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# THE USE OF A 90 METRE THERMOSIPHON COOLING PLANT AND ASSOCIATED CUSTOM ULTRASONIC INSTRUMENTATION IN THE COOLING OF THE ATLAS INNER DETECTOR

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## ABSTRACT

A new 60kW thermosiphon fluorocarbon cooling plant has been commissioned to cool the silicon tracker of the ATLAS experiment at the CERN LHC. The thermosiphon operates over a height of 90 metres and is integrated into the CERN UNICOS system and the ATLAS detector control system. The cooling system uses custom ultrasonic instrumentation to measure very high coolant vapour flow (up to 1.2 kg/second), to analyse binary gas mixtures and detect leaks. In these instruments ultrasound pulses are transmitted in opposite directions in flowing gas streams. Pulse transit time measurements are used to calculate the flow rate and the sound velocity, which – at a given temperature and pressure – is a function of the molar concentration of the two gases. Gas composition is computed from comparisons of real-time sound velocity measurements with a database of predictions, using algorithms running in the Siemens SIMATIC WinCC SCADA environment. A highly-distributed network of five instruments is currently integrated into the ATLAS DCS. Details of the thermosiphon, its recent operation and the performance of the key ultrasonic instrumentation will be presented.

## INTRODUCTION

The inner tracker of the ATLAS experiment contains silicon microstrip and pixel detectors, evaporatively cooled with $C_3F_8$ (octafluoro-butane: R 218) and $CO_2$.

The present compressor-driven $C_3F_8$ recirculator [1] is being replaced with a new 60kW thermosiphon [2] (Fig. 1) exploiting the 92 metre depth of the ATLAS cavern to generate sufficient liquid hydrostatic pressure (16 bar) to circulate $C_3F_8$ through the tracker, without any moving parts in the primary coolant loop. Vapour returns by pressure differential to the above-ground condenser; the lowest pressure part of the system.

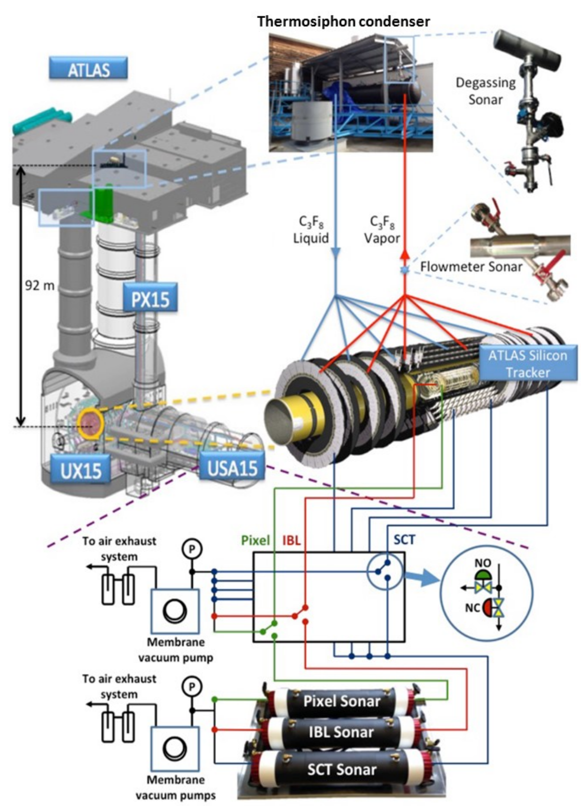


Figure 1: The ATLAS thermosiphon recirculator for the $C_3F_8$ evaporative cooling of the inner silicon tracker, showing the linked ultrasonic instruments.

The thermosiphon has a cooling capacity of 60 kW and circulates $C_3F_8$ at a high mass flow of up to 1.2 kg/second.

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It is integrated into the CERN UNICOS system and interfaced to the ATLAS detector control system (DCS).

In addition to improved reliability over a compressor-driven system, the thermosiphon offers the possibility of lower operating (evaporation) temperatures within the cooling channels of the silicon tracker, affording the microstrip and pixel detector modules better protection against radiation damage as the LHC luminosity increases.

The thermosiphon was successfully commissioned with the silicon tracker in tests made during April 2017. During that time the ATLAS elements of the silicon inner tracker were evaporatively cooled with $C_3F_8$ at their maximum power dissipation of 60kW with multiple changeovers ("swaps") made between the compressor and thermosiphon recirculators with the silicon modules remaining powered. The maximum temperature excursion on the silicon modules during these swaps was 2 °C, well within safety limits. The thermosiphon will replace the compressor driven recirculator during 2018.

Custom ultrasonic ("sonar") instrumentation [3], [4] is extensively used in the thermosiphon and silicon tracker cooling control systems to:

- Measure the very high $C_3F_8$ coolant vapour flow returning to the thermosiphon condenser.
- Measure air ingress into the thermosiphon condenser and detect leaks of coolant into the nitrogen-purged anti-humidity envelopes surrounding the silicon tracker sub-detectors, through the use of binary gas mixture analysis.

Two axial sonar instruments with 498 mm acoustic paths analyze gas aspirated at constant low flow (~0.1 $l.min^{-1}$) from the $N_2$ envelopes of the ATLAS silicon pixel and SCT detectors to locate trace concentrations of $C_3F_8$ coolant leaks. A third tube is used to detect $CO_2$ coolant leaks into the envelope surrounding the innermost IBL pixel detector layer (Fig. 1). Long term temperature stability of ±0.2°C can be achieved by water circulation through the double wall construction of these tubes.

It can also be seen from Fig. 1 that the ultrasonic instruments are widely distributed in location, requiring an extended communication network. Figure 2 illustrates their implementation within the ATLAS DCS.

The local electronics of each instrument pass sound transit time, temperature and pressure to a PowerEdge 610 SCADA computer running Siemens WINCC-OA [5] under Linux, where more complex tasks such as gas composition analysis or flow calculations are performed. The computer is located in an underground technical cavern and connected to the ATLAS DCS Ethernet network. The custom WINCC project gathers data from all the instruments. Its tasks include:

- Communication with all five ultrasonic instruments using Modbus TCP/IP over Ethernet.
- The graphical user interface for all the instruments.
- The calculation of flow and mixture composition using on-line transit time, temperature and pressure data.
- The manipulation of valves and vacuum pumps to sequence the aspiration of gas streams to be sampled.
- The data storage, including calculated flow and mixture compositions to the ATLAS DCS database.
- The selection of critical data parameters to be sent to the ATLAS alarm handling FSM (finite state machine) and control room personnel.

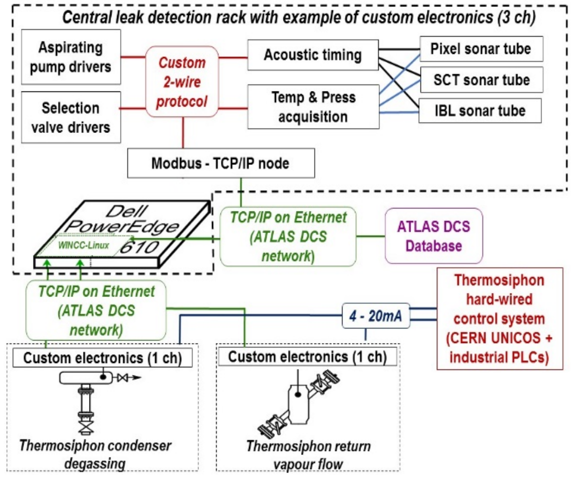


Figure 2: Interconnection architecture for the sonar instruments in the ATLAS detector control system.

In addition to long distance communication via Ethernet the custom electronics integrates a custom 2-wire communication protocol for local liaison between acoustic modules, analog (temperature, pressure) input modules and valve and vacuum pump drivers (Fig. 2).

## ULTRASONIC INSTRUMENT OPERATION

The custom electronics - illustrated in Fig.3 - is based on dsPIC33F microcontrollers and centred on use of the

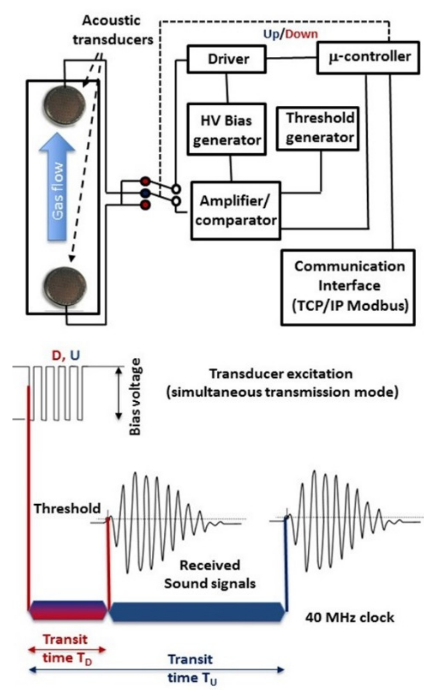


Figure 3: Ultrasonic driver/amplifier and timing circuit.

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SensCorp Model 600 capacitative 50kHz ultrasonic transducer [6].

These transducers use low inertia gold-coated Mylar membranes with fast (< 5 µs) 10-90% signal rise-time in response to arriving ultrasound pulses. The transducers are sensitized for reception with +300 V bias and energized for transmission by (300➔0V) square wave pulse transitions. The receive chain contains differential & programmable gain amplifiers followed by comparator also implemented in the µ–controller.

Ultrasound pulses are transmitted in opposite directions in flowing gas. Synchronous with the leading edge of the first transmitted sound pulses 40 kHz readout clocks are started, which are stopped by the first pulse that exceeds the user-defined threshold for the signal from the opposing transducer. Time-stamped bi-directional transit times are measured approximately 20 times/second along with temperature and pressure. Parameter values from rolling averages of typically 100 readings are calculated and sent from the FIFO memory to the SCADA computer.

## BINARY GAS MIXTURE ANALYSIS

Five ultrasonic instruments are integrated into the ATLAS DCS. Binary gas mixture analysis and flow calculation are carried out in scripts running under Siemens SIMATIC WinCC on Linux in the SCADA computer.

Differences in transit times in the opposing directions are used to calculate the flow rate while their averages can be simultaneously used to calculate sound velocity,

Gas composition is computed on-line from comparisons of real time sound velocity measurements with a prediction database composed of sound velocity/concentration look-up tables for different gas pairs over the concentration, temperature and pressure ranges of interest. The look-up tables can based on prior measurements in calibration mixtures and/or theoretical predictions made with an appropriate equation of state for example using NIST-REFPROP [7].

The binary gas analysis algorithm is based on the general equation for sound velocity, c, in a gas:

$$c = \sqrt{\frac{\gamma R T}{M}} \tag{1}$$

where ***R*** is the molar gas constant (8.314 J·mol$^{-1}$·K$^{-1}$) and ***T*** is the absolute temperature in degrees Kelvin.

The value of $\boldsymbol{\gamma}$ for a binary mixture is given by the ratio of the weighted sums of molar specific heat at constant pressure ($\boldsymbol{Cp_{i=1,2}}$) to that at constant volume ($\boldsymbol{Cv_{i=1,2}}$) for the two components:

$$\gamma_m = \frac{C_{pm}}{C_{vm}} = \frac{\sum_i w_i Cp_i}{\sum_i w_i Cv_i} \tag{2}$$

where $\boldsymbol{w_{i=1,2}}$ are the molar fractions of the two components. Similarly, the molar mass of the mix, ***M***, in kg·mol$^{-1}$, is given by:

$$M = \sum_i w_i M_i \tag{3}$$

In this way equation (1) becomes:

$$c = \sqrt{\frac{\frac{\sum_i w_i Cp_i}{\sum_i w_i Cv_i} RT}{\sum_i w_i M_i}} \tag{4}$$

Figure 4 illustrates the variation of sound velocity with the concentration of $C_3F_8$ in $N_2$ in the range 0 ➔ 1%. The added indices illustrate the relationship between the uncertainties in measured sound velocity, $\boldsymbol{\partial c}$, and mixture determination, $\boldsymbol{\partial(mix)}$. At any concentration of the two components;

$$\partial(mix) = \frac{\partial c}{m} \tag{5}$$

where ***m*** is the local slope of the sound velocity/ concentration curve.

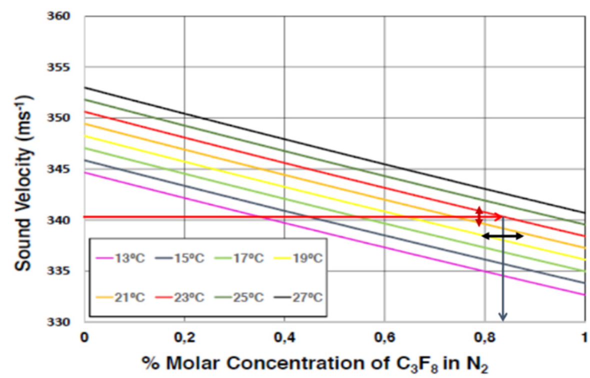


Figure 4: Variation of sound velocity with concentration of $C_3F_8$ in $N_2$ in the range 0 ➔ 1%. The added indices illustrate the relation between the uncertainties in measured sound velocity and mixture determination.

Contributions to the ±0.025 ms$^{-1}$ overall sound velocity measurement error typically seen in our instruments come from:

- ±0.1°C temperature uncertainty in gas (±0.02 ms$^{-1}$).
- ±1 mbar pressure uncertainty (±0.003 ms$^{-1}$).
- ±0.1mm transducer spacing uncertainty (±0.002 ms$^{-1}$)

From calibration in pure gases with known sound velocity dependence on temperature and pressure [7].

- ±100 ns transit time uncertainty (±0.002 ms$^{-1}$).

The gas pair illustrated in Fig. 3 is of interest to monitoring the leakage of $C_3F_8$ evaporative coolant into the $N_2$-purged envelopes of the ATLAS pixel and SCT subdetectors, as illustrated in Fig. 1. In the $C_3F_8$ range of interest between 0 and 1%, the average local slope of the sound velocity vs. concentration curve yields a mixture uncertainty of ±2.10$^{-5}$ via eq. (5).

Figure 5 illustrates the change in baseline $C_3F_8$ concentration seen in the ATLAS pixel detector $N_2$ envelope on cooling system startups separated by one year. Gas is permanently aspirated from the pixel envelope

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through a sonar tube, as illustrated in Fig. 1. No increase in leak rate was seen between 2016 and 2017. Although individual leaking circuits have been identified through successive isolation the current leak rate is considered tolerable.

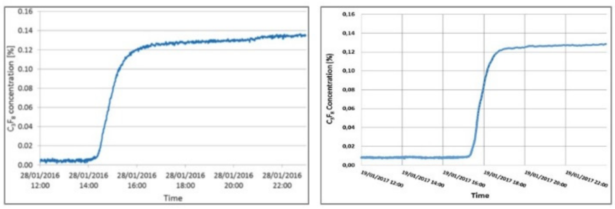

Figure 5: $C_3F_8$ concentration increase seen in the $N_2$ -purged anti-humidity volume of the ATLAS pixel detector during cooling startup, January 2017 & 2017.

The concentration finding algorithm uses look-up tables stored as arrays of parameters of fits of sound velocity *vs.* composition over the desired concentration, temperature and pressure range of interest for a particular gas pair. Grid spacings of 0.5 ºC and 20 mbar are used for the sonars monitoring coolant leaks into the sub-detector environmental volumes, while a coarser granularity of 1 ºC and 100 mbar is used for the "degassing" sonar of the thermosiphon condenser discussed below. The concentration finding algorithm linearly interpolates stored fit parameters to values corresponding to the measured temperature and pressure. These are then used with the measured sound velocity to calculate the corresponding binary gas molar composition.

Figure 6 illustrates the instrument installed vertically above the thermosiphon condenser, externally on the roof of the ATLAS buildings at CERN. This instrument forms a part of the thermosiphon control system and is intended to detect and eliminate ingressed air which would otherwise reduce the efficiency of $C_3F_8$ circulation by raising the condenser pressure.

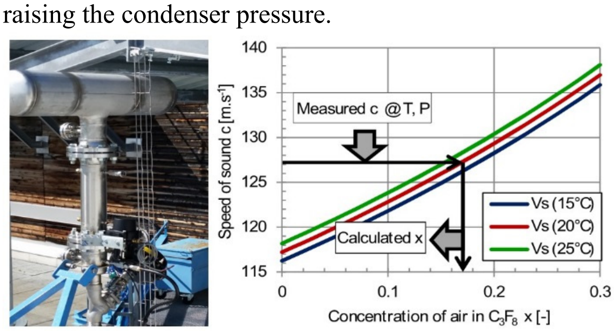


Figure 6: Left: the degassing sonar installed above the condenser of the ATLAS thermosiphon prior to the fitting of the PID-controlled heater jacket and thermal insulation. Right: Sound velocity *vs.* air/$C_3F_8$ composition at 3 sonar tube temperatures: condenser pressure 300 $\text{mbar}_{\text{abs}}$.

Since air is nearly a factor 10 lighter than $C_3F_8$, any ingress will concentrate in the sonar and collection tank, causing the sound velocity to increase, as illustrated in Fig. 6. The analysis precision is less demanding in this instrument: an air concentration of a few percent can trigger venting by closing a valve between the sonar and the condenser and opening another valve to evacuate its contents. Too low a threshold would waste expensive $C_3F_8$, while too high a level might allow the condenser pressure to rise to a level that would unacceptably reduce the $C_3F_8$ vapour return flow.

In the range 0-10% air contamination in $C_3F_8$ the average slope of the sound velocity *vs.* concentration curve is ~0.56 $ms^{-1}\%^{-1}$. The typical sound velocity measurement precision of ± 0.025 $ms^{-1}$ would yield an uncertainty in air concentration of ± 0.05%.

## GAS FLOW DETERMINATION

Ultrasonic instruments can be configured for simultaneous gas flow measurements, based on the difference in transit times of ultrasound, $t_{up}$ and $t_{down}$, in opposite directions in flowing gas. We have found that instrument precision can be enhanced through decomposition of the acoustic path into the two component acoustic lengths:

- ***L***, where the gas is in laminar motion.
- ***L'*** where the gas is considered static or moving perpendicular to - or in a closed vortex in - the acoustic path.

The gas flow velocity, ***v***, can be expressed as:

$$v = \frac{c(ct_{up} - (L+L'))}{(ct_{up} - L')} \quad \text{or as} \quad v = \frac{c((L+L') - ct_{down})}{(ct_{down} - L')} \tag{6}$$

with the volumetric flow obtained from multiplication by the area of the gas flow tube.

We have developed instruments [1], [8] with the acoustic path aligned with the gas flow and angled with respect to it. The principal constraint in each geometry is that the acoustic path should sample the entire profile (diameter) of the flowing gas. In a linear geometry this implies that the flow tube diameter cannot exceed that of the transducers, limiting flows to lower values than in angled geometries with transducers located outside the gas flow and transmitting sound obliquely across a much larger tube.

Figure 7 illustrates the case for the angled ultrasonic flowmeter constructed to measure the return $C_3F_8$ vapour flow to the thermsiphon condenser. The 568 mm acoustic path crosses the 131.7 mm diameter gas flow tube at 45°.

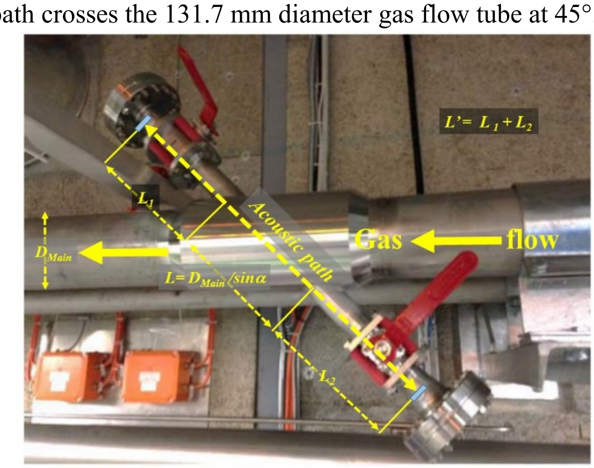


Figure 7: The angled ultrasonic flowmeter installed in the ATLAS thermosiphon vapour return line.

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The positioning of the ultrasonic transducers to minimize pressure drop and turbulence in the sound path was the subject of an extensive CFD simulation [1]. They are mounted on stainless steel UHV flanges equipped with and ports for evacuation and the injection of calibration gas into each side arm. Quarter-turn ball valves with 40mm diameter orifices allow the sound to pass but can be closed for transducer access without interrupting the $C_3F_8$ vapour flow or exposing it to air pollution. A pressure transducer and three thermistors monitor each side arm of the flow meter to allow the density of the circulating $C_3F_8$ vapour to be calculated, via [7], to convert the volumetric flow into an equivalent mass flow.

The acoustic path in moving gas is given by $\boldsymbol{D_{Main}/\sin\alpha}$, where $\boldsymbol{D_{Main}}$ is the internal diameter of the main tube (and $\boldsymbol{\alpha}$ is the acoustic path crossing angle. The acosutic path in static gas $\boldsymbol{L}$` is made up of components $\boldsymbol{L_1}$ and $\boldsymbol{L_2}$ in the two side arms. Equation (6) respectively becomes:

$$v = \frac{c\left(ct_{up} - \frac{D_{Main}}{\sin\alpha} - L'\right)}{\cos\alpha\,(ct_{up} - L')} \quad or\ v = \frac{c\left(\frac{D_{Main}}{\sin\alpha} + L' - ct_{down}\right)}{\cos\alpha\,(ct_{down} - L')} \qquad (7)$$

The flowmeter demonstrated linearity in air flows up to 10 $ms^{-1}$ (131 $l.s^{-1}$) before installation, with an *rms* precision of ± 2.3 % of full scale. Figure 8 illustrates measurements made with the flowmeter in $C_3F_8$ vapour circulating in the thermosiphon to cool the ATLAS SCT and pixel detectors in April 2017.

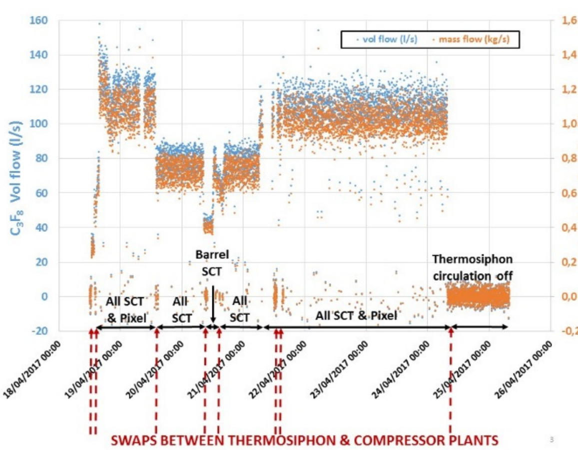

Figure 8: $C_3F_8$ volumetric and mass flow measured in the angled ultrasonic flowmeter in the ATLAS thermosiphon vapour return line (April 2017).

During these commissioning tests the ATLAS SCT and pixel subdetectors were evaporatively cooled with $C_3F_8$ at power levels up to their maximum combined dissipation of 60kW. With only the barrel SCT silicon microstrip modules powered the dissipation of nearly 22 kW required the circulation of around 0.4 $kg.s^{-1}$ of $C_3F_8$. The corresponding mass flow with the full SCT (barrel and endcap modules) powered was around 0.75 $kg.s^{-1}$, while that required to cool the combined SCT and pixel detectors was around 1.1 $kg.s^{-1}$, as illustrated in Fig. 8. The mass flow resolution of the ultrasonic flowmeter during these runs was around ± 0.05 $kgs^{-1}$.

During the commissioning tests repeated transitions (cold "swaps", illustrated by red arrows in Fig. 8) were made between the thermosiphon and compressor-driven recirculators with the silicon modules of the SCT and pixel detectors remaining powered. During compressor operation no flow is seen in the $C_3F_8$ vapour return line to the condenser since the vapour is redirected to the compressor inputs.

## CONCLUSION

The ATLAS thermosiphon recirculator was commissioned in tests made during April 2017, during which the ATLAS SCT and pixel sub-detectors of the silicon inner tracker were evaporatively cooled with $C_3F_8$ up to their maximum combined power dissipation of 60kW. Numerous cold "swaps" were made between the compressor and thermosiphon recirculators with the silicon modules kept cooled and powered. The maximum temperature excursion on the silicon modules during these swaps was 2 °C, well within safety limits. The thermosiphon will replace the compressor-driven recirculator as baseline system during 2018.

Custom ultrasonic instrumentation, integrated into the ATAS detector control system played an important role in the thermosiphon commissioning tests by monitoring the flow of circulating $C_3F_8$ and for verifying the absence of air leaks into the thermosiphon condenser during these operations. This instrumentation has been integrated into the ATLAS detector control system.

The combined architecture provides a high level graphical user interface and data archiving for an ensemble of distributed instruments with the abstraction of critical parameters and rapid hardwired feedback to industrial control systems.

Other potential applications requiring binary gas analysis and simultaneous flowmetry include anaesthesia, the analysis of hydrocarbons and vapour mixtures for semiconductor manufacture.

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