tested and has exceeded its specification. The first cryopump load has been automatically cooled down and limited integrated tests carried out.

1. INTRODUCTION

The Joint European Torus (JET) has an on-going requirement for large quantities of He and N_2 in liquid form, and also N_2 gas. JET requires to keep cold and operational two large neutral injection (NI) cryopumping facilities each with a pumping speed of 8×10^6 Ls^{-1} for H_2. The cryopumps utilise LHe for this purpose and also use LN_2 for their radiation shields. Each cryopump was estimated to require ≃ 80 W of cooling power at 3.6 K and ≃ 20 kW at 80 K respectively. In addition, JET has other smaller cryopump systems housed in a NI test bed facility which also require cooling. JET's vacuum systems have a total volume conservatively estimated as ≃ 400 m^3 including the main Torus vacuum vessel. Periodically, it is required to vent these vacuum systems to the atmosphere, using vapourised pure and dry N_2 gas (< 5ppm(v)H_2O) which is stored in liquid form. N_2 delivery rates up to ≃ 400 m^3h^{-1} are required for venting systems to atmosphere. To meet these requirements cryogenic systems have been built at JET and consist of the following:

i) LHe refrigerator, storage and distribution systems.
ii) He gas recovery and high pressure storage systems.
iii) He gas purification systems.
iv) He gas analysis systems.
v) LN_2 storage and distribution systems.

Both LHe and LN_2 cryosupply systems have been fully commissioned and tested, including the recovery and purification and have met their specifications.

One NI cryopump has been partially commissioned in conjunction with the cryosupply system and a number of cryopump operation modes have had limited tests.

2. THE MAJOR CRYOGENIC LOAD

A primary technique for heating the thermonuclear plasma is to inject an intense beam of energetic neutral atoms into the plasma. The neutral particles are ionised and give up their energy to the bulk plasma, via collisions, increasing its temperature. JET has installed one NI system[1] capable of delivering 5 MW of 80 keV neutral hydrogen particles to the plasma and a second system is currently in preparation. To keep the neutral beam re-ionization losses in H_2 gas at a minimum, and to limit the flow of H_2 gas towards the Torus vacuum large scale cryopumps are required in the NI system's design.

Each cryopump[2] provides a pumping speed of 8×10^6 Ls^{-1} under a H_2 gas load of 300 $mbarLs^{-1}$. This guarantees base pressures of 3×10^{-5} mbar in the NI vacuum tank. The cryopump operates at 3.6 K for H_2 pumping and 4.3 K at a later stage of JET operation when pumping D_2 is required.

3. LHe REFRIGERATOR AND DISTRIBUTION SYSTEM

After producing a comprehensive technical specification, in the Summer of 1982, JET invited tenders for a contract to supply, install and test, a LHe refrigerator/liquifier complete with a supply and distribution system, and a contract was awarded in December 1982.

The supply contract included:

i) Main He gas compressor, electric motor and switch gear, pure He gas buffer tank and associated valves.
ii) Refrigerator cold box including turbines, heat exchangers, cold valves, purifiers and adsorbers.
iii) Distribution valve box, LN_2 and LHe sub-coolers, calorimeter and cold valves.
iv) LHe storage tank.
v) Impure He gas storage and recovery system complete with recovery compressor, He gas balloons, high pressure storage system, gas drier and all valves.
vi) Gas analysis system.
vii) Vacuum thermal insulation pumping systems.
viii) Interconnecting cryogenic transfer lines.
ix) Various gas heaters.
x) Safety and purge systems with all valves.
xi) Interconnecting pipeworks and cabling.
xii) All control and instrumentation including a control panel with mimics and a dedicated programmable controller with a two way link to the JET central computer (CODAS)[3].

The overall layout of the JET site showing the refrigerator position with respect to the Torus is shown in Fig. 1.

Flow diagrams of the refrigerator system and one of a pair of purifiers are shown in Figs. 2 and 3. The LHe/LN_2 distribution system and the recovery system are shown in flow diagrams in Figs. 4 and 5.

3.1 Performance Requirements

The performance requirements are listed in Table 1. An upgraded performance was also included in the specification which meant that all the major components including the compressor were to be sized to meet this requirement (500 W, 3.8 K) should JET decide to take up this option at a later date.

3.2 Operational Requirements

JET placed great importance on certain operational requirements which determined many aspects of the plant. Continuous operating cycles of 3000 - 6000 hours without maintenance were called for. This meant that only plant with a proven history of operation would be considered.

Reliability considerations led JET to believe that oil lubricated screw compressors, currently in use or proposed for many plants, were not best suited to JET requirements. If oil clean up systems were to

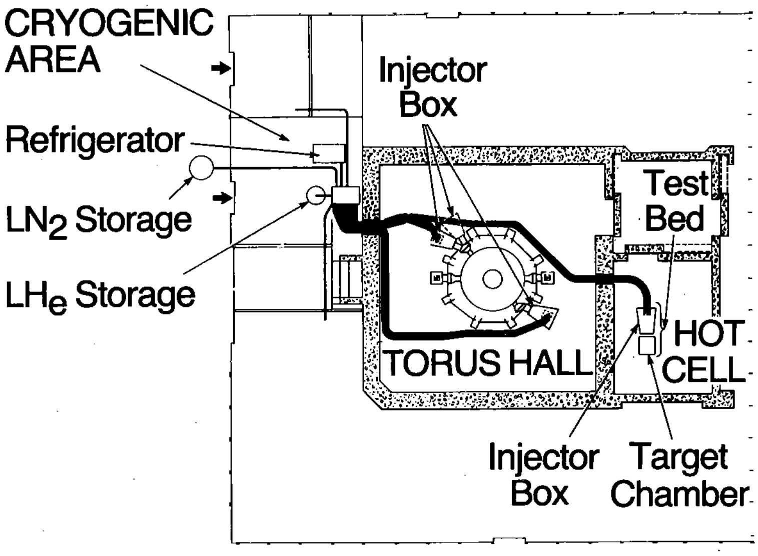

Fig. 1 Layout of JET

fail progressively, then hydro-carbons could penetrate along transfer lines to the Torus and JET may be faced with a radioactivity problem once DT operation was established at a later date. JET therefore declared its preference for a gas compressor designed specifically to prevent oil coming into contact with the main He gas flow.

By specifying that the cryopanels should be operated sub-atmospheric, using a warm ejector instead of conventional pumps, JET offset the possibility of air penetration of the He systems which is sometimes experienced with mechanical pumps. The use of a warm ejector although representing a thermodynamic inefficiency was nevertheless prefered by JET because of the above reasons.

JET defined as important that the plant should not be operationally labour intensive. Great emphasis was placed on running fully automatic and unattended similar to others^{4}. It was required that plant operation be initiated remotely at CODAS in the central control room using mimics and touch panels and staff not necessarily cryogenically experienced. This latter requirement meant that refrigerator control systems must be programmed to prevent adverse effects in the event of operator mal-operation. Plant purging and compressor start up however were defined by JET as local manual operations.

The refrigerators control system was specified to be installed locally, in a control panel. Control features associated with the remote operation at CODAS up to a prepared interface were to be supplied by JET and the rest was specified as the contractors responsibility.

3.3 Cryopump Operation Modes

A number of operational modes were foreseen for the three JET cryopump systems. These are,

i) cool down and fill,
ii) fill and dynamically operate,
iii) regenerate ie, H_2 defrost,
iv) warm up.

It was specified that any of the above modes could be selected for use with a cryopump by an operator local at the control panel or at CODAS remotely.

Each cryopump mode was to be executed in a fully automatic way once selected. Furthermore, any cryopump or cryopumps could be selected for any mode irrespective of, or without affecting the status of any other. In addition, should the need arise, the ability to arrest any automatic operation and run manually was requested.

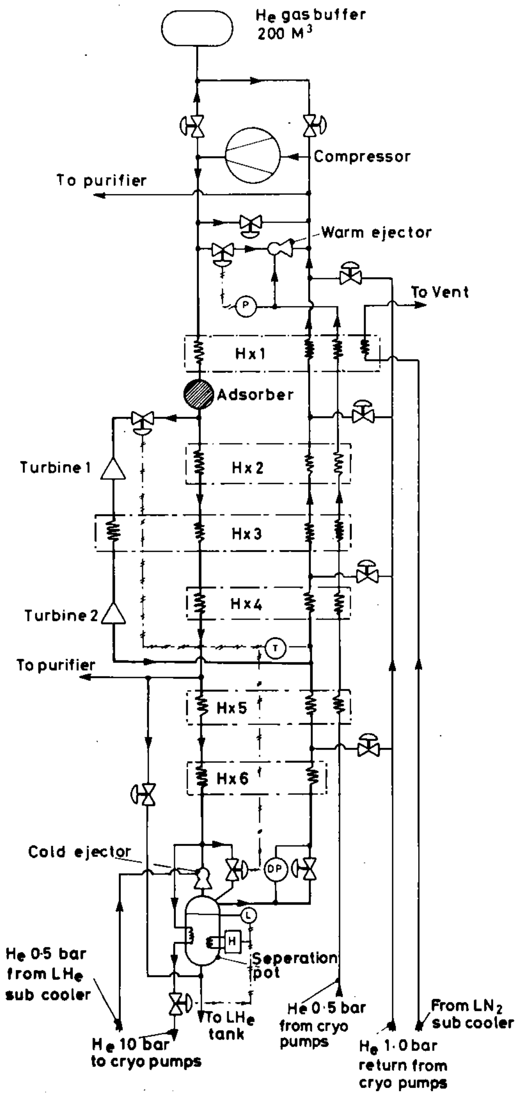

Fig. 2 Refrigerator Cycle

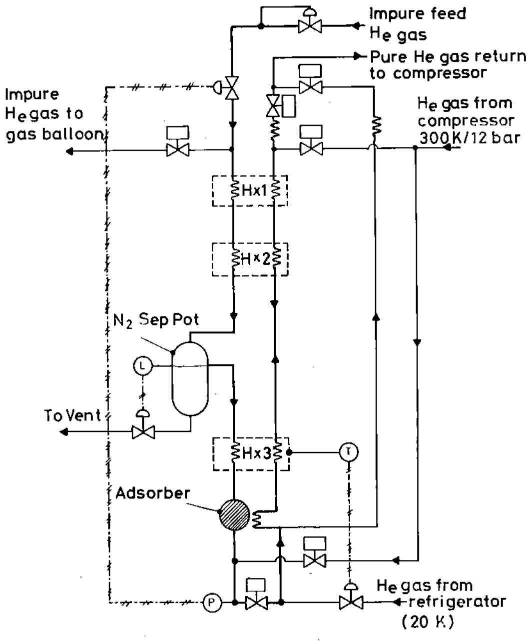

Fig. 3 Purifier System

JET established an integrated flow diagram for all the above aspects of the plant including the refrigerator. These proposals were accepted by the Contractor with some modifications.

3.4 LHe Plant Components

Because the plant fabrication, etc, was to be carried out in a number of different countries a number of different design codes and standards covering pressure vessels and pipeworks, materials, lifting facilities, electical installation, etc, had to be applied. To assure the quality of all these safety related aspects the design and manufacture was subject to stringent inspection controls throughout the entire work period. JET employed independent authorities to monitor and test these aspects.

A description of the He/N_2process flow complete with a schematic showing the integrated system has been previously presented elsewhere[5] but the following briefly describes the systems main components.

3.4.1 Main Compressor and Warm Ejector

The main compressor is a three cylinder two stage labyrinth seal compressor with the 1st stage comprising two cylinders working in parallel. With this configuration the machine has a compressor ratio of 10 and a total He throughput of $\simeq$ 140 gs^{-1} with a delivery pressure of 11 bar.

These types of compressor are well documented[6] and have successfully completed many hours of operation ($>$ 10^6 hours) in use with He gas. In particular, at CERN, Geneva, these machines have shown that there has been no oil penetration into the He compressor spaces.

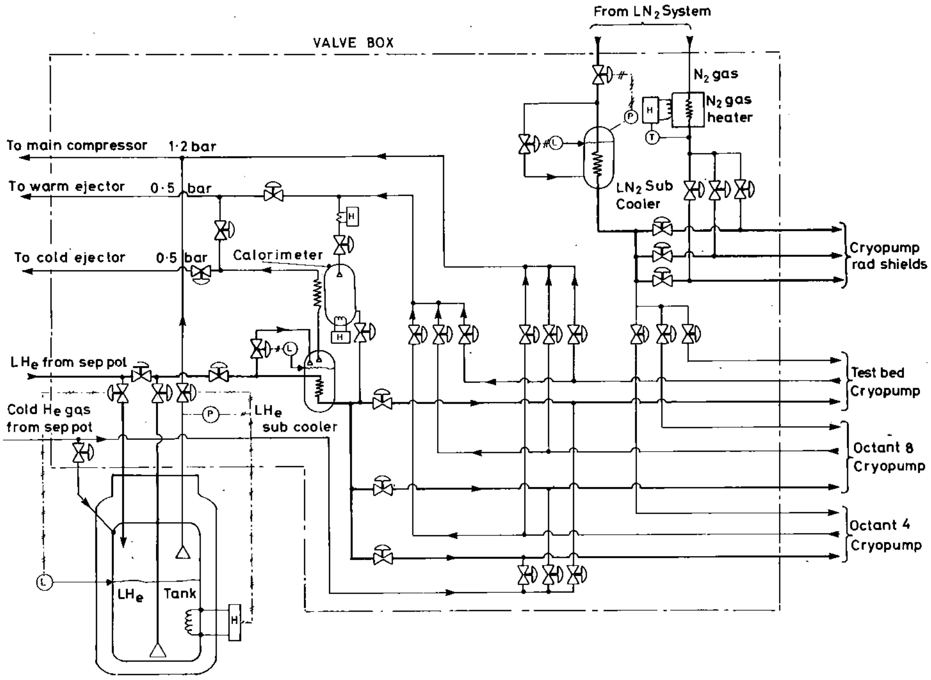

Fig. 4 LHe/LN_2 Distribution System

In order to provide necessary cryopanel pumping (15.4 gs^{-1}, 0.5 bar), the warm ejector is estimated to require 43 gs^{-1} for its primary flow throughput. This is for Ref. case 1 of Table 1 and represents ≃ 30% of the main compressor flow.

The compressor is directly coupled to a 500 kW electric motor and mounted with it on a common 60 t foundation block. The block is floated on 26 independent and identical rubber pads so as to decouple it from the surrounding area and other adjacent equipment.

The compressor has been fitted with a sound enclosure which is designed to permit easy personnel access, transmit light and reduce the noise level from 85 db(A) to 75 db(A) at 1 m distance from the electric motor.

		AT VALVE BOX EXIT TO CRYOPUMPS				
REF.	LN_2 PRE-COOL	REF. OUTPUT + SENS. HEAT (watts)	LHe SUPPLY LIQUID SUPPLY P (bar)	T (K)	He GAS RETURN GAS RETURN P (bar)	T (K)
1	No	300 + 30	0.7	3.8	0.53	4.0
2	No	225 + 30	0.67	3.6	0.53	4.0
3	Yes	320 + 30	0.7	3.8	0.53	4.0
4	No	470 + 30	1.6	4.4	1.18	4.5
5	Yes	600 + 30				
LIQ.	LN_2 PRE-COOLING	LIQ.RATE (gs^{-1})				
1	No	4 (120 Lh^{-1})				
2	Yes	5 (150 Lh^{-1})				
LN_2 DIST.		FLOW RATE (gs^{-1})				
CRYOPANEL RAD. SHIELDS		330 (1500 Lh^{-1})	1.9	82		
TRANSFER LINE SHIELDS		7.5 (35 Lh^{-1})				

Table 1 : Performance Requirements

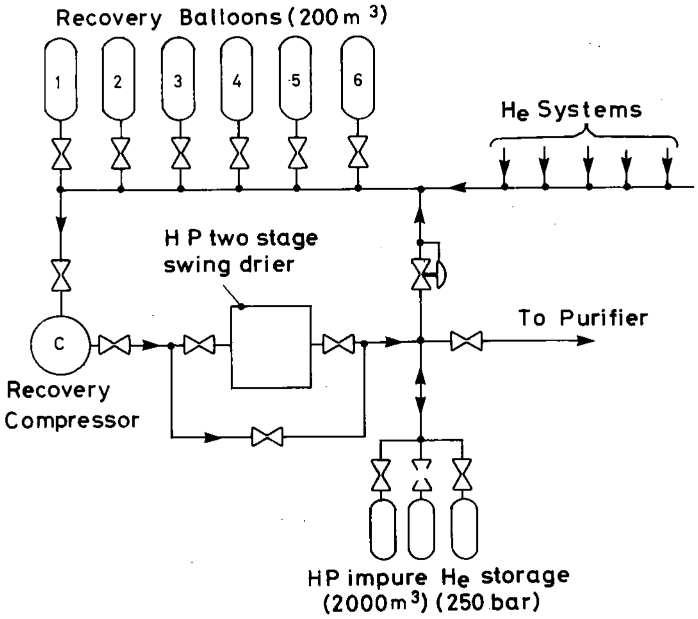

Fig. 5 Recovery System

3.4.2 Cold Box

The cold box assembly which can be seen in Fig. 6 houses all heat exchangers, valves, LHe separation pot, cold ejector, adsorbers and two gas bearing turboexpanders. In addition the He gas purifiers are installed in the cold box.

The main refrigerator heat exchangers are aluminium alloy plate fin type.

The cold ejector is used to pump the LHe sub-cooler to sub-atmospheric pressures and it has the advantage of being enclosed in vacuum eliminating air leaks into the He gas circuit.

The cold box contains two single stage centripetal turbines[7] fitted with directly coupled single-stage centrifugal brake compressors. The turbines have self acting gas bearings and a maximum speed of 230,000 rpm. The first and second turbines provide for Ref. case 1 of Table 1, $\simeq$ 2.7 kW and 1.1 kW of cooling power, respectively, and have a throughput of 51 gs^{-1}. If LN_2 pre-cooling is used the flow reduces to 43 gs^{-1} and their cooling power to $\simeq$ 1.7 kW and 0.93 kW.

3.4.3 Distribution Valve Box

The valve box houses all distribution cold valves, both the LHe and LN_2 sub-coolers and also a calorimeter for measuring the refrigerator power output.

The sub-coolers provide LHe and LN_2 at higher pressures than normal equilibrium at entry to the cryopump transfer lines. Typical LHe output conditions from its sub-cooler are 1 bar at 3.8 K and for LN_2 2 bar at 80 K. Sub-cooling ensures that single phase flow is delivered to the cryopumps irrespective of the normal static heat load and pressure drop of the transfer lines. This requirement is needed to ensure that cryopump thermosiphon cooling[2] is not impaired by any two-phase flow on entering and also to provide a higher pressure head than normal at the operating temperature (3.8 K) for delivery through the long transfer lines (100 m).

LN_2 supply to the valve box is from a 5000 L storage tank with its own control and distribution system.

The valve box is shown in Fig. 6 and contains 35 cold valves and is penetrated by 18 transfer lines.

3.4.4 LHe Tank

The 5000 L LHe tank is fitted with two actively He cooled radiation shields. Both the inner vessel and the shields are individually wrapped with superinsulation. Each is wrapped with $\simeq$ 30 layers of aluminium foil separated by "Dexter" a fibre glass paper.

The tanks contents are monitored using a super-conducting level gauge. A heater for pressurisation is also included. The LHe tank may be seen in the foreground of Fig. 6.

3.4.5 Recovery System

He gas liberated from relief valves and also other vents, eg. cryopanels during regeneration, etc, pass to the He gas recovery balloons where it remains until pumped by a recovery compressor into a high pressure cylinder store.

3.4.5.1 Recovery Balloons

JET has six recovery balloons situated under the roof above the crane in the Cryogenic area of JET (see Fig. 1). The balloons have a total volume when inflated of $\simeq$ 200 m^3 and are each $\simeq$ 1.9 m in diameter and $\simeq$ 12 m long. They are fabricated in "Strongan" a PVC polyester with a He leak rate out of 1 L/m^2/day at 100 mbar. The balloons are protected from overpressure by a relief valve which operates at 20 mbar, although the manufacturer defines the safe working pressure as 60 mbar.

The balloons provide sufficient volume for the total He contents of the cryopanels and the refrigerator, but not the LHe tank. One balloon is dedicated for all normal routine venting from the plant and the other five are left in reserve for emergency use, eg. accidental regeneration of cryopanels. The dedicated balloon is automatically emptied by the recovery compressor when $\simeq$ 60% full. The balloons are connected together by a common manifold, but the dedicated balloon fills preferentially to the rest because the others each have a 1 t weight upon them, preventing them from inflating until their pressure is sufficient (5 mbar) to cause the weights to lift. The weights also cause the remaining five balloons to inflate together and uniformly along their entire length.

3.4.5.2 Recovery Compressor and High Pressure Store

The recovery compressor (C5U-214) is a 5 stage air-cooled oil lubricated reciprocating compressor. The machine is fitted with a 45 kW electric motor and has a throughput of 6 gs^{-1} with an output pressure of up to 240 bar. The water content of the He gas as it exits the compressor is reduced to 400 ppm(V) prior to passing to the HP storage cylinders. After each stage the compressor is fitted with gas coolers and water and oil separators complete with automatic drain valves. Filters are provided at the exit. The maximum oil content of the He gas on discharge is $\sim$ 0.01 ppm.

Discharge from the recovery compressor is to 2000 m^3 (NTP) of high pressure gas storage in the form of 4 cylinders, 60 cms in diameter and 11.5 m long.

3.4.5.3 Swing Drier

To reduce the water content of the He gas to a minimum prior to entry to the purifier a swing drier has been installed. The drier consists of two independant cartridges of molecular sieve a porous dehydrating agent each with a volume of $\simeq$ 2500 cm^3. The drier operates at a maximum pressure of 230 bar and each bed is automatically regenerated every 15 mins. The drier which can be seen in the bottom left-hand corner of Fig. 6 reduces the water content of the He gas when operating at 230 bar to $\lesssim$ 5 ppm(V).

3.4.6 Control Systems

For controlling the refrigerator a programmable controller (PC) has been installed in the control panel shown in Fig. 6. Fig. 7 shows

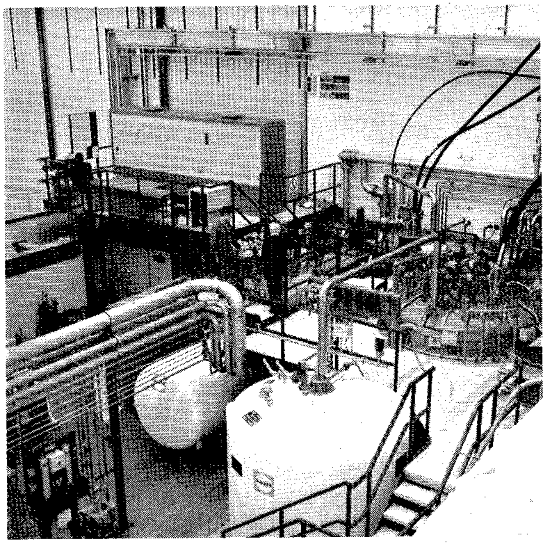

Fig. 6 JET Cryosystem

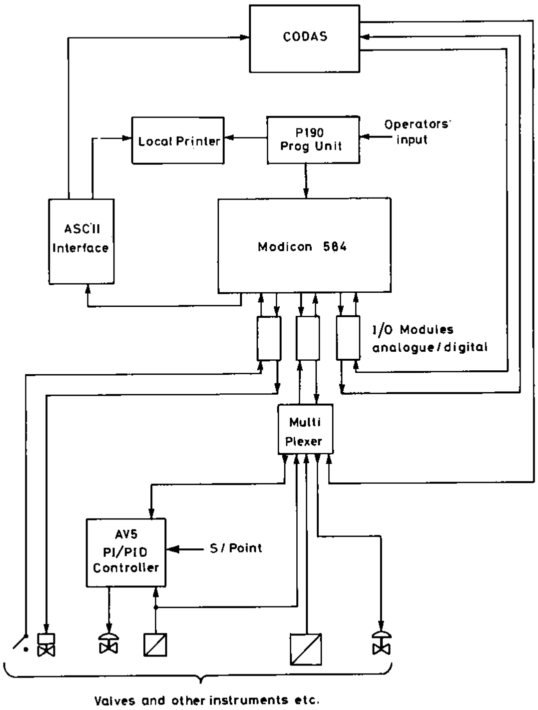

Fig. 7 Control System Schematic

a schematic layout of the control system. As can be seen the PC is accessed by the operator by means of a portable programming unit which incorporates a CRT and an integral tape loader for storing and loading programs. Also exploited are the full ASCII capabilities of the system permitting messages to be sent to the local printer and CODAS for use in mimic displays. The data for updating mimics is sent every 30s. Another fast communication route is provided for high priority signals eg, CODAS commands, alarms etc. This route allows messages to be sent to and from CODAS. Typically a CODAS command to cool down a cryopump is sent high priority, but confirmation of receiving and acceptance is sent via the ASCII.

The PC makes available to the user relay ladder logic for controlling all aspects of the plant. The plant also uses the PC analogue control capability and typically the turbines use these control features. In addition, other analogue controls are carried out by conventional hardwired PID control systems. In general these PID systems are used wherever fast reaction control is required, eg. compressor pressure control.

As previously highlighted[8], the use of a PC does not preclude the possibility of field hardware failures, eg. sensors, transmitters, etc, and dangerous actions may be initiated. The JET cryo system will offset these problems by using a parallel safety system which uses vital independent signals from the plant and overides actions by shutting down and isolating parts of the cryosystem.

3.5 LHe Plant Performance

LHe refrigerator performance testing was successfully completed in two stages. The first stage was to operate the plant and measure the power produced in the LHe separation pot in the cold box. These measurements were not part of the specification, but gave an opportunity for the Contractor to demonstrate the plants performance at 4.6/4.8 K. Some 580 W at 4.6 K was produced in the separation pot and this was regarded as satisfactory. These first stage tests were complete by June 1984.

The second stage tests were to prove the values specified in Table 1. These tests started in October 1984 and it was clear that there were problems in realising the full power in the calorimeter. This was because the cold ejector although able to achieve lower pressures than specified in the LHe sub-cooler, was unable to cope with the required throughput. A replacement with a modified profile was fitted and some weeks later a series of tests started which proved successful.

The results of this work which continued until March 1985 are shown in the Table 2. When compared with that specified in Table 1, it is seen most results are in excess of that specified. Some test results shown in Table 2 are identical to those specified in Table 1, ie, Ref. cases 1 and 5. This is because the test was terminated as soon as the specified power had been realised. Similarly in some tests. ie, Ref. cases 2 and 4, there was no attempt to measure the output in conjunction with the sensible heat.A major problem for the liquefaction cases was the purification rate which is limited to $\simeq 4$ gs^{-1}. The 200 m^3 (NTP) buffer tank is soon emptied of its contents causing the liquifaction tests to be terminated and then restarted after purification runs allowed the buffer tank to be refilled.

The two purifiers are run automatically either together or individually, and each regenerates itself when required to do so. The flow rates for each are 2 and 1.8 gs^{-1} and when both are running, some 40 W of refrigeration are used. It is not yet possible to relate this loss to the level of impurities in the He gas coming from the recovery system.

Operations with the refrigerator and the recovery systems are all conducted fully automatically.

Over 3000 hours has been completed by the refrigerator compressor and similar operational hours have been achieved with the cold box and its associated components, eg, turbines.

The LHe tank after cool down and filling and coming into thermal equilibrium showed a loss rate of 0.6 - 0.8% of volume/day. However some 3 to 4 weeks was required after filling for the tank to achieve thermal equilibrium.

4. LN_2 STORAGE SYSTEM

A LN_2 storage system with a capacity of 5000 L, capable of supplying up to 1500 L/hour of LN_2 and 400 m^3/hour of dry pure N_2 gas has been installed and has been in constant operation since the Summer 1983. The plant is equipped with both pressuring and gas producing vapourisers and a 5 kW auxiliary heater for use in cold weather. The plant is controlled by a PC which communicates with and sends data to CODAS for use in mimic displays. The plant is supplied with LN_2 by

		AT CALORIMETER		
REF.	LN_2 PRE-COOLING	REF. OUTPUT + SENS. HEAT (watts)	LHe CONDITIONS	
			P (bar)	T (K)
1	No	300 + 30	0.7	3.87
2	No	270	0.54	3.63
3	Yes	330 + 30	0.53	3.62
4	No	480	1.15	4.38
5	Yes	600 + 30	1.10	4.32
LIQ.		LIQ. RATE (Lh^{-1})		
1	No	130	1.3	4.53
2	Yes	157	1.54	4.6

Table 2 : Measured Output

road tankers whenever required as demanded on a regular basis.

5. REFRIGERATOR/CRYOPUMP INTEGRATED TESTS

Integrated commissioning tests have been restrained due to operational priorities of the Torus. These priorities have meant that the first cryopump must remain cold and filled for as long a period as possible. Only limited attempts at testing cryopump regeneration and warm up procedures have been carried out.

However automatic cool down and fill procedures are now fully developed and after initiation at the local control panel, the operator can leave the plant unattended and know that the cryopumps radiation shield and cryopanel will cool down and fill automatically.

In the event of a failure, the PC puts the cryosupply into a safe condition and allows the cryopump to vent to the recovery balloons. After failures, once the refrigerator has been automatically re-established, the operator may restart the cryopumps cool down. The PC determines the cryopump status, eg, temperature, levels and pressures and takes whatever action is required.

All current cryosupply actions have so far been initiated through the local control panel, but software will shortly be implemented permitting the cryopump to be cooled down, regenerated and warmed up from CODAS, ie, remotely.

ACKNOWLEDGEMENTS

The Authors express their thanks to all those working for Sulzer Bros. Ltd in Aldershot, UK and Winterthur, Switzerland, who have made contributions to this work and brought it to a successful conclusion. In particular, we would like to especially mention H. Quack K Kurtcuoglu, H Erlach and A Hostettler at Winterthur and also A Steel, K Pym, H Herzog and P Clarke at Aldershot.

REFERENCES

1 G Duesing, "JET Neutral Beam Injection Construction and Component Tests", Proc. 13th Symp. on Fusion Technology, Varese (1984) 59

2 W Obert, G. Duesing, E Küssel, P Kupchus, C Mayaux, P-H. Rebut, and H. Santos, "The JET Cryopump System and its Cryolines for Neutral Injection", Proc. 13th Symp. on Fusion Technology, Varese (1984) 311

3. F. Bombi "Architecture of the Control and Data Acquisition System of the JET Experiment", Proc. 10th Symp. on Fusion Engineering, Philadelphia (1983) 1362

4. A. E Senn, R. L. Roberts, "A Fully Auto-Controlled He Refrigerator System for Daresbury SRS Superconducting Wiggler Magnet System", Proc. 8th Int. Cryogenic Engineering Conference, Genoa (1980)348

5. W. Obert, R. L. Roberts, H. Santos, F. Spath, "LHe and LN_2 Cryosupply and Distribution System for the JET Neutral Injection Cryopumps", Proc. 9th Int. Cryogenics Engineering Conference, Kobe (1982) 247

6. H. R. Klay, "Reciprocating Compressors with Labyrinth Pistons for Helium", Cryogenics, Vol. 15, No 10, (Oct 1975) 569

7. V. Giger, H. Quack and A. E. Senn, "Combined Helium Refrigerator and Liquefier with Gas Bearing Turbines", Nuclex 75, Sulzer Technical Review

8. J. D. Branum, "Design Lessons from using Programmable Controllers in the MFTR-B Personnal Safety and Interlocks System", 10th Symp. on Fusion Engineering, Philadelphia (1983) 287