FERMILAB-Conf-03/352-E November 2003

Cooling of Electronics in Collider Experiments

R. Stanek, W. Cooper, M. Demarteau, G. Derylo, J. Fast, D. Glenzinski
A. Hocker[a], J. Howell, S. Moccia, F. Raffaelli[b], R. Rucinski, R. Schmitt

Fermi National Accelerator Lab, P.O. Box 500, Batavia, IL USA
[a] Department of Physics & Astronomy, U. of Rochester, Rochester NY USA
[b] Instituto Nazionale di Fisica Nucleare, Pisa, Italy, I-56100
rstanek@fnal.gov

Abstract

Proper cooling of detector electronics is critical to the successful operation of high-energy physics experiments. Collider experiments offer unique challenges based on their physical layouts and hermetic design. Cooling systems can be categorized by the type of detector with which they are associated, their primary mode of heat transfer, the choice of active cooling fluid, their heat removal capacity and the minimum temperature required.

One of the more critical detector subsystems to require cooling is the silicon vertex detector, either pixel or strip sensors. A general design philosophy is presented along with a review of the important steps to include in the design process. Factors affecting the detector and cooling system design are categorized. A brief review of some existing and proposed cooling systems for silicon detectors is presented to help set the scale for the range of system designs.

Fermilab operates two collider experiments, CDF & D0, both of which have silicon systems embedded in their detectors. A review of the existing silicon cooling system designs and operating experience is presented along with a list of lessons learned.

I. SYSTEM DESIGN

Silicon detectors form the core of present-day tracking systems for collider experiments. Physics requirements drive the sensor design into finer segmentation coupled with increased radiation hardness, and the detector design towards a configuration that has lower mass, more complete coverage of the interaction region and greater hermiticity. This puts a strain on the thermal and mechanical designs and analyses performed for these devices. The result is that new and innovative methods must be established to effectively deliver the increased cooling capacity deep inside these detectors.

The design process is driven by the physics requirements but the key to success of the project is the "build-ability" of the detector and cooling scheme. Build-ability can be defined as the ability to fabricate a reliable detector within the project constraints of time, budget and available resources. Resources include both the necessary equipment and the right type of people needed to build the device. Meeting the physics requirements is an essential goal, which cannot be compromised. However, changing physics requirements or conditions can create uncertainty in the design process unless properly accounted for.

During the design process, the concurrent interaction of the tracking requirements, mechanical, electrical and thermal design, radiation resistance and physical integration issues is essential. All of these areas are interrelated and it is important to take them all into account early in the design stage. A common problem is assuring detector integration constraints are adequately addressed.

Finally, all designs have flaws and in all fabrication techniques there is a possibility of error. This is why it is extremely important to perform acceptance testing that includes verifiable, acceptable performance of the detector, even if this performance is only tested in discrete, logical segments. The key to success is assuring the subsystem performance is tested prior to insertion into the real detector.

A. Factors Affecting the Design

There are many factors that affect the design of a silicon detector as well as its associated cooling system. They have been grouped into three major categories and listed in Table 1. The degree to which each of these factors is a valid concern for the system design depends on detector specifics. However, the list may be used as a guide in determining relevant parameters for any initial specification. [1]

Table 1: Design Factors

Mechanical/Environmental Factors
- Physical Size and Low Mass requirements
- Stiffness and Positional Accuracy
- Radiation Hardness
- Magnetic Effects
- Motion Requirements
- Remote Operation/Control
- Thermal Barrier Requirement

Fluid Dynamic/Thermal Factors
- Material Properties of Support Frame (k,c_p, CTE…)
- Low Thermal Mass of Fluid (thermal time constant)
- Material Compatibility Requirements
- Type of Fluid/ (non-corrosive, non-flammable, non-conductive, non-toxic, and non-ozone depleting)
- Properties of Fluid (k,c_p, ρ, μ, T_s…)
- Segmentation/Modularity of Cooling Circuits
- Maximum Temperature Rise Across Detector
- Leakless Operation
- Quiet Operation (vibration free)

Organizational/Cultural Factors
- Level of Comfort with Design
- Reliability/Redundancy Requirements
- Disassembly/Modification Requirements
- Safety Requirements

B. *Cooling Schemes*

There are several types of cooling schemes available depending on the requirements. Most cooling systems can be categorized into one of the following:

Evaporative two-phase cooling
Convective mono-phase liquid cooling
Convective gas cooling
Conductive cooling

Evaporative two-phase cooling schemes offer flexible temperature control with the temperature-pressure relationship defined by the liquid-vapor curve of the fluid chosen. There is a range of fluorocarbon fluids to choose from and very likely one that fits the parameters of the design. Cryogenic fluids such as carbon dioxide and liquid nitrogen are also used as coolants. However, the low saturation temperature of these fluids requires that an optimized conduction path be established in order to keep the sensors within acceptable temperature limits. A potential problem for evaporative cooling schemes is the difficulty in calculating pressure drops particularly when the change in phase spans the range from liquid to all gas. Another difficulty occurs when the detector integration requirements impose a constraint of assuring that the return cooling fluid temperature be higher than the dew point of the collision hall to prevent condensation from forming. Typical solutions involve line heaters, heat exchangers, or insulation.

Convective mono-phase liquid cooling schemes are the most commonly used type of cooling system. Historically, water and water/glycol have been the preferred solution for cooling schemes due to the relatively inert nature of the fluids and the well understood methods for handling technical and safety concerns. Recently other fluids such as those in the Fluorinert products have been chosen to allow for operation at colder temperatures. The major constraint for the mono-phase cooling systems has been the limited cold temperature range and the subsequent higher pressure drop problems that exist when additives are used to lower the minimum temperatures. Higher viscosity and lower heat transfer coefficients coupled with the requirement for sub-atmospheric operation lead to larger diameter cooling channels which in turn conflicts with the low mass requirement. Still, mono-phase fluid cooling systems are an important and well-documented way to provide the necessary cooling to silicon detectors, particularly if the need for cold temperature operation is relaxed.

Convective gas cooling schemes are popular solutions when the heat load requirements are low and the movement of higher velocity gas across the surface of the detector and sensors does not pose an additional risk of damage. Due to the relatively low specific heat of the gas one of two options are typically chosen, increase the flow rate or lower the initial temperature of the incoming gas. Lowering the temperature may imply another type of cooling system with which to exchange heat. Although the use of convective gas cooling is limited, it can be combined with another form of cooling (such as mono-phase cooling) to assure an even temperature distribution and minimize hot spots.

Conductive cooling schemes take advantage of solid state cooling devices, thermoelectric coolers to provide vibration free cooling or heating in the range of 350 watts. Their application is limited in silicon detectors due to the physical size requirements but they can be effectively used in other area of the experiment, such as providing temperature control for photomultiplier devices or other electronic enclosures.

All of the cooling schemes mentioned above can take advantage of enhanced heat transfer methods including the use of conductive epoxies, high-conductivity carbon fibre materials, and extended internal "fin" surfaces to improve the thermal performance of the system. In all cases, it is important to weigh the improvements in performance against the added complexity and material compatibility issues.

C. *Working with Multiple Detectors*

When working with multiple experiments and/or detectors there are two approaches: (1) create a Central Cooling Group to service all cooling systems or (2) allow each Detector Group to provide its own system. Which one is chosen depends on many factors including the sources of funding, available technical resources, time to design, test and install the system, and who will eventually be charged with the operation and maintenance of the systems.

The creation of a Central Cooling Group has many advantages. First, it provides a singular point of contact for experiments and a central repository for fluid and thermal property data. This assures that all personnel use consistent information when designing and analyzing the cooling system performance. Second, the Central Cooling Group can promote standardization and consistency with respect to equipment choices and thereby minimize operation and maintenance costs. This approach works best when all detector groups are given sufficient input regarding the choice of cooling system specifics, adequate resources are available to analyze and test different options, and time is available to allow for this testing to be performed.

When individual detector groups are charged with the design and construction of their own cooling systems, many of the benefits mentioned above can still be achieved as long as there is good communication and cooperation. This approach works best when the system design is targeted to take advantage of existing conditions, when time is short, and the need is to build on what was successful in the past and when each group has adequate resources. By allowing the individuality of the groups to influence the design, the goal would be to come up with a scheme that is best suited for each detector and therefore to maximize the performance of the systems. This can come at the cost of increased operation and maintenance expenditures.

D. *System Design Process*

Independent of how the cooling system is designed or fabricated and which specific cooling scheme is chosen, there are several important steps in the "design process" that should be followed. Table 2 lists the typical steps of this process.

Table 2: System Design Process

1. Define Initial Specification
2. Develop Conceptual Design
3. Perform Initial Testing of Concepts
4. Review Conceptual Design
5. Develop Detailed Design & Analysis
6. Perform Necessary Testing
7. Review Final Design
8. Perform Prototype Testing
9. Fabricate “Large” Scale Model
10. Perform Safety Analysis (independent review)
11. Review Results and Issue Notice to Proceed
12. Fabricate Cooling System
13. Perform Acceptance Testing of System
14. Integrate System with Detector
15. Perform Acceptance Testing of Integrated Cooling and Detector (can be done in discrete steps)
16. Install Detector in Experiment
17. Perform Final Safety Review and Sign-Off
18. Commission System

One key to a successful cooling system design is to understand and accept that conditions and requirements coming from the detector can change. Therefore, it is imperative that the cooling system be flexible in its parameters and allow for a certain degree of modification. An approach, which helps identify the adaptability of the design, is to perform a sensitivity analysis during the final design phase. This means that individuals familiar with the system design should look at each of the parameters defined in the initial specification and determine the amount of coupling the system has with that parameter. For example, if the initial specification calls for a coolant temperature of -5°C, can the actual coolant temperature be lowered to -15°C without major changes to the cooling system? Major changes would be those that affect the cooling channel size on the detector or significant cost repercussions for the off detector components. However, if the cooling system had to just switch fluids to allow for a lower operating temperature, this would be considered a relatively minor change and show a certain degree of insensitivity to the operating temperature parameter. In the end, major versus minor changes and the degree of coupling must be determined by the experiment. The important point is to perform this type of analysis before setting the final design in place.

II. PAST, PRESENT & FUTURE COOLING SYSTEMS

Silicon detectors have played a major role in all recent collider experiments and they continue to find application in all types of detectors. They have become synonymous with vertex detection and as experiments strive for higher luminosity operation and better segmentation, they have become more complex. The amount/area of silicon sensors in an experiment has continued to increase as shown in Figure 1. It is interesting to note that space-based experiments, such as GLAST, contribute heavily to the projected totals. [2]

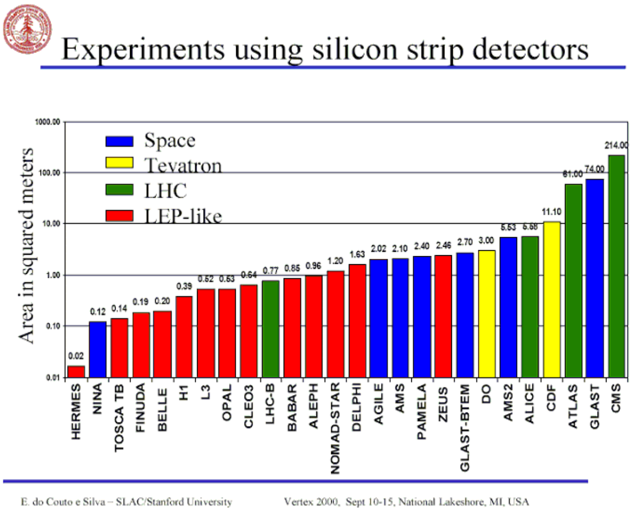

Figure 1: Usage of Silicon in Experiments

When making a survey of silicon detector cooling systems used in high-energy physics experiments, see Table 3 [3, 4], it is important to understand the direct influence of the physics requirements on the choice and design of the cooling system. Radiation hardness requirements for the sensors coupled with the desire to control the signal to noise ratio push the operating temperature of the coolant lower. Low mass specifications limit the size and position of the cooling channels and the amount of fluid in the detector. The state of the art for electronics is also crucial in that it will determine the size, location and power requirements of the silicon detector readout chips. Therefore, in the end, the correct choice of cooling system depends on the environment of the detector and the specifics of the silicon system design.

Table 3: Cooling Systems for HEP Experiments

System	**Size (kW)**	**Coolant**	**Temp (°C)**	**Type**	**Comments**
B Factory					
BaBar	0.45	Water	8°C	Mono	SVT
Belle	0.17	Water	15°C	Mono	SVD
CLEO III	0.49	PF200IG	19°C	Mono	
Tevatron					
CDF	2.8	Water-Glycol	-6°C	Mono	SVXII
CDF	1.9	Water	6°C	Mono	ISL
D0	4.1	Water-Glycol	-10°C	Mono	SMT
LHC					
CMS	123.0	C6F14	-25°C	Mono	Pixel, SST & preshower
ATLAS	76.5	C3F8	-25°C	Evap	Pixel & SCT
ALICE	2.0	C4F10	13°C	Evap	Pixel
LHC-B	0.38	CO2	-25°C	Evap	Vertex

A. *LHC Silicon Cooling Systems*

For the LHC cooling systems the degree of uncertainty is higher as the systems have yet to be built. The data in Table 3 represents the latest information available. There are other systems that do not appear in the table, such as those associated with the LEP-era experiments, however these were chosen as a representative sample. One thing to note is the general trend towards more silicon, higher heat loads, and lower temperatures.

It is clear that historically, water systems have been the fluid of choice but that the evaporative cooling scheme is becoming more prevalent in future systems. The evaporative scheme, whether it is used with a fluorocarbon or cryogenic fluid, involves calculating two phase flow regimes, pressure drop and heat transfer. This analysis can be subject to substantial uncertainty and it is highly recommended that extensive testing be performed to verify results. Even with prototype test results, the ability to scale these flow characteristics up to the size and segmentation needed for LHC-era experiments is not certain. The CERN ST/CV Cooling Group is doing a very good job of addressing all of these issues and providing realistic data.

B. *CDF & D0 Silicon Cooling Systems*

The CDF and D0 silicon systems form the core of their respective detector tracking systems. The designs of the two cooling systems, although similar, are not exact duplicates. Detailed system parameters are shown in Table 4.

Table 4: Cooling Parameters for CDF & D0

	CDF SVX	**CDF ISL**	**DO SMT**
Coolant	Water Glycol	Water	Water Glycol
Operating Temperature (^oC)	-6	6	-10
Heat Load of Detector (kW)	2.8	1.9	4.1
Detector Design	Barrels with bulkheads	Barrels w/cooling channels	Barrels and Disks
Number of Sensors	864	888	1248
Available Cooling Capacity (kW)	10	10	5.2
Maximum Pressure in System (MPa)	0.28	0.28	0.24
Total Flow Rate (L/m)	110	110	40
Subatmospheric Operation	Yes	Yes	Yes
Pump type	Centrif. direct drive	Centrif. direct drive	Centrif. magnetic coupled
Online Spare Chiller Available	Yes (shared)	Yes (shared)	Yes

One of the ways the two systems differ is in the approach taken to maintain subatmosheric operation inside the detector tracking volume. At CDF, "leakless operation" is assured using individual control valves on the inlet lines, pressure transducers on each feed line inside the tracking volume, and a vacuum pump on the air separator vessel. The active control loops and interlocks work together to guarantee the pressure in the detector stays below atmospheric. In D0, this subatmospheric pressure is maintained using an expansion tank on the primary inlet line, which is vented to atmosphere under a nitrogen purge. The elevation of this expansion tank relative to the detector along with the pressure drop of the input lines combine to assure subatmospheric operation inside the tracking volume with few moving parts.

The CDF and D0 systems also have different philosophies with respect to their interlocks. CDF uses a Siemens Quadlog PLC (a SIL 2 rated device) to provide the primary safety interlocks. Additional detector-level interlocks, which help to insure smooth operation, are incorporated into the main controller, a Siemens Simatic 575 PLC. The exclusive use of a PLC solution for detector interlocks required research into possible failure scenarios and extensive discussions with the safety committee. The fact that the Quadlog system is designed and produced specifically to be used as a safety interlock controller and had a Safety Integrity Level rating was the deciding factor. Flexibility, ease of programming, and the ability to use multiple inputs as part of the decision process are just some of the advantages of the PLC interlocks.

The D0 interlock system utilizes a primary safety system based on hard-wired devices embedded in the detector power supply system. Sensor devices such as flow, pressure and temperature switches are summed together and send a permit signal to the power supply. The central controller, a Siemens PLC, provides a second level of interlock support and utilizes "fail-safe" wiring (requires a positive feedback) to keep the silicon system within specified temperature and dew point limits. The three-layer alarm strategy differentiates between low, medium and high alarm states and takes the appropriate predetermined action.

The chiller systems used at both CDF and D0 are commercially supplied units produced by a local vendor. Although the basic components of the systems are similar, they are not exact duplicates. The D0 chiller employs a magnetically coupled centrifugal pump and an air-cooled condenser on the Freon circuit. The CDF system uses a direct drive centrifugal pump and a water-cooled condenser on its chiller package. Each system incorporates filters, inline beryllium specimens to check for possible corrosion, electrical conductivity measurements, pH sensors, and various pressure and temperature transducers to monitor the operating parameters.

C. *Operating Experience*

The CDF and D0 cooling systems have each operated for over 20,000 hours with very few problems. The operating efficiency for both systems is in excess of 99.9%, after initial commissioning. A list of problems for each system is given in Table 5. However, in both cases, the availability of an online spare chiller has helped to minimize downtime.

Table 5: Causes of Cooling System Downtime

CDF	Initial problems with subatmospheric operation (chiller had to be rebuilt)
	Power outages
	Pressure transmitter errors due to magnetic fringe field
	Pressure transmitter failures due to beam loss incident
	Accidental manual valve closing during access time
D0	Power outages
	False trips due to incorrect signals from detector RTDs
	Problems with tracking volume purge flow
	Flow meter and hygrometer failures

Whenever a cooling system is built and operated, valuable information is gathered and opinions are formulated about aspects of what worked well and others that would be executed differently if they were to be done again. Such is the case for the CDF and D0 systems. Given the problems involved in subatmospheric operation and some of the other causes of downtime discovered during commissioning, it is deemed extremely important to set up inspection schedules and acceptance tests for vendor supplied equipment. A good rule of thumb would be to leave nothing to chance and verify all requirements through some predetermined set of tests. This is also relevant for cooling circuits embedded in the detector. Acceptance test criteria should be established so that all parameters of the detector operation can be verified, before it is installed in the experiment.

There are several types of analysis that can be performed to discover possible causes of lower operating efficiencies, including Sensitivity Analysis, Failure Mode and Effects Analysis, and What If Analysis. These methodologies are all good at highlighting single point failures and determining possible negative interactions with other parts of the detector. Finally, knowing the safety related requirements upfront and getting the review committees involved in the early stages of fabrication and testing is very important and helps to assure a smooth commissioning period. As part of the planning for an extended run of the CDF detector, a vulnerability study was performed on the silicon cooling system. The goal was to establish a list of issues that might affect long-term operation. Although the present operating efficiency has been very high, several concerns were raised regarding running the system and the detector for the next five years. These include:

Loss of system expertise. This issue was of particular importance in the area of control system maintenance and programming, since this part of the system was supplied by one of the university groups.

Operating procedure training and updates. The initial operating procedures worked well, but over time, additional information on how best to run the system and recover from upsets has been gained. Capturing this experience in updated procedures is crucial, so downtime is minimized. Detector operators should become familiar with these procedures even though these upset conditions do not occur very often.

Spare component inventory and redundant equipment readiness for operation. During commissioning, a list of spare components was prescribed and all required parts were accumulated. However in the past two years, several parts have been used either on this system or for other parts of the detector. It was recommended that the inventory of spare parts be updated and replenished to initial levels and that redundant chiller equipment be exercised on a regular basis to assure readiness when needed.

Long term data trending and material degradation studies. All modern control systems are capable of tremendous data collection. The challenge is to have someone look at this data set with an eye towards identifying any long term trending leading to a failure condition. This also applies to material degradation studies that may have been part of initial prototype testing. Since it is impossible to observe what is actually happening inside the detector, setting up equivalent running conditions or implanting material specimens in accessible locations may be the next best alternative. Maintaining these tests and periodically observing the results may give valuable insight into future material issues.

III. SUMMARY

Collider experiments operate in a harsh and unforgiving environment and silicon vertex detectors are at the heart of these experiments. The list of important criteria that becomes part of the initial specification for this type of detector is lengthy and forces these devices to be built on the leading edge of their technologies. Cooling systems are an integral part of silicon detector designs and the goal of maximizing operating efficiency means that these systems must run flawlessly. In the past, most cooling systems operated with water as the cooling fluid and convective force flow as the primary heat transfer mode. Some new systems are looking to solve the problems associated with higher heat loads, colder operating temperatures, lower mass requirements and smaller spaces for cooling tubes by changing to an evaporative heat transfer system. These innovative cooling schemes bring with them additional questions concerning accurate pressure drop analysis and flow balancing of multiple input lines. Prototype test models become a critical element in the design process to verify concepts that are difficult to analyze.

Much can be learned from the operating experience being acquired in current experiments. It is important to understand both the successes and failures of those systems that face similar conditions. Communication is the key to avoiding a repeat of any mistakes and the sharing of data can help keep the cost of these detectors under control.

IV. REFERENCES

[1] M. Oclese, “Mechanics and Cooling of Pixel Detectors”, Pixel 2000, Jun 2000.

[2] E. do Couto e Silva, “Space Experiments with Silicon Strip Detectors”, Vertex 2000, Sept 2000.

[3] M. Bosteels et al., “ST/CV Group- Home Page” http://st-support-cooling-electronics.web.cern.ch

[4] A. Warburton et al., “Active Cooling Control of the CLEO Detector using a Hydrocarbon Coolant Farm”, NIM, Jan 2002.