Requirements to the cooling of the ITS

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Contents

1 Introduction

This document describes the requirements for the external part of the cooling system for the ITS, *i.e.* where the responsability of the individual subdetectors ends. The document is organized as follows. For each subdetector, *viz.* SPD, SDD and SSD, first an estimate of the total power is given, then the external shield is described, and finally the requirements are given for temperature, pressure, etc, of the coolant(s). A summary of general requirements includes operations and safety issues. The last section is devoted to a comparison of the various coolant options.
It is assumed that the reader is familiar with the ALICE TDR 4 ITS [1].
The editor has combined all the information that was kindly put as his disposal by members of the various subgroups: A.Pepato, G.Giraudo, A. van den Brink and J. Buskop. This document presents the current state-of-knowledge of the editor: when new information comes available, a new version will be issued.

2 SPD Cooling system

2.1 General

The design features of the Silicon Pixel Detectors (SPD) changed since the last version reported in the ITS TDR. The most relevant modifications concerned the pixel dimensions and the global detector sensitive surface dimension (update of the sensitive angle for the whole ITS). Such modifications have affected the design parameters by reducing both the total power dissipated in the pixel ladders and the power per unit surface. The data we are using for this note are still preliminary and could be slightly modified in the near future: the SPD collaboration received the final CHIP version in the last few weeks and testing of the chip is still in progress. The uncertainty in the power dissipation is also due to our lack of knowledge of the real chip performance. The pixel chips are expected to generate a heat load of about $2x8 = 16$ W/stave. The additional heat load coming from the pilot chip was expected to be negligible in the TDR, but is presently estimated to be about 3.5 W per half stave (value still uncertain). The detailed geometry of the endcap electronics is still under study. We consider exploiting the same cooling system with introduction of heat bridges (e.g. ultra high thermal conductivity carbon fibre) to the cooling ducts. This is a potentially critical problem since it introduces unexpected complications in an element which may depend critically on temperature. Silicon pixel detectors are not very sensitive to temperature. We will operate the SPD at around room temperature. We aim at keeping the temperature spread on the barrel within about 10 K.

The estimated powers dissipated in the SPD layers are listed in table 1.

At present, we plan to place a stripe of conductive grease on the CFSS and between the cooling duct (CD) and the half-Staves (hS). The hydraulic layout is two feeding lines per sector, each one serving three staves.

The choice between two different stacking solutions for the stave geometry named "A" and "B" solutions is still open. The modularity of the cooling system has also been modified, as twenty independent lines feed the same number of sections, each subtending an angle of about 18 (one half CFSS). We have also a better definition of the global cooling circuit dimensions ([4]) and decided not to employ the leakless system solution, since the losses due to pressure drop would be very high and not compatible with the needed fluid flow. Any hybrid system is avoided in favor of more conservative configurations. We will anyhow make references to the previous tests we performed with de-ionized water (leakless and normal systems) and with C_6F_{14}[2].

Unavoidably, some fraction of the power will tend to propagate away from the cooling ducts. An external shield (see 2.2) will ensure that no heat is irradiated towards the external ITS layers. A moderate flow of dry air through the detector volume and through ducts in the external shield is needed to remove the residual heat.

2.2 External Shield

Owing to the extreme thermal stability requirements of the ALICE SDD detectors, positioned just outside the SPD barrel, a thermal shield will surround and isolate the SPD volume. This external shield (ES) also provides mechanical protection and structural support for the installation procedure, during which the SPD system will have to be held in position in a cantilever mode (see TDR Section 7.2). The 10 CFSS are rigidly connected to the ES, which is in turn fixed to the inner flanges of the ITS cones, with a conical protrusion of the transversal section of the cylinder structure (skins and Omega ducts protrusion) The ES shown is composed of two skins: a woven plane tape and two unidirectional tapes of high-resistance carbon fiber, separated by omega-shaped stiffeners made by a woven tape and a unidirectional tape. The inner surface of the cylinder is coated with an evaporated aluminum layer in order to reflect radiant heat, providing thermal de-coupling between the SPD and SDD systems. The omega-shaped stiffeners define trapezoidal ducts where dry air can flow, providing extra thermal de-coupling. One in two of these ducts is assigned to the air flow between the cylindrical skins, while the remaining ducts will be blind in the cylindrical region (insert placements for the sector positioning) and are used to convey the air flow to the innermost cylinder region (detector occupancy volume). The feed of the airflow will be located at the dump side and split in two systems as described above, being channeled by the omega ducts of the protruded cone. The air will not be collected at the opposite side.

Table 1: Estimation of the power dissipated in the two layers of the ALICE SPD

ALICE SPD	Layer 1	Layer 2
Number of staves	20	40
Power/stave: Modules	16 W	16 W
Power/stave: EndCaps	7 W	7 W
Total Power dissipated	0.5 kW	0.9 kW

Table 2: Requirements for the liquid coolant supply for one SPD ladder

ALICE SPD liquid	nominal	maximum	minimum
Pressure difference[1]:			
water	0.7 bar	0.95 bar	0.45 bar
C_6F_{14}	0.7 bar	0.95 bar	0.45 bar
Coolant flow :			
water	13 cm^3/s	16 cm^3/s	8 cm^3/s
C_6F_{14}	9 cm^3/s	11 cm^3/s	9 cm^3/s
Inlet temperature below ambient:			
water	13 K		
C_6F_{14}	10 K		

Table 3: Requirements to the air coolant of the SPD

ALICE SPD air	nominal	maximum	minimum
Total power to be removed:	? W?	? W	? W
Pressure difference:	? bar	? bar	? bar
Coolant flow			
thermal screen	1.2 m^3/h	2.5 m^3/h	? m^3/h
inner volume SPD	1.2 m^3/h	1.2 m^3/h	? m^3/h
Inlet temperature below ambient:	13 K		
Inlet dewpoint:	10 K		

2.3 Requirements to the cooling system outside ITS

The system described here requires a coolant supply from a source outside the ITS. In order to function properly pressure and temperature should be within certain limits. These are given in table 2 for the liquid and in table 3 for air. The data are referred to a single duct. The acceptable pressure drop is limited due to the weakened shape of the cooling duct. We assume to have a common maximum value of pressure drop (for water and C_6F_{14}), with a worse temperature distribution for the C_6F_{14} use.

We remind that SPD will have twenty feeding lines, each one serving three staves (one stave of the layer one and two staves of the layer two). The pressure values given are the pressure drop over a stave, plus the pressure losses over connecting tubes, manifolds and other appendages. For the control and safety of the system, sensors and actuators are to be added. We assume to insert miniaturized thermistors under each chip, at the inner face of the carbon fibre support. They will be connected in series and driven by a slow control system, allowing a switching off of the electrical power on the staves affected by local or global

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[1] The pressure drop is defined between the two patch panels (dump side and the service structure at the opposite side). For the SPD that represents the total pressure drop to which we have to add the pressure drop outside the ITS. The data are referred to the cooling tests performed with water fluid (the C_6F_{14} are extrapolated from the tests performed with a different cooling set-up geometry) and contains the single ducts, the collectors, the diameter transition etc.

overheating (the heating-up speed of the system being very high: ($\sim$1 K/s). The air coolant flow requirement appears more difficult to correctly estimated, due to the uncertainties of its efficiency and to the correct estimation of the heat exchanging factors to adopt in the calculation. We have not performed specific tests on air cooling with the SPD geometry, so the data reported have to be considered very preliminary. We only compared the temperature distribution on our cooling setup in adiabatic and ambient conditions (typical clean room environment: natural convection): the temperature distribution difference was absolutely negligible . The air velocity in the barrel region is necessarily limited (*e.g.*: $v = 1$ m/s), while it can be increased along the thermal screen channels (*e.g.*: $v = 2$ m/s), the global cross section being equivalent.

3 The SDD cooling system

3.1 General

The design of the cooling system responds to the need to thermostabilize the SDD and the front-end electronics. The system will be operating close to ambient temperature, to minimize stresses at turn-on and turn-off. The most stringent requirement is the very accurate thermal stability of the SDD, controlled with a precision in the 0.1 K region. The estimated powers dissipated in the SDD layers are listed in table 4.

Table 4: Estimation of the power dissipated in the two layers of the ALICE SDD

ALICE SDD	Layer 3	Layer 4
Number of Ladders	14	22
Modules/Ladder	6	8
Power/Ladder: Modules	21 W	28 W
Power/Ladder: EndCaps	40 W	50 W
Total Power dissipated	0.9 kW	1.8 kW

3.2 External Shield

Owing to the extreme thermal stability requirements of the ALICE SDD detectors, a thermal shield will surround and isolate the SPD volume, section 2.2. Another external shield (Cylinder) provides structural support for the endcones. This Cylinder can also play a role in thermally isolating the SDD and SSD, and in guiding the airflow. At present, this has not been studied.

3.3 Requirements to the cooling system outside ITS

The system described here requires a coolant supply from a source outside the ITS. In order to function properly pressure and temperature should be within certain limits. These are given in table 5 for the liquid and in table 6 for the air.

Table 5: Requirements to the liquid coolant supply for one SDD ladder

ALICE SDD liquid	nominal	maximum	minimum
Pressure difference over one ladder tube:			
water	0.7 bar	?	0.45 bar
C_6F_{14}	0.9 bar	1.5 bar	0.5 bar
Coolant flow	10 cm^3/s	12 cm^3/s	6 cm^3/s
Inlet temperature below ambient:			
water	5.5 K		
C_6F_{14}	10 K		

Table 6: Requirements to the air coolant of the SDD

ALICE SDD air	nominal	maximum	minimum
Total power to be removed:	260 W?	? W	? W
Pressure difference over one ladder:	? bar	? bar	? bar
Coolant flow	? m^3/h	?	?
Inlet temperature below ambient:	10 K		
Inlet dewpoint:	14 K		

Note that the pressure and flow are given for one ladder: for the total SDD the flow has to be multiplied by (number of ladders) . The pressure values given are the pressure drop over the ladder tube; pressure losses over connecting tubes, manifolds and other appendages have to be added. For the control and safety of the system sensors and actuators are to be added.

4 SSD Cooling System

4.1 General

The silicon strip detectors produce less than 1 mW of heat per channel, mainly produced by the HAL025 Front End chips. The other passive components (capacitors) dissipate a negligible quantity of heat. A large amount of heat is produced by the EndCap electronics. It is foreseen to use here temperature sensors on both the electronics and the coolant. The estimated powers dissipated in the SSD layers are listed in table 7.

It is critical to evacuate from the SSD a maximum of the heat produced in order to disturb as little as possible the thermal equilibrium of the Silicon Drift layers. In the present study, we assume a functional temperature of the SSD Front End Electronics lower than 35°C with a stability of 1 K.

An often overlooked source of heat is the dissipation in the powerlines. A total of $\sim$0.5 kW is the current estimate. Half of this will be dissipated in the narrow space between the Muoncone and the TPC. The layout of the cables and cooling lines can be made such as to evacuate most of this heat via the cooling liquid. In the case of aircooling, a large flow of air, although already heated by

Table 7: Estimation of the power dissipated in the two layers of the ALICE SSD

ALICE SSD	Layer 5	Layer 6
Number of Ladders	34	38
Modules/Ladder	22	25
Power/Ladder: Modules	11 W	13 W
Power/Ladder: EndCaps	20 W	20 W
Total Power dissipated	1.1 kW	1.3 kW

the ladders, is available for extracting this heat.
In the following we will describe tests done on aircooled and watercooled systems, a comparison and, finally, a description of the proposed cooling system.

4.2 Requirements to the cooling system outside ITS

The system described here requires a coolant supply from a source outside the ITS. In order to function properly pressure and temperature should be within certain limits. These are given in table 8. Note that the pressure and flow are given for one ladder tube: for the total SSD the flow has to be multiplied by 72(number of ladders) * 2 = 144. The pressure values given are the pressure drop over the ladder tube; pressure losses over connecting tubes, manifolds and other appendages have to be added to these numbers.

Table 8: Requirements to the coolant supply for one SSD ladder

ALICE SSD	nominal	maximum	minimum
Pressure difference over one ladder tube:			
water	0.25 bar	0.5 bar	0.2 bar
C_6F_{14}	0.35 bar	0.5 bar	0.2 bar
Coolant flow	4 cm^3/s		
Inlet temperature below ambient:			
water	4.2 K		
C_6F_{14}	5.1 K		

5 External Shield

In order to isolate the ITS and the TPC a low-mass external shield is foreseen at the outside of the ITS barrel. No quantitative requirements exist as to:

- mass
  Being within the TPC and the ITS outer layer, any multiple scattering occuring here, will directly deteriorate the track matching between ITS and TPC.

- temperature
  The temperature requirements of the TPC are severe (0.1 K). It is not known, however, what temperature variations along the inner barrel can be tolerated.

Unknown at present is, whether sufficient air flow can be obtained in the annular space between ITS outer layer and TPC inner barrel, to even out hot spots. Without some forced air, the top will always be warmer than the bottom. Also in Z-direction the power is not evenly distributed. When one sums for all the detector layers, one gets: upstream Endcaps: 1.8 kW, active volume: 2.7 kW, downstream Endcaps: 1.8 kW. One should realize that there is no thermal shield in the endcap regions.

Notwithstanding these uncertainties, there exist ideas for a shield:

- a thin aluminized mylar foil
  This would reduce the transfer of radiation and also prevent natural convection from SSD ladders towards the TPC. Depending on the airflow inside the ITS, hotter and cooler regions may still exist.
- a temperature stabilized shield
  The aim is to produce an outer layer which presents a temperature-stabilized surface to the TPC. This can be done in two ways:
  - cooled shield
    A structure with cooling ducts for liquid or air could do the job, at the possible expense of large mass.
  - heated shield
    By implementing thin-foil heaters on a thin aluminized mylar foil the temperature could be well regulated, at the expense of 1) additional power, and 2) an outside temperature which is always higher than the inner ITS temperature.

6 General requirements to the cooling system outside ITS

6.1 Introduction

The systems described here require a coolant supply from a source outside the ITS. Each of the detector groups has taken the responsibility for the design of the cooling system up to the manifold which supplies the coolant to the different ladders / staves. In order to function properly pressure and temperature should be within certain limits. These are given in tables 2, 5 and 8 for the liquid coolant and in tables 3 and 6 for air. Note that for the SSD no power has to be removed by air flow. Yet, some circulation is needed to remove hot spots, see section 5.

An overall flow scheme was given in fig. 6.34 of the TDR. In the mean time, there has been an evolution into three independent, but similar, systems for the SPD, SDD and SSD. The St.Petersburg group has worked out a detailed scheme [3].

6.2 Systems aspects

Besides the requirements in terms of fluid flow there are several other requirements to the cooling system, which are not explicitly given in [3]. These requirements[2] are given in the following points:

- Control requirements
  Temperature and pressure monitoring should be done as close as possible to the manifold, though here we have the problem of the magnetic field of the L3 magnet, space is limited and depending on the location of the sensors, radiation length can be of importance. Flow should be controlled for each segment. Because of the magnetic field these controls have to be pneumatic. Again, space for controls is limited inside the ITS and radiation length can become an issue. An alternative is to take the controls outside the magnet, as outside the magnet standard industrial controls could be used. The drawback is that this requires more piping as each segment has its own controls. Important is that space be reserved for these control racks.

- Filling and draining
  It has been remarked by many that filling without bubbles or draining without droplets remaining will not be easy. However, this is required for the proper functioning of the system. (The St.Petersburg scheme for a self draining circuit is without procedures or analysis.)

- Safety
  The cooling system should prevent damage to the ITS and other detectors. A list of requirements of the type: 'what to do if' is needed. On basis of this list a scheme can be made, indicating where sensors and actuators are needed and how they should be connected. More on this subject in section 6.3.

- Air quality
  The dew point of the air inside the ITS should be kept below the temperature of the liquid coolant in order to prevent condensation on circuit elements. The air to be supplied for cooling has to be filtered to remove particles (liquid or solid) according to clean room class TBD. This filtering serves two purposes: a) prevent dust from blocking the cooling ducts, and b) prevent particles from landing on sensitive surfaces of the detectors or electronics.

6.3 Safety system

The system will have to protect the whole ITS against failures. This protection is provided by two types of measures: passive and active. The passive measures are designed into the system by a careful choice of components and circuits. The active measures are actions taken automatically by the safety system when certain parameters are out-of-range.
Some *passive* measures are:

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[2] The desired magnetic field purity inside the ITS, for which the requirements are to be found elsewhere, may put restrictions on the use of magnetic materials in tubes, fittings, controls, *etc.*

- pressure drop control
  By carefully distributing the flow resistance in the total circuit, one can achieve that neither in the case of a leak, nor in the case of a blocked line, excessive pressures or flows will occur. This requires the splitting of the cooling system into at least three separate cicruits, one for each subdetector. To achieve the balancing it may also be necessary to introduce flow restrictors in the system.

- operating temperature
  The design of the cooling plant should be such that temperature extremes are not possible, even during switching on/off. This is very important because the combination of pressure and higher temperatures can cause significant deformation of the plastic tubing.

- pollution control
  The coolant should be kept in its original state of purity. Filters and ion exchangers need to be included to remove dirt, dissolved chemicals and the products of oxidation and radiolysis, like free radicals. The cooling system should be designed using a minimum of different materials. This not only from point of view of mutual contamination, but also to prevent galvanic corrosion.[3]

The *active* measures are:

- Overpressure protection
  Normally, pressure controllers and one-way valves will prevent overpressure. When they fail, a passive relief valve will open to a pressureless overflow line.

- Power failure
  In the case of electrical power failure the ladders will be isolated, due to the use of normally closed type isolation valves. To (re)start the system, the underpressure switches have to be bypassed.

- Leak detection
  There are two possible main strategies:
  Monitor the total amount of liquid using time integration of a fluid level signal. This allows the detection of minute leaks. As leaks often start out very small, this method allows actions to be taken before leaks can cause any damage. It requires, however, the entire cooling circuit to have a high level of leak tightness. This puts high demands on the leak tightness of components, like valves and pumps, ruling out the use of ordinary industrial components.
  A variant of this strategy is the monitoring of the air inside the ITS for coolant vapour. For a fluorine based coolant, detectors exist with very high sensitivity. In the case of water, the high natural water content of air prevents the detection of small amounts of water vapour and thus small leaks.
  A different approach is to monitor pressure changes in the system. This

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[3] Because the arteries at the detector are made of stainless steel, the above requirement means that appendages like valves and sensors should be made out of stainless steel as well.

requires the pressures to be monitored as close as possible to the point where we would expect a leak to occur. This method, however, is much less sensitive in detecting small leaks in comparison with the previous method. If a pressure sensor is too far downstream from a small leak one may not see it as other pressure fluctuations may be of the same magnitude. In this respect it becomes difficult to put forward real requirements, as it is not known what kind of pressure drop will result from small leaks. So it is necessary to design the flow resistance of each part of the circuit in such a way that leaks in the critical region give a maximal pressure change at the pressure read out point.
Flow measurements are not seen as a solution because standard flow meters do not have sufficient resolution to detect small leaks against the normal fluctuations in the flow. They are also usually not reliable enough, too bulky.

- Overtemperature protection
  Thermoswitches at critical places will protect the electronics from overheating by switching them off. Thermosensors at *e.g.* inlet and outlet will enable the monitoring of the correct functioning of the cooling system.

6.3.1 Example: a catastrophic liquid leak

The most probable and serious leak is in the connecting hoses at the ladders. In such a case the pressure in the sector manifold will drop to almost atmospheric pressure. For the supply side this is caused by the high flow resistance in the ladders and the upstream flow restrictor. On the return side, the one-way valve will prevent backward flow. When the pressure is low enough an underpressure switch on the ladder manifold will open. The two switches on both manifolds of one circuit are electrically connected to both the upstream and the downstream isolation valves, so both will close, thereby isolating the circuit. An electrical connection will also be made to shut off the power supply of the corresponding ladders. Note that all the liquid in the circuit between the valves may end up in the detector volume...

6.3.2 Air cooling

Most of the safety measures described above apply to the air cooling system as well. Although air leaks will not lead to direct damage, the air leaking out will not reach the places which it is to cool. A blockage of the air ducts may lead to overpressure, damaging the fragile walls of the air ducts inside the ITS. Separate control and monitoring of flow, pressure and temperature of the air is needed.
Another safety aspect of aircooling is the occurrence of vibrations. Certain flow regimes in the system may excite mechanical resonances in ladders or ducts. It is essential that such flow conditions can never occur, either by careful design of ducts etc. or by active control.

6.3.3 EndCaps

Whereas uni-directional *air*flow seems inevitable, the cooling *liquid* has to be supplied from both sides of the ITS. So for the liquid there will be one pair of identical circuits for each subdetector, flowing in opposite directions and only connected at the cooler/pumping unit. When the EndCaps are cooled by the exhaust liquid from the ladders, this presents no problem. However, when the EndCaps are cooled in a parallel circuit, an Endcap on *e.g.* the muon-side will extract liquid from the anti-clockwise circuit and put it back in the clockwise circuit. This has serious implications for the design of the safety valves: situations may exist where a leaky ladder, which was closed off by a safety valve, will be supplied in counterflow via an EndCap. To prevent this, additional valves and or manifolds are needed. It may be clear also, that the design of the EndCap cooling circuit will be different for both cases. In the parallel case, the circuit has to operate on ladder pressure. In the series case, it has to operate with laddder flow, while minimizing its pressure drop.

6.4 Segmentation

The segmentation for cabling and cooling should be compatible, to enable the switching off the power of a segment (and no more than that) fo which the cooling is off. It is not possible to combine ladders of different layers in the segmentation due to assembly problems. From physics point of view it might be preferable to have more segments in layer 6 than in layer 5. However, a boundary condition is the space available for services on the muon plug patch panels. The current segmentation is given in table 9.

Table 9: Segmentation ITS layers

SPD		20 segments
SDD	layer 3	7 segments
	layer 4	6 segments
SSD	layer 5	8 segments
	layer 6	8 segments

6.5 Control

Control is an essential part of the cooling system. The control of the cooling is linked to the detector control and part of the overall slow control. To allow a design of the cooling circuit outside the ITS first the control requirements have to be defined. Control should be seen in its broadest view. It ranges from manual settings of valves during installation to fully computer-controlled regulation of temperature and pressure.

6.5.1 Modes of operation

There are several types of situations that have different requirements to the Control system. At the moment the following situations are defined

- Installation
- Normal start-up

- Start-up, segments disabled.
- Normal operation
- Normal operation, segments disabled
- Normal shutdown
- Shut down leak
- Emergency shutdown leak
- Emergency shutdown
- De-installation of detector

These situations can be sub-divided for the different detector layers and the combination of the different detectors working together. This is worked out in the following. It is understood that electrical power can only be applied when the cooling system is working. The opposite may also be true.

Installation During installation there are the following situations. During filling of the cooling circuit a number of controls (valves) may need to be bypassed to allow a complete filling of the circuit. Test runs with the cooling will be needed when the ITS is not yet installed, which are different from tests with the ITS installed.

Normal start-up Start with different levels of detectors in use and different combinations of SPD, SDD and SSD working together. Important for start-up is the order in which the different systems are switched on, for example first fluid cooling, detectors on, air-cooling on. This could be different for SPD, SDD and SSD.

Start-up, segments disabled Start-up with some segments of the cooling circuit switched off: the segments are switched off in such away that they cannot up switched on until a full reset.

Normal operation During normal operation the cooling should be regulated in such away that the temperature in the ITS remains the same independent of difference in heat production, read-out levels. During normal operation segments can be switched on and off individually.

Normal operation, segments disabled As in normal operation, but the disabled segments cannot be switched on. This mode would be used when there are cooling or electrical problems with (parts of) a segment.

Normal shut-down The shut-down sequence depends on the requirements of the different sub-layers. Depending on the position of a leak (inside or outside the ITS) one could choose not to stop until the end of a run. When the leak is inside the ITS a segment can be disabled.

Emergency shut-down leak Immediate switch-off of all electronics, followed by shut-down of the cooling. A shut-down of all cooling might not be possible for some length of time to prevent the electronics from over-heating. The order of actions depends on the location of the leak and the shut-down sequence of the sub-detector.

Emergency shut down Overall emergency shut-down from Alice. Switch-off electronics, depending on regulations followed by shut-down of cooling.

De-installation For de-installation the ITS has to be drained. It has to be decided whether draining is mandatory in case the circulation is stopped for a longer period.

At which levels segments are disabled, depends on safety considerations. One could for example disable a segment by manually closing a valve that cannot be automatically opened. Another possibility might be disconnecting the electrical controls, by this taking the valve out of the automatic control.

One should also consider whether or not valves should be open or closed position in case the automatic control system fails. So always cooling unless automatic control turns off the cooling, or no cooling unless turned on by automatic control.

6.5.2 Monitoring

Correct operation of the cooling system requires the monitoring of:

- Flows of liquid and air
- ITS air temperatures, detector temperatures, fluid temperatures
- Pressures of liquid and air
- Leaks

The sensors should be placed in such a way that the different control actions can be monitored.

For leaks one would also like to know the position of the leak in the cooling circuit. One might decide not to switch off the cooling circuits if the leaks are outside the Alice magnet.

For the further design of the cooling circuit outside the ITS, this document should be completed with the specific demands from the different sub-detectors of the ITS.

7 Comparison of coolant options

The choice of the cooling fluid is still open. The choice is between demineralized water and C_6F_{14}. There are problems with both fluids. The discussion on the decision of the cooling fluid is hampered by a lack of information on the effects of radiation on the fluids.

In the remainder of this section, first it is discussed which fluids can be applied in the ITS environment. This is followed by a comparison of the main alternatives: water and fluorcarbon.

7.1 Available fluids

The choice for the cooling fluid has been limited to either demineralized water or C_6F_{14}. For the ITS pixels there is a third alternative, C_5F_{12}. Demineralized water and C_6F_{14} would be used in a mono-phase cooling system, C_5F_{12} would be used for an evaporative cooling system. It is preferred to use only one type of cooling system for the three sub detectors of the ITS.[4] Most of the alternative cooling fluids used in industry, based on hydrocarbons, are forbidden because of fire safety regulations. The fluorocarbon based cooling fluids with sub-groups of iodine, chlorine or esters cannot be used. These sub-groups of the molecule dissociate too easily, making them sufficiently aggressive to damage materials of the cooling system. Most other fluids for mono-phase cooling have very poor thermal properties and are therefore not considered to be a viable alternative.

7.2 Limitations in the ITS

For the active area of the ITS detector stainless steel cooling tubes with a wall thickness of 40 μm and an outer diameter of 2 mm, are taken as baseline for the cooling system design. This choice has been made to limit the radiation length of the cooling system. These tubes have the lowest radiation length for commercially available alternatives, within the requirements for strength and the thermal properties. The strength is related to the wall thickness and the maximum pressure in the cooling system. The thermal conductivity of the tube wall is the very important, a larger heat resistance increases the temperature drop in the cooling system.)

The total temperature drop in the cooling system, *i.e.* between the coolant and the heat producing elements, is limited. The upper limit is given by the maximal allowable temperature in the detector, which is currently set at 24 °C. The lower limit is given by the dew point of the air in the detector, in order to prevent condensation.

In the current design of the ITS plastic/elastomer tubes are used to make the connections in the cooling system inside the ITS. Within the ITS the space available for the connections and the allowed forces on them are limited. Metal bellows are not seen as an alternative because the assembly of the sub systems of the ITS does not allow to install a fully pre-assembled cooling system. There is not enough space available to make the connections of the metal bellows in-situ.

7.3 General

In the following, several aspects will be compared for the coolant options: water and fluorinated hydrocarbons (FC).

- Leaks
  Direct mechanical damage is not likely because of the low pressures involved in any of the systems. However, water leaks can be desastrous by causing electrical short circuits and corrosion. An underpressure prevents big disasters, but small amounts of water(vapour) may still escape, possibly leading to corrosion. An FC leak may be harmfull because it acts as a

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[4] An evaporative cooling system requires a more complex control system than mono-phase systems.

chemical solvent for some plastics/glues. Its high vapour pressure causes rapid evaporation, cooling the surfaces hit by the leaking fluid, but also reducing the exposure-time to the fluid.

- material compatibility
  Corrosion due to water is a well known process, which can be kept under control by controlling the water quality, *viz.* conductivity. The long-term effects of FC on *e.g.* elastomers are generally difficult to assess. The influence of ionizing radiation may play a role as well. An all-metall system seems safer in this respect.

- Radiation aspects
  The effects of radiolysis of water are known to be controllable by the use of ion-exchangers and recombiners (to reduce the risk of explosion of the H_2+O_2 mixture produced)[5]. Radiolysis of FC in ALICE will be much less than in CMS because of the lower radiation dose. Measures taken for CMS will certainly be adequate for ALICE.

- Cooling efficiency
  Compared to water, the heat transfer capacity of FC is a factor of ∼3 smaller, which can be compensated by lowering the inlet temperature, see *e.g.* table 8.

- Material budget
  Compared to water, the larger radiation length of FC is a drawback.

- Price
  Detailed price comparisons have not been done. The high price of the FC fluids may be a serious drawback, considering the large amount of liquid needed (∼0.1 m^3).

In the following sections these items will be discussed in detail for water and fluorcarbon, respectively.

7.4 Demineralized water

7.4.1 Radiation effects

Although the radiation levels in the ITS will cause radiolysis, the radiolysis products are not expected to be problematic for stainless steel. This statement is based on experience with water as cooling fluid around accelerators.

7.4.2 Leas

There are two main concerns regarding demineralized water. First, demineralized water is relatively aggressive. Depending on the leak-rate there could be an accumulation of it inside the ITS. What damage that could do to the detectors is not known at present. However, the beryllium beam-pipe is very susceptible to corrosion in the presence of water. A drop of water is expected

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[5] Nevertheless, this explosion risk was the reason not to choose an alcolhol/water mixture as a bi-phase coolant for the ATLAS inner detector.

to cause a leak in the beam-pipe within a week. The difference between demineralized water and ordinary water in this respect is not known. The corrosion is related to the ionization of the demineralized water, if the evaporation rate of the water is high enough, the time available for the demineralized water to do damage becomes the important parameter. Second, the water might cause damage to the electronics. Although demineralized water is an insulator, due to its aggressiveness it will dissolve metals which will increase its conductivity rapidly, causing short circuits.

7.4.3 Compatibility with plastics

There is no good understanding of the problems in the use of plastics. Several plastics can be used in combination with demineralized water, but the effect of radiation is not well known. It is known that plastic degradation can be influenced by radiolysis products of water, but it is not known what the extra damage is in comparison with plastic degradation under influence of radiation alone.

7.4.4 Leak detection

Leak detection based on monitoring the relative humidity in the outgoing air from the detector is not a viable option: the concentration changes are very small in case of small leaks and the sensitivity of available humidity sensors is not sufficient. A further difficulty is to discern between humidity change caused by leaks or by changes in the humidity variations in the ambient environment.

7.4.5 Thermal behavior

The current design of the cooling system in combination with demineralized water can cope with the expected heat load within the temperature range dictated by the expected dew point.

7.4.6 Experience

There is extended experience with the use of demineralized water around accelerators. The problems of operating a demineralized water system extend through the whole range from rather difficult to quite easy. Many water based cooling systems have been operating successfully around accelerators.

7.4.7 Summary

For demineralized water the effects due to radiation are expected to be limited. A leak is reason for serious concern because the damage that demineralized water could do might be considerable. The limitations in the use of plastics are not clear. This is mainly because it is not clear what the combined effects of radiation and radiolysis of demineralized water on plastics are. The detection of small leaks near the detector is very difficult. A mono-phase demineralized water cooling system would be able to cope with the heat load of the different subdetectors from the ITS.

7.5 C_6F_{14}

7.5.1 Radiation effects

Although C_6F_{14} is a rather inert fluid, the concern is the production of free fluorine radicals under the influence of radiation. At the moment there are no good estimates of the production of free fluorine radicals. A first estimate is given in appendix A.2. Significant concentrations of fluorine radicals cannot be accepted: with the exception of rhodium no material is sufficiently resistant to chemical attack by fluorine radicals. This is of mayor concern because of the small wall thickness of the proposed cooling tubes.

7.5.2 Leaks

The effects due to leaks are expected to be less severe than for the case of demineralized water. The fluid will not cause short circuits. Effects on the beryllium beam-pipe are not expected. The main concern is the effect on the plastics in the structure of the ITS, like carbon-epoxy, see below. The fluid has a low vapour pressure, so in case of small leaks the fluid will evaporate at the leak. This would prevent the accumulation of fluid inside the ITS in case of small leaks.

7.5.3 Compatibility with plastics

Several types of effects have been observed in the use of plastics in C_6F_{14}. The most important effects are;

* Increased ageing

* Swelling or shrinkage of plastics

* Washing out of part of the base material of the plastic

* Degradation in material parameters due to the washing out effect, especially of importance for structural composites

There is an active research programme at CERN to test the compatibility of C_6F_{14} with different plastics. There is also a lot of knowledge from past experience from the use of C_6F_{14}, see appendix A.1. Based on the research activities and the knowledge from past experiments a selection of useable plastics is possible.

7.5.4 Thermal behavior

As the thermal properties of C_6F_{14} are worse than for water a larger temperature difference is required to transfer the total heat load. Because the maximum temperature is fixed, a larger temperature difference may require a lowering of the dew point in the ITS. It would also require isolation of the cooling system outside the ITS to prevent condensation. Extremely important is that condensation is prevented near the beam-pipe, because water causes severe corrosion of the beryllium beam-pipe.

7.5.5 Leak detection

Leak detection of C_6F_{14} would be possible by detecting its vapour in the exhaust air. As the only source of C_6F_{14} would be a leak, one is not confronted with the problem of a varying environmental concentration, as in the case of water vapour detection.

The past experience with C_6F_{14} is limited; most of the experience with C_6F_{14} is gained in the Delphi Rich detector where C_6F_{14} was used as Cherenkov fluid. There is no documented knowledge on the use of C_6F_{14} as cooling fluid in accelerator experiments.

7.5.6 Summary

For C_6F_{14} the behavior under influence of radiation is the biggest concern. The effects due to leaks are expected to be limited. There are limitations on the use of plastics although there are several plastics that seem usable inside the ITS. Via vapour detection of small leaks of C_6F_{14} can be detected. A significant drawback is that a mono-phase system based on C_6F_{14} would not be able to cope with the heat load without lowering the dew point of the air in the detector.

7.6 Purity of the cooling fluids

For both demineralized water and C_6F_{14} the experience on how to purify the cooling fluid is available at CERN. In case of C_6F_{14} the formation of HF is to be prevented. HF can be formed in case the fluid is contaminated, *e.g.* with water. The use of plastics in the cooling system can cause problems when these are water permeable, allowing absorption of water into the cooling fluid.

7.7 Conclusion

For the Alice ITS the cooling fluid will be either demineralized water or C_6F_{14}. The choice is hampered by the lack of data on the effect of radiation on the materials. Neither of the fluids can meet all the requirements for the cooling. C_6F_{14} shows a distinct advantage, minimal effects due to leaks, assuming radiation effects can be neglected. A serious problem with the use of C_6F_{14} is its reduced heat transfer efficiency compared to water. This necessitates a coolant temperature at which condensation of the humidity in the atmosphere becomes a problem.

References

[1] ALICE Technical Design Report 4 Inner Tracking System, CERN/LHCC 99-12, June 1999

[2] Scarlassara *et al.*, Cooling tests for the Silicon Pixel Detectors, ALICE Internal Note 2000-18, 11 July 2000

[3] Igolkin, S.N. and A.M. Swichev, Heat and hydraulic calculations for ALICE SSD and SDD, ISTC 1666/Internal Note ITS02 16 September 2000, Central Design Bureau of Machine Building, St.Petersburg

[4] Charles Gregory, presentation in integration meeting

A Appendix

The appendix gives summary of the information gathered on the different aspects of the cooling fluid. Also in the appendix is a coarse estimate of the possible damage from free fluorine radicals.

A.1 Information on the cooling fluids

This summarizes the information gathered on the behavior of both fluids and an estimate of the expected effect of fluorine on the cooling tubes.

The discussions do not give a clear answer on the expected effect of radiation on the cooling fluid. The estimates for C_6F_{14} range from below one percent to several percents of the weight of the fluid are converted to pre-polymers. No estimate is given about the percentage of free fluorine radicals that is to be expected.

A.1.1 Experience with fluorocarbons in Delphi[1]

The problem started after some years of operation with the Barrel RICH detector. The RICH detectors have two Cherenkov fluids. C_4F_{10}/C_6F_{14} in the Forward RICH and C_5F_{12}/C_6F_{14} in the Barrel. The liquid (C_6F_{14}) system is placed inside the gas radiator. Big losses of fluids were then observed from the liquid system into the gas. This went on more or less unnoticed until the time when the gas was fully saturated with the liquid at that temperature and pressure (40 °C and 1030 mbar). Then we started to look.

The main observations are the following:

- All composite materials will either contract or swell in contact with fluorocarbons.
- All plastic materials, defined as materials with plastifiers, will get hard, loss of plastifiers, in contact with fluorocarbons.
- Cycling, going from dry to wet to dry ..., will accelerate the process.
- Normal epoxy glue will normally not change in contact with fluorocarbons. An effect like post-curing can be observed. There is a difference between fluorocarbons and Cl/Br based freons. The latter can change the epoxy matrix structure and greatly weaken the glue.
- Charged composite materials, epoxy charged with carbon fiber or glass fiber, will undergo a slow washing out of the binding matrix between the epoxy and the fibers. This is very dependent on how the fibers are exposed to the fluorocarbons. This will change the material defining constants of these charged materials.
- Accelerated ageing can be done by raising the temperature and by circulating the fluorocarbons. Something like a factor of 2 for each 10 K can be expected. The circulation is needed in order to make sure that the fluid is not saturated.
- No chemical attack has been observed.

A.1.2 Tests as done for Atlas SCT and Pixels

The corrosion issue is a part of document on cooling for Atlas SCT and Pixels: Fluorocarbon evaporative cooling developments for the Atlas Pixels and semiconductor tracking detectors. The document can be found at:
http://documents.cern.ch/cgi-bin/setlink?base=preprint&categ=cern&id=cern-open -2000-093

Refrigerant irradiation study

Effects of Neutron irradiation Small, static liquid samples of perfluoro-n-hexane (C_6F_{14}), CF_3I, solid Teflon and iodine (12) were irradiated up to 3x10^{13} fast neutrons.cm^{-2} to simulate the expected environment at LHC. Studies showed the main longest-lived radioisotopes to be ^{18}F (106 min: 511 KeV (emitter) and ^{128}I (25 min: 433 KeV (emitter). From neutron capture cross section data the expected activity levels for these radionuclides are in the range 10^4-10^5 Bq.g^{-1} during circulation (for an instantaneous rate (10^6 n.$cm^{-2}S^{-1}$). Which is believed to be acceptable in a closed circuit system. However, the overall measured level of I_2 activation was measured to be very high.

Radiation-Induced Chemical Modifications Small, static liquid samples of C_6F_{14} and CF_3I were exposed to ^{60}C gamma irradiation. After an absorbed dose of 3 Mrad, about 1% by weight of C_6F_{14} liquid had been radiochemically modified: there was chemical evidence of the production of reactive HF, due to impurities containing C-H groups. Scanning electron microscopy and Auger electron spectroscopy were used to characterize the morphologies and elemental compositions of C, F and O^- containing polymeric deposits formed on stainless steel and aluminum samples immersed in liquid during irradiation. After 6 Mrad, surfaces were almost uniformly covered to a depth of $\sim$0.4 μm. Degradation and plate-out were greater in a sample of C_6F_{14} to which 3 % (vol.) n-heptane had been added to act as a H-source. Since saturated fluorocarbons ($C_nF_{(2n+2)}$), are synthesized from alkane precursors, batch testing for residual H contamination (using the characteristic Fourier Transform Infra-Red signature of C-H bonds) is advisable. Techniques for the catalytic removal of $C_nF_xH_{(2n-x)}$ contamination were developed for the DELHPI RICH detector, where high fluid purity is needed for good UV transparency: similar techniques could be used in the present application. After irradiation to 2 Mrad, liquid CF_3I had become opaque, and breakdown of CF_3I into I_2 and HI was seen. This was not a complete surprise, since CF_3I is a refrigerant with a short ((24 hr) atmospheric half-life. Oily residues (pre-polymers) were observed after the evaporation of the irradiated CF_3I and thick deposits, including crystalline I_2 were observed on aluminum and stainless steel immersion samples. Although it was possible to clean the CF_3I to remove I_2 and re-establish the transparency, CF_3I was finally abandoned as a coolant owing to its chemical aggressiveness, even in the un- irradiated state, to elastomer seal materials.

Comments to tests done for Atlas SCT[2] C_3F_8 is rather radiation resistant as the bonds are comparatively strong. (You find them by going into http://www.chemfinder.com/ and follow the links.) In addition, F_2 cannot be formed. On the other hand, if there are H's floating around in the CF structure, HF can be formed and the resulting double bonds in the CF structure will give rise to longer chains. In principle, the HF's can be taken out by acid cleaners. There are some links on the web. Another problem might also be the $CHF2^+$which is toxic and one might therefore also assume that COF_2 is. In addition to all this, there is the induced radioactivity, mainly by ^{18}F which is a beta emitter. Sorin came to something like 1 kbeq/cm^3 for the CMS tracker.

Until now, fluorocarbons are the most promising cooling fluid. However, it will need more work and probably some rather extensive cleaning procedure of the fluid. That is to make it water and oxygen free and to take away polymerized products.

For water as a cooling fluid, there are the following combinations to take into account:

- H
- O^+
- H_2
- H_2O_2
- H_2O_3

These reaction products will cause havoc to the cooling circuit.

Comment *Measurements show nearly no free fluorine radicals after radiation, this is also not expected, as fluorine radicals are very aggressive. An indication of the formation of free fluorine radicals could be the formation of pre-polymers. In the document this is mainly contributed to opening of double bonds in the* C_xF_y. *The question is what is the main mechanism.*

Remarks[4] *with respect to the chemical analyses.*

Regarding the question about possible free fluorine radicals and polymerization of the fluorocarbons was that this was a very preliminary analysis and requires further investigation.

A.1.3 TUE corrosion expert

Using fluorocarbons the biggest concern is pitting corrosion. The corrosion issue should not be considered different for the 40 μm wall thickness tube from a 1 mm or more wall thickness tube. Though one should not forget the cumulative effect of the different forms of corrosion. Main problem is to estimate the cumulative effect on Stainless Steel for the life time period of the detector. A problem might be foreign crystals in the SS as these might have sizes up to 10 μm. CuNi might be a good alternative for SS if the system can be kept oxygen free, oxygen in the system will cause significant corrosion effect.

Preferred is the use of de-mineralized water in combination with pure titanium or tantalum. The use of pure titanium or tantalum is preferred because these are mono phase materials. Neither titanium nor tantalum is suitable in combination with fluorocarbons, as excessive corrosion occurs on combination with fluorine or HF.

A.1.4 New document

Another more recent document, which gives information about the cooling fluid problem, is: Qualification of coolants and cooling pipes for future high-energy-particle detectors, CERN-TIS-2001-003-TE. The information with regards to the use of fluorocarbons is mainly similar to the information in document: Fluorocarbon evaporative cooling developments for the Atlas Pixels and semiconductor tracking detectors, which discussed earlier in this document.

A.2 Estimate of possible fluorine damage

Here we give an estimate of the possible damage due to fluorine on the cooling tubes. The estimate is based on the assumption that all the absorbed energy due to radiation is used to produce fluorine radicals and that all these fluorine radicals bind with the iron of the cooling tube. This estimate has to be verified by the experts in this field.

The free fluorine radicals are produced from the cooling fluid C_6F_{14} by the radiation load on the cooling fluid.

The estimate is based on the following: The total radiation dose in the experiment is 100 krad. This energy allows the production of X fluorine radicals assuming 10 eV is needed to produce one free fluorine radical. One fluorine radical binds with one iron atom. All damage is homogeneous thoughout the detector and only in the detector. Fluorine does not react with the other components in SS and these components do not cause a catalytic reaction. Based on these assumptions one can estimate the thickness of the layer, which reacts from Fe to FeF. The calculation is as follows. Using the conversion: 1 rad = 10^{-2} Joule per kg, a dose of 100 krad over the life span of the detector deposits 1 kJ per kg of cooling fluid. So 1 kJ, equivalent to 6.3x10^{21} eV, is the energy available, due to radiation, for the production of free fluorine radicals within 1 kg of cooling fluid. Assuming that 10 eV is required to produce one free fluorine radical, this would result in the production of 6.3x10^{20} free fluorine molecules per kg. One kg of C_6F_{14} contains 18x10^{23} molecules. So under the total radiation load 0.04 % of the cooling fluid molecules is converted into free fluorine radicals, this is $\sim$0.001 mol per kg C_6F_{14}. Assuming that the reaction product of the free fluorine radicals is FeF, each mole of free fluorine binds one mole of Fe. So in this reaction 0.001 mole of Fe is removed from the tube walls per irradiated kg of C_6F_{14}. One mole Fe being 55 gram, $\sim$0.06 g Fe is dissolved per kg of C_6F_{14}.

If one takes the SSD detector as an example, the total amount of cooling fluid in the system is approximately 0.5 kg, so $\sim$0.03 g of Fe is converted. If one assumes the reaction is homogeneous throughout the detector, one is able to calculate what the reduction of wall thickness of the tubes will be. The resulting reduction in wall thickness would approximately be 7 nm. (The total surface area of the cooling system is 0.5 m^2.)

From this one can conclude that the production of free fluorine radicals under the influence of radiation is of no serious concern for the corrosion of the cooling tubes.

A.3 Sources of information

1. Personal communication with O. Ullaland, CERN physicist, experience from Delphi.
2. Personal communication with O. Ullaland and responses from S. Ilie relayed by O. Ullaland
3. Personal communication with L.J.J. Janssen, corrosion expert from the Technical University Eindhoven, the Netherlands
4. Comments from S. Ilie relayed by O. Ullaland