11.7 Cooling

11.7.1 Introduction

The cooling of silicon detector modules in LEP and other experiments has been achieved, in most cases, by exploiting the relatively high specific heat of water. It is clear, however, that two of the main drawbacks to the use of water for the SCT modules are its relatively high freezing point and low efficiency. If the silicon detectors are to be maintained at around -7°C, the addition of a freezing point depressant would be necessary to extend the operational range of water as a coolant, albeit at the cost of a slightly reduced specific heat. Binary-Ice® [11-72] has been chosen to offer a relatively simple system which provides high efficiency, relative to water, and near isothermal cooling.

The development of Binary-Ice cooling for the ATLAS SCT tracker has been divided into three, distinct phases. The present work has concentrated on a research and development stage, culminating in the proof of principle that Binary-Ice is a viable and sufficient solution to the problem of cooling the SCT [11-73]. This stage of the overall program set out to show that the proposed solution was capable of removing the heat dissipated within the tracker, and of being engineered into a full size system. It also needed to demonstrate that it could be developed into a cost effective and thermally efficient scheme, that posed no undue risk to either personnel or other equipment. It was also necessary to show that it could be built within the time available, be robust and require low maintenance.

The second stage will include all of the above points together with the requirement to design, purchase, control and operate a plant to cope with a large fraction of the final power of the SCT (around 20%). In conjunction, a smaller unit will be used to cool silicon modules within an ATLAS test beam at CERN to prove operation under realistic conditions. This second unit would be an existing prototype machine. It would be used with fully automated control and data logging software to permit “stand-alone” operation.

The final stage is for a system to be installed, commissioned, operated and maintained within the ATLAS experiment. The plant will be fully integrated into the ATLAS DCS, slow control and safety systems described in Section 13.5.2 and Section 16.3.1.

Binary-Ice cooling utilises the latent heat of fusion of water to provide a high capacity, fluidic coolant that displays essentially isothermal operation [11-74, 11-75, 11-76]. The coolant is an aqueous solution of a freezing point depressant which is chilled by a commercial refrigerator. As the temperature of the liquid reaches its freezing point, crystals of ice nucleate on the cooled surfaces of an ice generator and are removed by a motor driven scraper running inside this vessel. A suspension of microscopic ice crystals is formed and the resulting slurry is passed through the cooling tubes of the detector. As the heat generated by the detectors and front-end electronics is removed, the ice concentration decreases with only a small rise in fluid temperature. At 10% ice concentration, the effective energy density of the fluid is about 8.5 times that of pure water. It has been observed that the presence of ice crystals causes the heat transfer coefficient to be typically a factor of 2 higher than that of water [11-77]. The typical size of such crystals is between 10 µm and 500 µm, depending on the operating temperature, the type of antifreeze used and the method of production. Further details on the production and transport of Binary-Ice can be found elsewhere [11-78]. ATLAS benefits from the fact that Binary-Ice has already been developed for large-scale industrial applications and a relatively small capacity plant compared with current industrial units is being used. The problems specific to ATLAS are mainly related to the low-mass small diameter pipes and radiation hardness.

The cooling of the SCT will be covered by six different systems. These are separated by their specific functions, as detailed below.

- A series of Binary Ice units to cool the modules and power cables within the tracker volume. This is clearly the primary role of the cooling system although the coolant from these plants will also need to cope with heat flowing into the cooling pipes from the surrounding atmosphere and also from active insulation used to maintain the outer, insulated surface of the pipes at the same temperature as the surrounding gas or air.
- A chilled water system will be required for the Binary-Ice compressors.
- To ensure that all parts of the tracking detector modules and their associated support structures are free from condensation and frost and also to eliminate the possibility of reverse annealing occurring due to operation or storage at elevated temperatures, it is essential that the atmosphere inside the insulation jacket of the tracker be maintained at a temperature close to the mean silicon detector operating value. To achieve this a supply of chilled, inert, dry gas is required. The cooling will be provided by the Binary-Ice and the gas will ensure that a uniform environment is maintained.
- Active insulation will be required within the tracker volume to maintain thermal neutrality with the beampipe, the TRT and the calorimeter. Since the gas within the tracker will be maintained at the mean silicon temperature and not at the module cooling pipe temperature, it will be necessary to use an additional Binary-Ice plant running at a somewhat higher temperature than the main plant. Since this increased temperature requires a different water / antifreeze mixture, an additional Binary-Ice system will be needed. It is planned that this plant will either made be available from the test systems used prior to installation, or possibly, built into the final Binary-Ice plant as a separate ice generator and pump being cooled and controlled by the same compressor and Programmable Logic Controller (PLC).
- A cooling plant will be needed during the removal of the irradiated SCT components. At the time this is done, all power supplies will be switched off. The cooling unit will therefore only need to cope with the heat transfer through the thermal, protective jacket. The capacity of this unit will be in the 3-5 kW range. It is envisaged that this would be a chilled gas circulator since an inert, dry atmosphere must also be maintained. As each section of the SCT tracker will be withdrawn on a purpose-built cradle, the cooling plant would be sited on this cradle and would connect to the openings in the thermal jacket. Three such systems would be required for the barrel and end cap sections of the SCT. If the pixel detector sub-systems were to be withdrawn separately, this would require further such units.

Finally, additional plant will be needed for testing the irradiated SCT components in a surface building after removal from the experimental hall. The capacity of this unit will be in the 10 - 20 kW range. It is envisaged that this would be a Binary-Ice plant previously used for prototyping and pre-installation testing. This system would be attached to the same cooling connections as the pre-installed pipes within ATLAS. The environmental control within the tracker sub-section's thermal jacket would be provided by the same gas cooler as used during the removal of the tracker element above.

The majority of the following sections will cover the requirements of the Binary-Ice plant and cooling system associated with it since the other systems use relatively standard commercial units.

11.7.2 Binary-Ice Prototype Results

A study of the fluid parameters of Binary-Ice and the operation modes of a Binary-Ice cooling plant was started 3 years ago with the purchase of a 1.7 kW, single phase machine. Initially, this system was operated with a coolant mixture of water plus 8% of 1,2-propane diol (propylene glycol). Although this gave satisfactory results at -5°C, it was clear that the relatively high viscosity would impose severe restrictions on the design of the cooling pipes within the tracker. The antifreeze was first replaced with ethanol and later with methanol. In each case a substantial reduction in viscosity was observed. The mixture now in use is 24% methanol and 76% water which gives rise to a viscosity of typically 12,000 µPa s for 7% ice at -15°C.

A test facility has been constructed which consists of the 1.7 kW machine and its associated compressor which is, in turn, cooled by a 3 kW water chiller. The output of the machine can be supplied to two test stations. The first is an insulated enclosure of 1m x 1m x 1.8m volume which is supplied with chilled air that has been over-cooled to reduce the relative humidity, at the chamber temperature, to around 50%. This cabinet has been used for testing thermal prototype modules for both the barrel and forward sections of the SCT. The second chamber, consists of a commercial freezer supplied with a dry nitrogen atmosphere. This system is used for tests of leakless cooling operation.

The tests performed have provided information on cooling pipe diameters, flow rates and pressure drops which have been used to define the cooling specification shown in Table 11-31. They have also provided experience in the control of binary ice systems.

The principle of operation of this system is to control the ice concentration within the circulating fluid by means of internal balancing heaters. These heaters can remove about 75% of the output capacity of the machine, the remainder is consumed by the ice concentration monitoring, the modules under test and the heat loss through insulated pipework to the ambient environment. The ice concentration is measured by diverting a small fraction of the output through an insulated, 200 Watt heater. The flow through this heater is adjusted to ensure that all of the ice crystals in the fluid are melted. This is confirmed by measuring a temperature rise of several degrees across the heater. Knowledge of the flow rate, input electrical power and temperature difference allows an energy equation to be written from which the ice concentration can be computed. This value is fed to a proportional integral derivative software (PID) control programme as the “process variable” and is used to vary the output of the power supplies feeding the balancing heaters. If the external load, from the modules under test, is varied, the ice concentration will vary which will cause a corresponding adjustment in the heater power supplies. The ice concentration will then return to the set point defined in the PID control. This is the same principle that will be used within the ATLAS experimental system, expect that the signal from the PID controller will control the compressors of the Binary-Ice machines rather than balancing heaters. This mode of operation will be more energy efficient.

One area of concern about any fluid cooling system is the effect of corrosion on the cooling pipes. Work is under way to define the final anti-corrosion inhibitor that will be used but this can only be specified once every material into which the fluid will come into contact has been defined. To test the severity of the problem a section of untreated, extruded aluminium tube with a wall thickness of 200 µm was left partially submerged in a Binary-Ice reservoir for a period of nine weeks. During this time, the inside and outside walls of the pipe were continually exposed to the Binary-Ice mixture and its associated vapour at temperatures ranging from +25°C to -19°C. The Binary-Ice mixture was of water and ethanol for the first 6 weeks of the test and subsequently water and methanol. Apart from some superficial surface oxidation no evidence of attack was seen.

Since Binary-Ice does not behave as a conventional, dilatant fluid (e.g. water) and its rheology is not well understood, it is essential to measure some of its properties directly. A knowledge of these properties will then enable the detailed design of a cooling system to be undertaken. The kinematic viscosity of Binary-Ice mixtures have been measured using a pressure drop method in a long section of 2.99 mm diameter pipe. In these tests, the viscosity was first measured for a methanol/water Binary-Ice mixture with a freezing point of -6.2°C. At the freezing point (0% ice) the value was 3400 μPa s, rising to 5800 μPa s for an ice concentration of 6.2%. When the freezing point was reduced to -11°C, the initial viscosity increased to 4600 μPa s, again rising to 9500 μPa s at about 6.5% ice. For a freezing point of -13.5°C, the 0% ice value was around 6000 μPa s, rising to 10900 μPa s at a mean ice concentration of 4.15% ice. It was noted that for both ethanol and methanol mixtures, the variation of viscosity as a function of ice concentration was almost linear. Figure 11-78 shows this variation for some methanol mixtures that have been measured. These measurements set a lower limit on the SCT cooling system pipe dimensions.

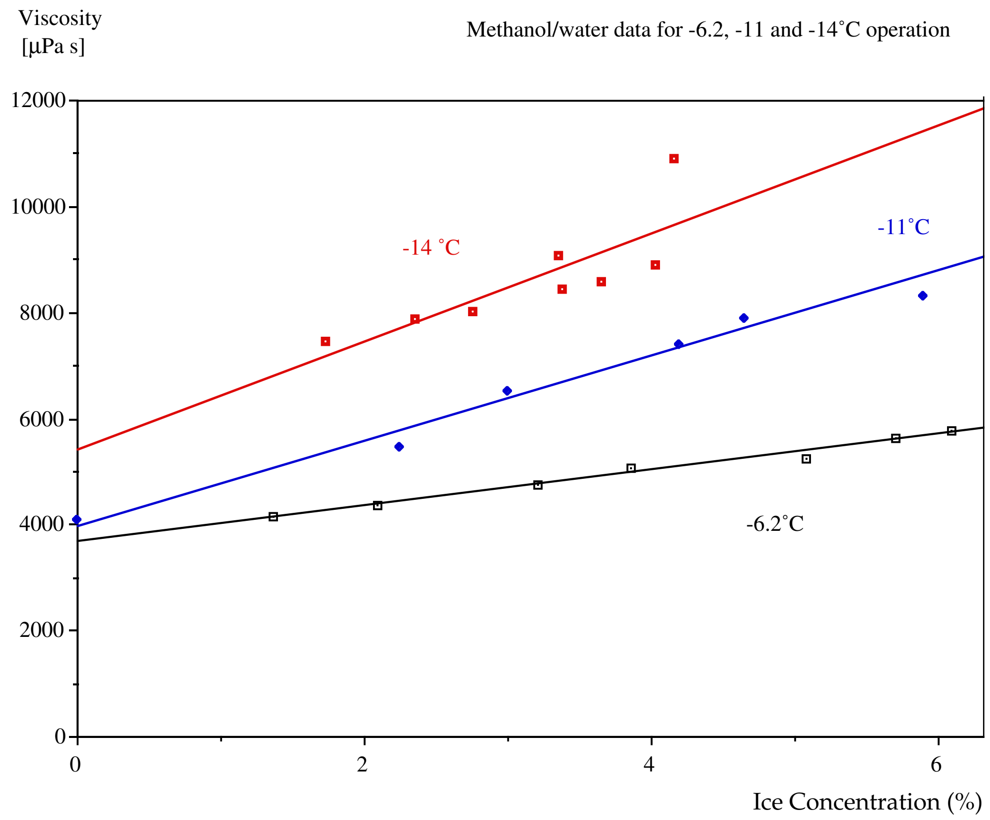

Figure 11-78 Viscosity as a Function of Ice Concentration.

In order that the effects of bends in cooling pipes could be assessed, several tubes have been fabricated with small internal diameter (1.8 mm) and containing a number of bends with a tight radius (≈ 3.5 mm). The pressure drop was measured as a function of ice concentration and compared against a straight tube of the same length (400 mm). Over the range of ice concentration used, from 0 - 5.5%, at an operating temperature of ≈ -14°C, the pressure drop was very similar for both tubes. It was concluded that the bend radii used in this design did not present a problem for ice flow.

11.7.3 Prototype Control System

The operation of any cooling system within a large experiment requires slow control circuitry, safety interlocks and data acquisition capability. If this system is to run for a minimum of ten years, it must also be able to operate for long periods, in automatic mode, with a minimum of human intervention. To develop these features, a control programme has been written using LabVIEW. At present this software is running on a Macintosh computer and instrument control is carried out over an IEEE bus. Typical measurement data are shown in Figure 11-79.

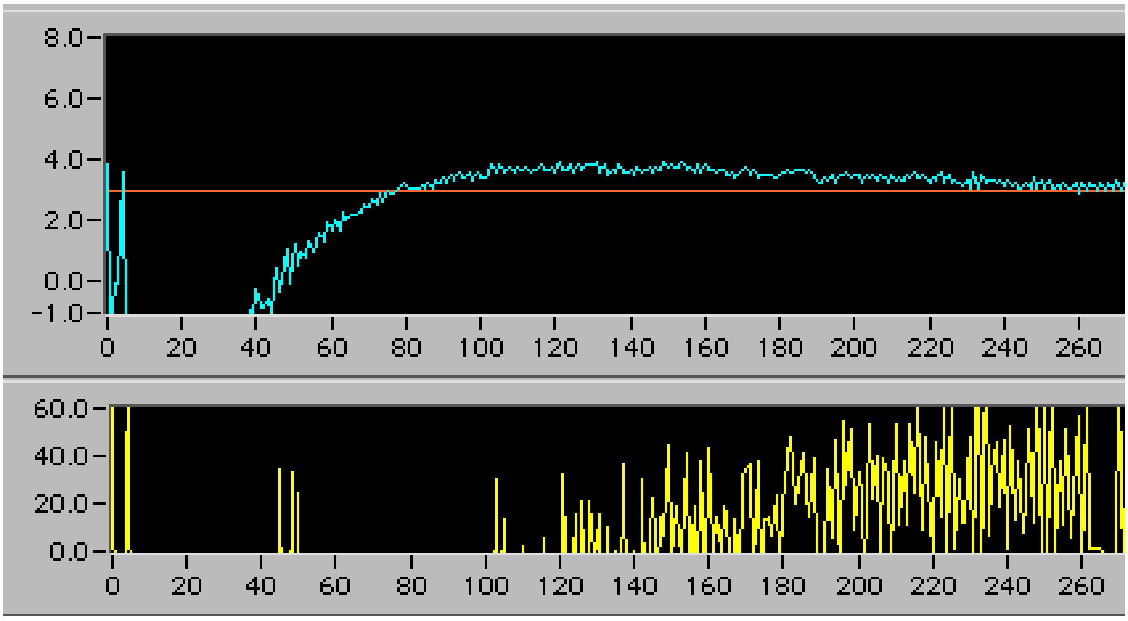

Figure 11-79 The upper plot shows the measured ice concentration as a function of time at the start of a data taking run. The lower trace shows the percentage output level of the computer controlled power supplies, being driven by the PID control software running within the LabVIEW package. The spikes at the start of the plots are due to miscalculations caused by the fact that it takes about 2 minutes to obtain the first flow rate measurements.

The data acquisition section of the programme controls the readout of up to 96 pressure, temperature and flow sensors. In the future, the data acquisition and control tasks will be split between 2 computers and a PLC. One computer will handle the machine interface with the Binary-Ice machine, the leakless cooling and the dehumidifier while the other will cope with a new, larger data acquisition system capable of reading out 400 channels. One of the computers will continue to run the PID control software however, this task will be transferred to the PLC at a later stage. The PLC will also control the machine start-up and shut-down procedures and the ice concentration measurements. In this way, the operation of the overall ATLAS control system will be simulated on a scaled down model. This will allow the development of the final PLC programme to start at an early stage. It is planned that the final PLCs will be supplied to the Binary-Ice machine manufacturers with the firmware already installed.

11.7.4 The final SCT System

The SCT cooling must cope with in excess of 100 kW of heat to be removed from a low ambient temperature environment. The system used must offer a minimum risk solution to the problem without imposing too large a penalty on the overall material budget. It must be capable of long periods of maintenance-free operation and must run inside the tracker volume in “leakless” [11-79] operation. The cooling plant must be capable of autonomous running during installation and set-up since there can be no guarantee that all aspects of the DCS (Detector Control System) and slow control bus architecture will be operational during these periods. As mentioned above, all sections of the cooling, including the water/antifreeze mixture itself, that enter the detector volume must be radiation hard. The hardness will be proved for all relevant combinations of materials. The coolant operating temperature must be variable to allow for further development in the design of the modules, their components and the thermal interfaces between modules and support structures. Similar arguments are made for the degree of flexibility in the cooling plants for the active insulation and the environmental gas systems.

The total heat load of the modules of the SCT and pixels will be about 53 kW. This figure will depend upon the final front end electronics specification and the acceptable power loss in the cables within the tracker volume. The figure is further inflated by the need to cool the inner wall of the thermal insulation. The heat loss to the pipes outside this thermal jacket will also add to the total figure. As all sub-detector systems should be thermally neutral, this may require active insulation, with heaters built on the outer skin in some critical areas. All of these might add a further 35 - 50 kW, leading to a total load of around 100 kW. A system capable of delivering 120 kW of cooling capacity at an operating temperature of -15 ˚C is therefore planned.

The specification for the main components and parameters of the Binary-Ice cooling are listed in Table 11-31 The fluid is based upon current research although a change could be made if a new mixture offering similar benefits allied to significantly lower viscosity became available. Mention has been made of a possible development along these lines [11-80], although details are currently covered by a commercial confidentiality agreement, to which ATLAS is not a party.

Temperature sensors will be platinum resistance devices with a nominal resistance of 1 kΩ. It is planned that these will be mounted on each end of a cooling pipe within the tracker and will provide a first check on the temperature profile of that pipe. These sensors will be read out by a separate DAQ system associated with the cooling plant. In this way, it will be possible to set-up and control the cooling system without the ATLAS control system running. This is an important consideration during installation of the detector. The pressure sensors will be differential devices which will connect between inlet and outlet pipes on the outside of the detector. This will substantially reduce the level of radiation hardness to which they need to be built and also reduce the material inside the sensitive volume of the tracker. The signals from these devices will be used to estimate the ice concentration within a specific pipe and to provide an additional check on the flow rate. Flow sensors may not be required on every pipe. Those that are used will be Pelton wheel (rotating vane) type and again will be mounted on the outlet pipes, on the outside of the ATLAS detector. Ice concentration measurement will be carried out by making a calorific estimate. This has proved to be a most reliable and accurate approach. The modularity and dimensions of pipes and the total power figures are current estimates which will be developed over the remainder of the design period.

The configuration of Binary Ice cooling system involves the use of 3 machines which would be located in the side cavern USA 15. These machines would form a primary circuit and supply the leakless cooling circuits on either side of the detector. The third machine would be on stand-by and would automatically intervene in the event of a malfunction of machine 1 or 2. The use of more machines has been considered as this would give more flexibility in operation with partial loads. This might be a desirable feature since the experiment is unlikely to start at the full luminosity and the problem of increased leakage current due to radiation damage of the silicon will not be a major issue in the first few years of operation. An alternative solution will be to use phase control of the compressors cooling the ice generators. This has been discussed with a potential machine supplier and appears a favoured solution.

The overall system can be considered as a number of work packages. The first of these comprises the "primary" side of the binary ice cooling system. This would include the refrigeration machines, pumps and the pipework up to and including the pressure defining tanks in the main cavern. This arrangement would allow for the future operation and maintenance of the primary circuit to be provided by CERN personnel.

CERN are presently considering the use Binary-Ice as a primary cold source for supplying heat exchangers around the LHC site and it may be conceivable to connect the Inner Detector exchangers to this circuit. The differing requirements of operating temperature would need to be addressed.

The question of whether to use active insulation or standard insulation on pipework outside the ATLAS detector has been considered. The current prototype systems use standard “Armaflex” insulation around the pipes containing binary ice. This appears sufficient to avoid any problems with condensation. Active insulation consists of an insulating material having a cold side and a hot side provided by binary ice tubes and electric heating tapes respectively. Inside the SCT, active insulation is proposed not just to prevent condensation but to keep the SCT and Pixel detectors thermally neutral with respect to the TRT detector and surrounding systems. Apart from thermal exchange considerations this would prevent possible problems between the respective control systems.

The total number of cooling loops is presently set at eight circuits for the silicon strip and pixels combined. Recently, the pixel design group have stated that they would prefer an independent leakless cooling system. This would comprise three sub-systems, one for the barrel and two for the forward regions. If this scheme is adopted, the number of sub-systems for the silicon strip detectors would remain at eight. In each cooling circuit there will be up to 70 small bore pipes connected to a common manifold. The question of how to guarantee the flow rate in each of the small bore pipes is under review. Automatic valves might give control problems due to cycling and there is only a small pressure differential available so control by fixed (balancing) impedances does not appear a satisfactory solution.

From the experience gained in prototype testing, it is clear that efforts must be made to ensure that any particulate contamination (small pieces of metal from pipes, for example) must be removed from the system. The question of how to filter the system without causing ice formation and blockages has been considered. The most promising technique has been to use vertically mounted traps (sumps) into which material is collected. These can be run in the initial stages of commissioning, before ice production starts, with mesh filters installed. After some period of circulation, the meshes are removed, the traps cleaned and ice production may commence. After that point, stray materials will still be collected in the traps due to gravitational separation.

Table 11-31 Summary of Binary Ice Parameters and Power Dissipation.

Item	**Specification**
Fluid	
Operating temp	-14°C input fluid temp.
Antifreeze	99.9% Methanol
Antifreeze conc.	24%
Corrosion inhibitor	Under test
Water purity	De-ionized water
Temperature control	
Temperature sensors	Pt1000 at pipe inlet & outlet
Differential pressure sensors	Piezo-resistive silicon transducers
Flow sensors	Pelton wheel / rotating vane
Ice concentration monitor	Calorific measurement
Cooling capacity	
Modularity	1 pipe per 1/4 barrel, 1 pipe per 1/2 wheel
Ice concentration	10% at machine 6% at cooling pipe inlet 1% at cooling pipe outlet
Flow rate @ 6%	4 cm^3s^{-1} for 12 modules
Flow speed (4 cc/s)	0.4 ms^{-1} for 12 modules
SCT barrel electronics power (upper limit)	12.3 kW
SCT barrel detector power (upper limit)	2.1 kW
SCT end-cap electronics power (upper limit)	11.5 kW
SCT madcap detector power (upper limit)	2.0 kW
SCT cable cooling (assume 10% loss)	2.8 kW inside cryostat
Pixel cooling	14 kW
Pixel cable cooling (assume 10% loss)	1.4 kW inside cryostat
Active Insulation	7 kW
Total cooling inside tracker volume	53.1 kW
Total cooling outside tracker volume	30 - 50 kW
Binary-Ice machines	
Cooling capacity	60 kW each
Number off	2 plus 1 spare on stand-by
Location	End of 'USA 15' cavern
Dummy loads	100% of on-line capacity

Table 11-31 Summary of Binary Ice Parameters and Power Dissipation.

Item	Specification
Control	Local with Fieldbus connection
Interlocks	To power supplies and gas cooling system
Data logging	Locally and via bus to DCS
Operation	
Power supplies	Uninterruptable 3 ph. supplies
Air conditioning	To cope with machine inefficiency and dummy loads
General running	Leakless within tracker
Reference pressures	
P tank - local support (rel. to header tanks)	150 mbar (typical)
P across local support (re. to header tank)	300 mbar (typical)
P local support- vacuum (re. to header tank)	100 mbar (typical)
Circulation. pump	Volumetric pump mounted below detector
Leak measurement	Vacuum pump duty cycle
Maximum allowable leak	To be defined
Commissioning	Stand-alone operation
Environmental control	Binary-Ice tied to gas cooling
Pipes	
local support pipe material	Aluminium
Typical cooling pipe i.d.	3.50 mm
Pipe o.d.	4.0 mm
Pipe from cylinder to patch panel i.d.	~13 mm
Pipe to / from Binary-Ice machine	11 off 55 mm (Flows and Returns)
Active insulation	Supplied by separate machine and pipework
Pipe connection	Welded joints with compression fittings on cooling pipes

11.7.5 Leakless Cooling System

The SCT liquid based cooling schemes will use the Leakless Cooling System [11-81] (LCS) that has been developed at CERN. The benefits of this approach are that the leak-tightness of an individual cooling loop is assured under all normal operational circumstances. The system does not represent a significant additional cost and it adds almost no extra material inside the detector volume. The principle of operation is that atmospheric pressure is applied to the bottom of the system and the highest point of the cooling loop is evacuated. Under these conditions, any leak in a pipe will cause gas to be drawn into the pipe rather than allow liquid to leak from the pipe. This is clearly of fundamental importance with an electrically conductive component such as water. In practice, atmospheric pressure is applied by using a lower reservoir that is (conceptually) open to air. The highest point in each cooling loop is connected to an evacuated reservoir, fitted with a level switch controlling the operation of a remote vacuum pump. If gas leaks into the system, the level of fluid at the upper reservoir falls, causing the vacuum pump to be started. The pressure is reduced in the upper tank as the admitted gas is evacuated; the fluid level then rises, causing the level switch to operate and so turn off the vacuum pump. It is clear that the duty cycle of this vacuum pump gives a measure of the system leak rate, assuming that the pumping speed is known.

Many LCS systems are already operating, including some in HEP experiments [11-82]. Each pipe leaves a pressure defining tank on the outside of the ATLAS detector and is brought into the SCT volume along an uphill path. This is done to ensure that in the event of a cooling shutdown, the fluid in the pipe will run back into the lower reservoir. The pipe will then be connected to the manifold which distributes the Binary-Ice fluid to the local cooling pipes. These cool the detector modules. At the end of the local cooling tube, the fluid is collected in a second manifold and a similar pipe run leads it back out of the detector, this time on a downhill path. At its exit point, it will empty the fluid into a collecting reservoir, from which the Binary-Ice mixture will be pumped back to the Binary-Ice cooling plant in USA 15. Since the ATLAS detector is not horizontal, each barrel cooling tube will be inclined. At the higher end of each tube a connection will be made to a vacuum pipe. The disk cooling pipe geometry will also ensure that each pipe is similarly inclined. A possible layout is shown in Figure 11-80.

One principle aspect of leakless cooling is the height available within the system. Tests have been carried out with the vacuum pump at 6m above the pressure defining tank without any problems The suggested design envelope is not to exceed a 3 metre height difference over the cooling loop to avoid problems of outgassing. This imposes severe constraints on the design and routing of services and increases the number of systems required within the ATLAS detector. There is a fine balance between the static height and the available pressure drop through the pipes. The total of these cannot exceed atmospheric pressure and must be low enough to avoid outgassing.

Prototype tests with Binary-Ice are under way in a LCS. These tests are necessary to investigate the pressure drops in various parts of the system, to identify the most suitable circulation pump and to study the operation of the entire system.

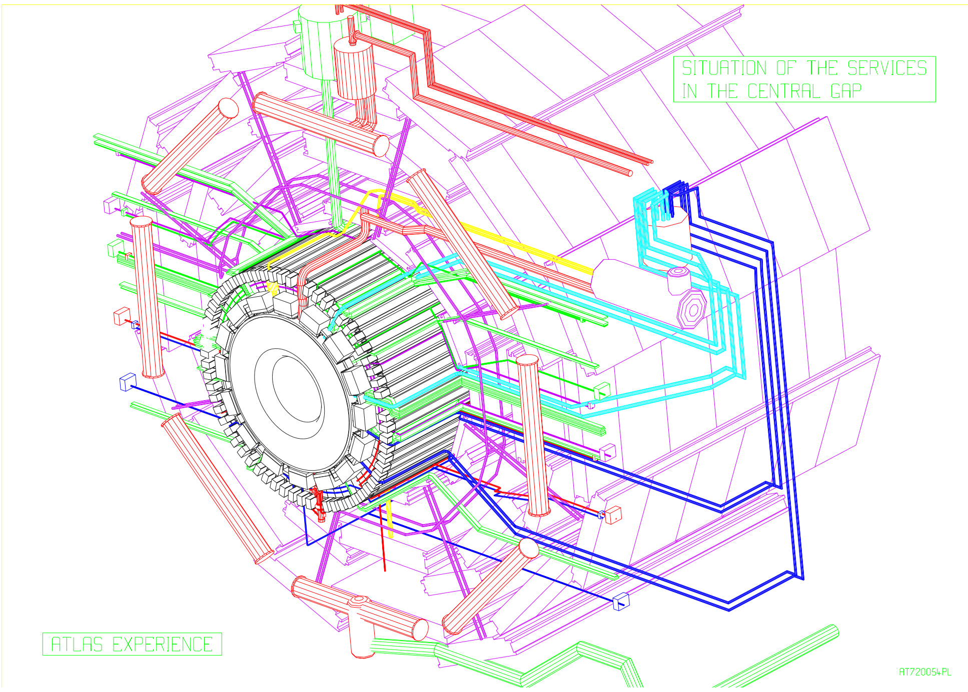

Figure 11-80 A possible layout of the SCT cooling feed and return pipes on the outside of the ATLAS detector. The pressure defining header tanks can be seen at four different heights at the end of the detector.

11.7.6 References

11-72 Binary-Ice is a registered trade mark of Integral Technologie GmbH, Flensburg, Germany.

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11-80 J. Paul, Integral Technologie GmbH, Flensburg, Germany. Presentation Binary Ice to Inst. of Refrigeration Engineers, London, 6th Feb. 1997.

11-81 International patents on LCS (leakless cooling systems) are held by M.Bosteels, CERN.

11-82 Both L3 and DELPHI use leakless system.