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STAR TPC gas system

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Abstract

The STAR TPC (Time Projection Chamber) Gas System supplies either of two mixtures, P10 (Ar 90% + CH_4 10%) or C_2H_6 50% + He 50%, to the STAR TPC (STAR Project, Brookhaven, USA) at a controlled pressure. This system regulates the pressure and composition of the gas while monitoring gas temperature, O_2 and H_2O. A computer data acquisition system collects and logs the gas system parameters, controls the purification of the recirculating mixture. A separate alarm and interlock system prevents the TPC from operating under unsafe conditions.

1. Description of STAR TPC gas system

The primary purpose of the STAR TPC [1] Gas System (Fig. 1) is to provide either of two pure gas mixtures, P10 or He + 50% C_2H_6, to the TPC at the correct temperature and pressure. Performance of the system is shown in Table 1.

A secondary function of the system is to cool the outer field cage resistor strings located in two channels at the top of the drift volume. The system operates nominally as a closed circuit gas system with the majority of gas recirculating through the TPC and delivery system. During normal operation a small amount of fresh mixture is added and an equivalent quantity (including TPC leakage) of the existing mixture is vented. The gas system can be operated in an open system configuration for purging.

The gas circulation rate is 36,000 l/h which, given the 50,000 l volume of the TPC, is one volume change every 1.4 h. The gas system contains two Rietschel's compressors, one active and one spare, each capable of 60,000 l/h at 100 mbar gauge. The 100 mbar output pressure from the compressor is reduced to 30 mbar by the first pressure regulator (PCV-1) and then to 2.4 mbar by the second one (PCV-4) upstream of the TPC. A water-cooled heat exchanger downstream of the compressors is used to remove the compression heat. The return gas manifold is maintained at 0.5–1.6 mbar above atmospheric pressure by a differential Dwyer's pressure transmitter (PT-6) and electropneumatic microprocessor (PID) controller that operates a bypass valve. The bypass shunts flow from the compressor discharge line directly back to the compressor's

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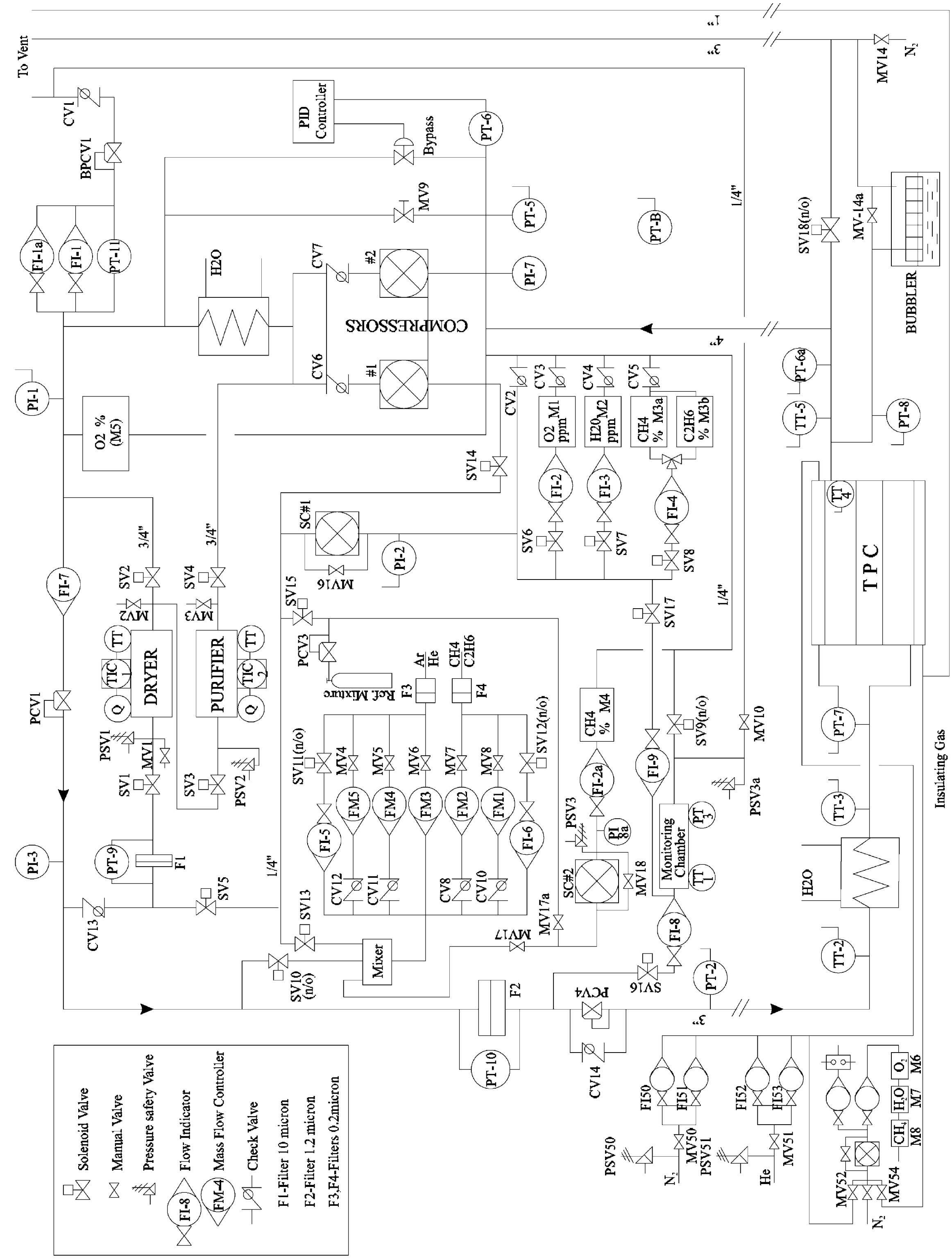

Fig. 1. STAR TPC gas system.

intake. A second bypass valve (MV-9) is manually adjusted to enable the automatic control loop to be used within its optimum range.

The purity and composition of the TPC mixture is monitored using O_2, CH_4 (C_2H_6) and H_2O analyzers. An additional CH_4 analyzer is installed to constantly measure the CH_4 content of the fresh mixture. A fraction of the recirculating mixture can be passed through a dryer and purifier to remove H_2O and contaminants as needed. Fresh gas is provided by the Gas Storage/Supply System.

A computer driven data acquisition/control system (Fig. 2) monitors all of the process variables. The computer system flags quantities that fall outside of predefined limits and initiates corrective action. However, where the safety of equipment or personnel are concerned, a relay-based, hard-wired interlock system connected to a redundant set of sensors controls the action of all key valves. The relay-based controls will bring the gas system to a safe state in the event the computer-based controls fail.

It is imperative, for the safety of the TPC, that the TPC pressure accurately tracks ambient pressure. A rapid change in atmospheric pressure is typical preceding storms and hurricanes, not uncommon in the Long Island area. To assure that the TPC follows a fast rise in ambient pressure, a relatively large flow of inert gas will be admitted into the vessel if normal pressure controls fail to keep up with falling external pressure. The vent lines and associated valves are sized to allow for rapid venting of the TPC gas to prevent a high internal pressure should the external ambient pressure fall faster than the closed system controls can accommodate. A large valve (SV-18) is opened if rapid venting is required and a bubbler connected to the TPC exhaust manifold will vent in the event that all other measures fail. The SV-18 valve is a "normally open" solenoid valve, so it

Table 1
Gas system parameters

TPC Volume	50,000 l
Mixture	(10 ± 0.1%) CH_4 in Ar, (50 ± 0.1%) C_2H_6 in He
Compressor pressure	90–120 mbar
Supply pressure	2.2–2.4 mbar
Return pressure	0.5–1.6 mbar
Internal TPC pressure	2.0 ± 0.03 mbar
Recirculation flow	36,000 l/h
Purge flow	12,000 l/h
Make-up gas flow	3.0–33 l/h
Oxygen content	<25 ppm
Water content	<20 ppm

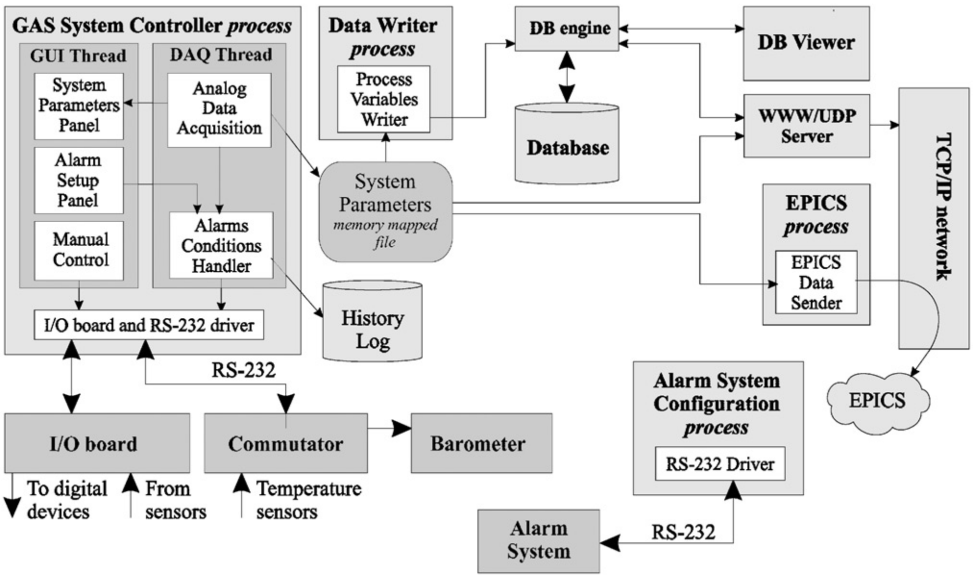

Fig. 2. DAQ and control diagram.

opens automatically when there is a power failure. A restrictive orifice has been placed upstream of the high-pressure regulators to assure that the TPC and vent piping is not overwhelmed by a high intake flow.

1.1. Pressure control

There are two sources of pressure in the gas system. The first is the compressor located at the exit of the TPC. The second is the flow of fresh gas through the mixing manifold. Normally the pressure within the TPC is controlled by maintaining a constant pressure downstream of the TPC by regulating the amount of gas shunted from the compressor output to intake.

As mentioned above, the output from the compressor is 60, 000 l/h at 100 mbar. The back pressure regulator (BPCV-1) in the outlet line maintains the 100 mbar pressure independent of compressor output and provides an exhaust to make up for the influx of fresh gas. Two pressure levels of 30 mbar and 2.4 mbar are controlled by the pressure regulators PCV-1 and PCV-4 upstream of the TPC. The TPC exhaust pressure, measured at the return gas manifold may be maintained in the range of 0.5–1.6 mbar by a Tescom electropneumatic microprocessor PID controller (ER2000). A Dwyer 0–2.5 mbar differential pressure transmitter (PT-6) produces a 4–20 mA output that the PID controller compares to a set point value. If the transmitter signal is different from the set point, the controller sends a pneumatic output signal to the bypass control valve. The bypass shunts flow from the compressor discharge line directly back to the compressor intake. Opening the bypass valve causes the TPC's exhaust pressure to rise and closing it makes the pressure fall. A second bypass valve (MV-9), manually adjusted during the initial system set-up, enables this automatic control loop to be used within its optimum range. Using PT-6a pressure transmitter, setting on the TPC instead of PT-6 permits to have more high TPC pressure stability.

There are additional levels of control in the event the primary pressure control loop fails or is insufficient to keep up with external pressure changes. When the internal TPC pressure, as measured by PT-5 and PI-7, is more than 2.0 mbar above ambient, the gas control system will close the solenoid valves SV-10, SV-20 and SV-21 in the gas supply lines and open the vent valve SV-18 allowing the TPC to vent directly to the atmosphere. If the pressure exceeds 3.0 mbar, the excess TPC mixture will vent to the atmosphere through the bubbler as well. This system of backups protects the TPC from over pressure due to mass flowmeter malfunction, rapidly dropping atmospheric pressure and a failure of the back-pressure regulator.

The TPC is also protected from under pressure. If there is a rapid rise in atmospheric pressure or, effectively, a fast drop in the TPC's internal pressure, the dual set point Dwyer differential pressure transmitter (PT-5) in the return manifold will trip as the pressure falls below 0.5 mbar, causing an audible and visual alarm. If the pressure at PT-5 falls further, to 0.3 mbar, a second set point trips and the computer control system will stop the compressor, shut-off the flow of flammable gas closing SV-21, 21a (Fig. 3) and pass inert gas through the CH_4 (C_2H_6) mass flowmeters by opening valves SV-22, SV-12, SV11 and maintain SV-10 in the open position to supply an additional 300 l/min of inert gas. This system can keep up with a rate of increase of atmospheric pressure of up to 6 mbar/min. An added level of protection against TPC under pressure is provided by another pressure-indicating switch (PI-7) with dual set points installed in the return manifold. This switch is not connected to the computer control system, but, instead, is hardwired to perform the same functions as the computer control system in the event of falling TPC pressure.

To protect TPC cylindrical case from the damage in the case of the overpressure inside the TPC insulation gap, PT7 measures differential pressure. If this pressure is less 0.0 mbar, SV23 will be closed by the control system.

The TPC is also protected from pressure extremes in case of power failure. A power failure will cause solenoid valves, SV-10, 11, 12, 19, 20 and 22 to open or remain open and will cause SV-21, 21a to close, causing 60 l/min of inert gas to flow through the TPC. This flow rate is adequate

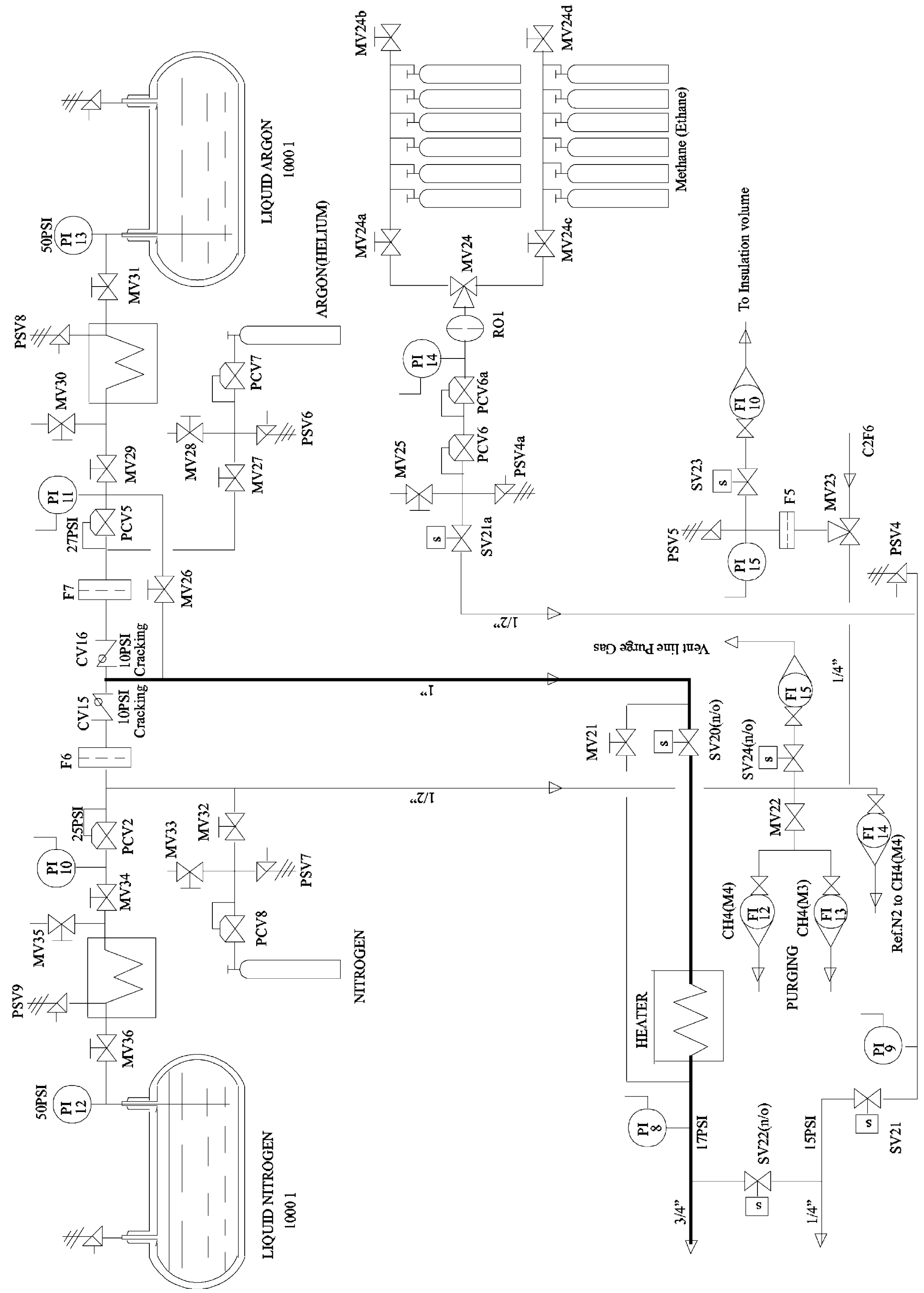

Fig. 3. STAR TPC gas storage/supply system.

to assure that fluctuations in the atmospheric pressure will not result in an excessive external pressure in the field cage and the TPC gas will not be contaminated by air being drawn back in through the exhaust vent. In the event that the Ar (He) supply is exhausted before power is restored, N_2 will automatically flow into the system to assure an adequate purge of all flammable mixtures. This N_2 back up of the Ar (or He) is provided by a completely passive system, see Fig. 3, where the supply of N_2 is maintained at a lower pressure than the Ar (or He) supply. As the primary gas runs out and the pressure falls, the N_2 begins to flow when the pressure exceeds the sum of the primary gas pressure and the check valve-cracking pressure. The check valves (CV-15, CV-16) cracking and reseal pressures were selected in conjunction with the delivery pressure of the primary (Ar or He) gas and N_2 to assure that back flow of either gas does not occur.

1.2. Mixture control

The gas mixture is controlled with mass flow meters, which feed fresh gas into the circulation loop between pressure regulators PCV-1 and PCV-4. The fresh gas mixing ratio is controlled for two different flow ranges by using different sets of flow meters. To rapidly purge the TPC, mass flow meters FM-2 and FM-3 are used to deliver fresh gas mixture at up to 200 l/min. Mass flow meters FM-1, FM-2, FM-3 and FM-4 are used for long term stable delivery at a reduced flow rate of 3.0–33 l/min for Ar–CH_4 or up to 50 l/min for the He–C_2H_6 mixture. The flow meters are operated as master-slave with FM-1 slaved to FM-4 and FM-2 slaved to FM-3. The masters are normally remotely controlled by computer but may be controlled locally if necessary.

1.3. Temperature measurement, drift and gas gain monitoring

Four temperature transmitters (TT-2, TT-3, TT-4 and TT-5) are used to measure the mixture temperature within the TPC. A fifth temperature transmitter, TT-1, measures the mixture temperature within the monitoring chamber. The temperature control of the TPC is a function of the cooling system and is independent of the gas system. The measured temperatures in the TPC are logged in a database.

Drift and Gas Gain measurements are provided by a separate, specially constructed chamber built and tested by Purdue University, for use in this application. Output from this chamber is read and evaluated by a separate data acquisition unit and archived for future reference.

1.4. Mixture sampling

The gas system is equipped with O_2, H_2O and CH_4 (or C_2H_6) monitors plumbed such that each section of the gas system can be selected separately for evaluation. Since some sample points are at low pressure, a small membrane compressor is used to maintain gas flow through the analyzers.

In the interest of safety, a second O_2 monitor upstream of the 30 mbar pressure regulator (PCV-1) provides a continuous monitor of the recirculating gas mixture. If the O_2 content exceeds the 0.1% set point, the flow of flammable gas will be shut off and inert gas will flow in its place. As an added precaution, during P10 running, a dedicated gas monitor at the output of the mixing manifold continuously measures the CH_4 content of the incoming mixture. In the event that the CH_4 content exceeds 11%, the monitor will trip and shut off the flow of CH_4 to the system. All analyzers are read and archived with the computer-based Data Acquisition System.

1.5. Purification

O_2 and H_2O contamination is controlled with a dryer and purifier which withdraw a portion, about 40–45 l/min, of the flow upstream of the 30 mbar regulator and deliver the conditioned mixture to the recirculating flow upstream of the 2.4 mbar regulator. This loop is controlled by the computer control system and used only as needed to maintain low O_2 and H_2O levels.

The dryer is made from a stainless steel tube containing 10 lbs (4.5 kg) of molecular sieve (Zeolite 13X) adsorbent. This amount permits the removal of about 3 lbs (1.4 kg) of water vapor to a level of 2–5 ppm at room temperature. Filters are installed upstream and downstream of the adsorbent to prevent Zeolite dust contamination of the rest of the system. The absorbent column is equipped with a heater coil and insulating jacket for regenerating the absorbent. The dryer is regenerated by heating to 350–400°C while purging with Ar or He gas. The purge gas enters at the top of the dryer and exits at the bottom, carrying with it the water vapor. A temperature transmitter fixed on the outside of the tube and connected to a Dwyer controller (TIC-1) regulates the coil temperature. Solenoid valves installed at the intake and outlet of the dryer isolate the unit from the main circuit when it's not in use. A H_2O analyzer is used to measure the quantity of H_2O in the circuit before and after the dryer to determine when the adsorbent is saturated.

The purifier is similar in mechanical construction to the dryer, but it is filled with a catalyzer that permits the oxidization of CH_4 (C_2H_6) by O_2, present as an impurity, to form alcohol. The dryer subsequently removes the alcohol. The catalyzed oxidization process takes place at 210–220°C. This purifier does not require regeneration but must work in conjunction with the dryer. The dryer can be used separately as required. Initial tests with the TPC show that the catalyzer must be used continuously to maintain an acceptable 19–22 ppm O_2 level with a gas refresh rate of 15 l/min. The equilibrium O_2 level is 60 ppm without the catalyzer.

Two safety valves, PSV-1 and PSV-2, prevent accidental over pressure of the dryer and purifier during purging. A 10-μm filter is installed after the purifier/dryer prevents dust from passing into the main mixture supply line. Dust buildup in the filter is monitored with a Dwyer's differential pressure transmitter (PT-9).

2. TPC gas system control and data acquisition

2.1. Alarm and interlock system

The alarm/interlock system provides warnings, prevents fault conditions and takes corrective action automatically if specified parameter limits are exceeded. These actions include stopping the gas system compressor and shutting off ignition sources in the TPC and turning off flammable gas at the source. The alarm/interlock system design is based on solid-state relays. This system operates in parallel with the computer control system and in many cases provides redundant control. A block scheme of the Alarm system is shown in Fig. 4. A list of fault conditions and the system's response is contained in Table 2.

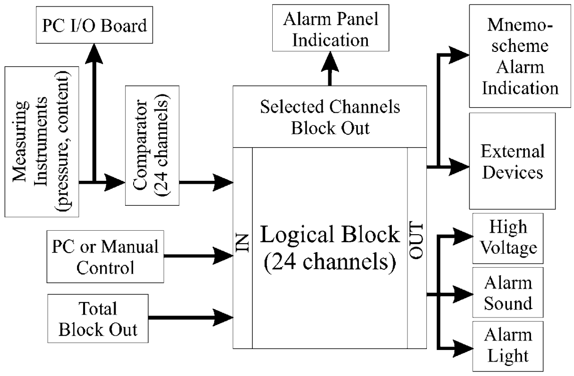

Fig. 4. Block diagram of alarm/interlock subsystem.

2.2. Data acquisition and control

The gas system is controlled by a PC-based DAQ subsystem (Fig. 2) that consists of three separate devices. The first one is a barometer for measuring the atmospheric pressure [3]. The second is a commutator for temperature measurements at multiple points. Each of these two devices is based on an Intel 8031 microcontroller and is connected to the main computer with a standard RS-232 interface. The third device is a custom I/O board, which was developed for the Gas System. This I/O board has 32 analog input channels, 8 analog output channels, 32 digital output channels and, optionally, 8 digital input channels. There are 32 sensors connected to this board: 10 pressure transmitters, 6 pressure indicators, 5 flowmeters, 2 flow indicators and 9 content analyzers. The board also controls 22 solenoid valves, 3 compressors, 2 alarm indicators and an interlock for ignition sources in the TPC. Analog output channels are used to control flowmeters. Each analog input

Table 2
List of fault conditions

Condition	Description	Action
PT1 < 50 mbar	Output of compressor—input of PCV1	Alarm
PT7 < 0.0 mbar	TPC Volume-TPC Gap	Alarm
PT5 < 0.3 mbar	Output of TPC—input of compressor	Alarm, stop compressor & HV, Purge
PT1 > 2.5 mbar	Output of TPC—input of compressor	Alarm, stop HV, Fresh Gas, Open SV18 (Vent)
CH_4 < 9.0%	M3a Methane return gas	Alarm, Stop HV
CH_4 > 11.0%	M3a Methane return gas	Alarm, Stop HV & Methane In
C_2H_6 < 49.6%	M3b Ethane return gas	Alarm, Stop HV
C_2H_6 > 50.4%	M3b Ethane return gas	Alarm, Stop HV & Ethane In
O_2 > 80 ppm	M1 Oxygen content of return gas	Alarm, Stop HV & Compressor
H_2O > 80 ppm	M2 Water content of return gas	Alarm, Stop HV & Compressor
PT9 > 80 mbar	Pressure across dryer filter	Alarm
PT10 > 12 mbar	Pressure across main filter	Alarm
PS1 < 0.5 mbar	Small compressor	Alarm
CH_4 > 11.0%	M4 Fresh methane	Alarm
PI8 < 0.5 bar	Argon supply Rack 3	Alarm
PI9 < 0.5 bar	Methane supply Rack 3	Alarm
PI13 < 0.5 bar	Argon supply on pad	Alarm
PI14 < 0.5 bar	Methane supply on pad	Alarm
PI15 < 0.5 bar	Nitrogen supply Rack 3	Alarm
PT2 > 2.5 mbar	TPC Inlet pressure	Alarm
O_2 > 0.1%	M5 Oxygen meter	Alarm

channel has overvoltage protection and uses signal averaging (0.2 mV accuracy in 0.7 s) to reduce the noise effect in the cables.

The software for microcontroller devices was written in 8051 assembly code. The barometer software reads out the pressure sensor, shows pressure in one of the three allowed units (mbar, mmHg and kPa) on a LCD indicator and responds to the main computer requests for pressure values. The commutator software provides reading of up to 16 temperature sensors connected in a four-wire scheme. The commutator code also handles four RS-232 ports, one master port for main computer and three slave ports for other devices. One of the slave ports is connected to the barometer. The software accepts requests from the main computer to establish a “transparent” connection to one of the slave ports or to send all the temperature values.

The main computer software (Fig. 2) has been developed with Borland Delphi 5 [2] for Windows 2000. It provides reliable data acquisition, alarm conditions handling and manual control of the Gas System. The software also logs all events and process variables, transfers data to EPICS [4] and publishes all the process variables on the World Wide Web. All these tasks are distributed between multiple processes that communicate making use of special operating system kernel objects.

Gas System Controller is the heart of the DAQ software. In order to make DAQ more reliable it has been divided into two threads: one for the Graphical User Interface (GUI) and one for the data acquisition. The GUI thread is composed of three windows: manual control window, system parameters window that shows process variables, and configuration window for all preferences and settings. The DAQ thread acquires all the process variables, writes them into shared memory and checks alarm conditions. Every alarm settings contains alarm threshold, alarm message and control template, which indicates alarm set and release action for every controlled device, e.g. valve or compressor. This allows user to have a very flexible configuration of system behavior.

The Data Writer reads current process variables acquired by the main process and writes them to the MS Access database. Using a separate process for this critical operation improves overall software stability and decreases response time for gas system events. The EPICS process is very similar. It just sends all process variables to EPICS software through a TCP/IP network [5]. There are two ways for the data—it can be either saved to a remote disk on a Unix machine or sent directly to the EPICS database making use EZCA library for Win32 platform.

All data from the TPC gas system are kept in MS Access database, giving one a possibility to use native MS Access tools for converting and analyzing these data. Besides, this simplifies dramatically access to the certain data in a huge database (for example, 3.5 month database has approximately 200 thousands of records). Sometimes it is useful to get fast results and charts from the database during the gas system operation. A special tool for working with the database has been developed. This program (DB Viewer) provides visualization of the data from any system sensor at any given date for one of three periods (day, week or month). It also allows user to convert data from the database to tab-delimited text file for external analysis. Web server for the gas system was built with Delphi and provides remote access to the database and current system parameters. It also works as a server for the special client using XDR-based UDP protocol.

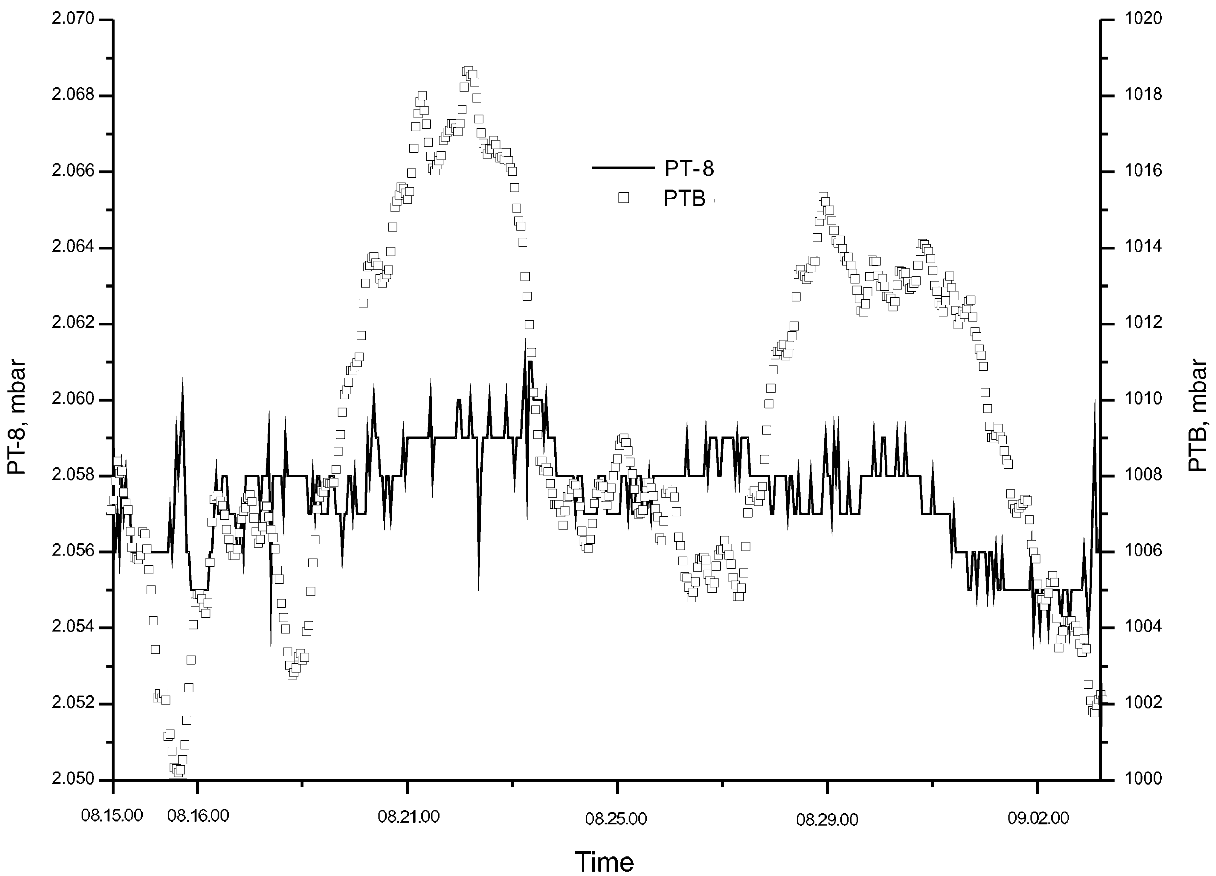

Fig. 5. TPC Pressure stability test. Rectangles correspond to barometric pressure (PTB), TPC internal pressure (PT-8) is shown as a solid line.

3. TPC gas system experimental pressure stability

The STAR TPC Gas System was tested at Lawrence Berkeley National Laboratory and Brookhaven National Laboratory.

The results of the pressure stability test with the full TPC volume are shown in Fig. 5, along with the barometric pressure. In this test the PT-6a pressure transmitter signal was used as the feedback signal by PID Controller. The pressure was measured with PT-8 pressure transmitter setting on the TPC. Although the barometric pressure varied in the range of ± 9.3 mbar during the testing period, the inside TPC pressure was stable at 2.057 mbar within the range of ± 0.0035 mbar. This shows that the TPC Gas System can support a constant pressure difference between the inside pressure and the outside barometric pressure with a stability of ± 0.004 mbar.

Using the PT-6 pressure transmitter as the feedback PID Controller signal gives ± 0.03 mbar internal TPC pressure stability.

References

[1] H. Wieman, et al., STAR TPC at RHIC, IEEE Trans. Nucl. Sci. 44 (1997) 671.
[2] Borland Delphi Home Page http://www.borland.com/delphi.
[3] S. Kozlov, L. Kotchenda, P. Kravtsov, Digital Barometer for Slow Control Systems, Instrum. Exp. Tech. 3 (2000) 166.
[4] A.J. Kozubal, et al., Experimental Physics and Industrial Control System, ICALEPCS89 Proceedings, Vancouver, 1989, p. 288.
[5] J. Lin, et al., Hardware Controls for the STAR Experiment at RHIC, IEEE Trans. Nucl. Sci. 47 (2000) 210.