FLUOROCARBON EVAPORATIVE COOLING DEVELOPMENTS FOR THE ATLAS PIXEL AND SEMICONDUCTOR TRACKING DETECTORS

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ABSTRACT

We report on the development of evaporative fluorocarbon cooling for the ATLAS pixel and Semi-Conductor Tracker (SCT) detectors. Data are presented from cooling studies on representative prototype pixel and SCT detector thermo-structures, using perfluoro-n-propane (C_3F_8), -butane (C_4F_{10}), trifluoro-iodo-methane (CF_3I) and custom C_3F_8/C_4F_{10} mixtures. Thermo-physical properties were calculated for custom mixtures.

For most of the structures tested at full projected power dissipation, operation of silicon detector substrates at temperatures below –7ºC (required for 10 year lifetime in the radiation environment of LHC) should be possible, albeit in some cases with increases in inner diameter (I.D.) of the coolant tubes from those of the present series of prototypes.

Heat transfer coefficients in the range $2\text{-}4.10^3 Wm^{-2}K^{-1}$ have been measured in a 3.6 mm I.D. heated tube dissipating the full equivalent power (~110 W) of a barrel SCT detector "stave", for a range of power dissipations and mass flows in the above fluids.

Aspects of full-scale evaporative cooling circulator design for the ATLAS experiment are discussed, together with plans for future development.

(1) INTRODUCTION

The SCT detector (1) will have 4 cylinders around the collision point (*barrel*) and 9 forward disks at each end. Each cylinder consists of "staves" containing 12 silicon strip detector modules. The total detector dissipation will be around xxx kW, with ~9W from each module, subdivided into ~2W (after 10 years of irradiation) from the silicon substrate, and ~7W from the readout electronics.

The pixel detector (2) has ten forward disks and three cylinders containing staves of 13 pixel detector modules. The total detector dissipation will be around xxx kW, with around 8.5W from each module (11.5W in the B-physics layer at a radius of ~4.5 cm from the beams).

Our studies are directed to cooling systems contributing the minimal possible material; particularly important for the pixel B layer. Evaporative fluorocarbon cooling combines high heat transfer coefficients with very low circulating coolant mass (1–2 gs^{-1} / 100 Watts to evacuate). Liquid refrigerant can be delivered to the detector in capillaries with IDs as small as 0.6 mm. Furthermore, fluorocarbon refrigerants are non-flammable, non-toxic insulators with zero ozone depletion potential.

Table 1: Selected Refrigerant Properties (-15º C)

Fluid (ref)	**L** **(Jg^{-1})**	**$Vol_{(vap)}$/ $cm^3_{(liq)}$**	**S.V.P (bar a) @ -15º C**
C_3F_8 (3)	97.0	71.4	2.46
C_4F_{10} (3)	101.1	242.6	0.58
CF_3I (4)	100.8	176.3	1.33
C_3F_8/ C_4F_{10} (50/50) (5)	98.3	147.6	$1.01P_{SV}$ ➔$1.65\ P_{SL}$

Latent heat data for the various refrigerants are shown in table 1, together with their saturated vapour pressures the volume of vapour produced per cm^3 liquid evaporated at –15ºC (a temperature chosen to accommodate probable thermal impedances between the silicon substrate and the coolant). A target evaporation pressure of 1 bar (abs) would allow the use of very low mass tube (~0.2 mm wall aluminium or composite) with various aspect ratios.

2. TEST RESULTS ON SCT AND PIXEL PROTOTYPE THERMO-STRUCTURES

2.1 The Refrigerant Recirculator

A closed-loop evaporative recirculator (figure 1) has been built for testing thermo-structures using all the fluids of table (1). Structures are placed in a chamber purged with inert gas and maintained at –7ºC, to simulate the environment of the SCT and pixels in the ATLAS inner detector.

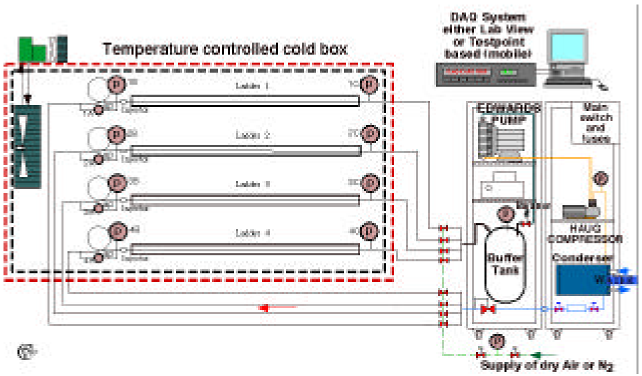


Figure (1) The Two-Stage Evaporative Recirculator

The present circulator contains two compressor stages and a water-cooled condenser, also serving as a high-pressure liquid refrigerant reservoir. The first stage compressor[1] is used only with low input pressure vapours as in the case of C_4F_{10} or C_3F_8/C_4F_{10}, since the pumping speed of the second stage[2] compressor is insufficient at input pressures below 1 bar abs. These compressors will soon be replaced with a single stage dry scroll compressor (Atlas Copco SF6-8-120) with a measured flat pumping speed of ~18 m^3hr^{-1} for both C_4F_{10} (P_{in} = 0.25, P_{out} = 4 bar abs) and C_3F_8 (P_{in} = 2.4, P_{out} = 8 bar abs).

Liquid refrigerant enters a four-channel supply manifold, whose pressure - defined by a regulator – determines the liquid mass flow. Fluid enters the test structures via capillaries with diameters varying between 0.6 and 1 mm, or via injectors made from synthetic ruby watch bearings with orifices varying between 210 and 300 µm.

The temperature of evaporation of fluid in the test structures depends on the pressure in a 4-channel vapour collection manifold tank, controlled via feedback from a pressure sensor[3] to a variable orifice valve located between the tank and the compressor input. The circulating mass flow is metered after the tank.

2.2 Tests on a Forward SCT Thermo-Structure

Figure 2 shows a recent model for the on-detector cooling for a quarter disk of the ATLAS forward SCT, in which 18 similar disks will each support 132 silicon strip modules, and dissipate a total of 132x9,6 Watts.

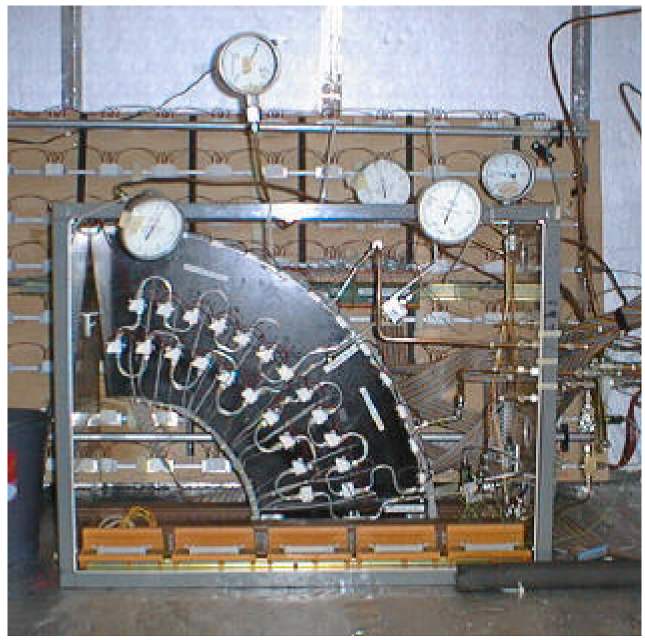


Figure 2. Forward SCT Quadrant Thermal Model

On the “front”, heat from two arcs of silicon micro-strip modules (simulated with resistive heaters), is conducted to the coolant via attachment blocks glued to the cooling tubes (figure 3). On the “rear” a third arc of modules will provide tacking hermeticity through overlap.

To accommodate thermal expansion effects, each quadrant has two serpentine circuits with 3.6 mm ID tubes, and lengths 2.5 & 3.5m (“A”&”B”), respectively cooling 14 and 19 modules. Each circuit first cools the inner front arc of modules, follows an arc at the outer radius, and then cools the modules on the rear of the panel.

Thermal connections to the cooling tube are of several types: some attachment blocks evacuate the simulated 7W power of the module readout electronics (“E”): those along the front outer arc evacuate only 1.8W of substrate (“S”) dissipation. The innermost front blocks traverse the support, and evacuate, in addition to the 8.8W (E+S) dissipation of the front inner modules, 1.8W from the simulated substrates of the rear modules. Blocks are of several different heights, and some span a gap between joined tubes, presenting a lower impedance for heat conduction into the fluid.

[1] Edwards ECP 30 Dry Rotary Scroll Vacuum pump
(rated 30 m^3hr^{-1} air; P_{in} 1 bar abs, P_{out} = 1.5 bar abs limit)
[2] Haug XXX Dry Piston Compressor
(rated 3.6 m^3hr^{-1} air, P_{in} 1 bar; P_{out} = 9 bar abs limit)
[3] MKS Baratron Model 720? Range 0-5000 Torr (abs)

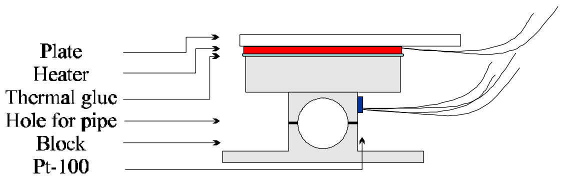


Figure 3. Module Heat Sinking in the Forward SCT through the use of Attachment Blocks.

Figure 4 shows the temperature profile along circuit "B" with C_4F_{10} at half-nominal power (3.42W (E); 0.97W (S)). The tube is everywhere <-10°C: with the exhaust cooler than the input (characteristic for evaporative cooling), in this case by 6ºC. Most blocks lie below the target temperature of -7ºC. The six with double sided heating are considerably warmer (-2º→-5º C) than the (S) blocks or those spanning a tube join.

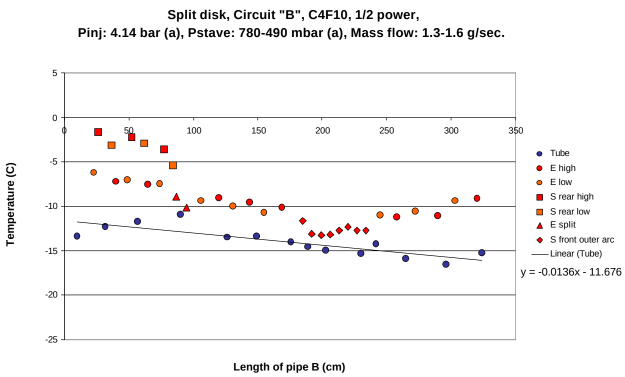


Figure 4: C_4F_{10} at half power: circuit "B".

We could not cool the present structure to –7 C at the full power dissipation with C_4F_{10}, due to the large pressure gradient along the 3.6 mm ID tube, generated by the relatively large volume of vapour produced (table 1) at the low boiling pressures around 500 mbar (abs).

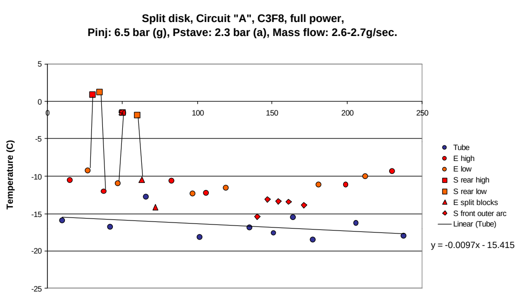


Figure 5: C_3F_8 at full power: circuit "A".

For C_3F_8 the results were significantly better. At full power (7W (E); 2W (S)) and a boiling pressure 2.3 bar a, the temperature of all blocks, with the exception of the rear "S" side of the double block (now being redesigned), were below –6ºC, and the temperature gradient along the tube was only ~2ºC. The temperature difference between the blocks and the tube was also less, probably due to a higher heat transfer coefficient for C_3F_8. By decreasing this boiling pressure, the temperature of the test structure could be further, uniformly, reduced.

2.2 Tests on SCT Barrel Structures

The present cooling circuit manifolding proposed for the SCT barrel is shown in figure 6. Coolant is injected through a capillary to a series pair of staves with a total tube length of 3.2m. A common exhaust is shared with a second series pair of staves mounted in parallel.

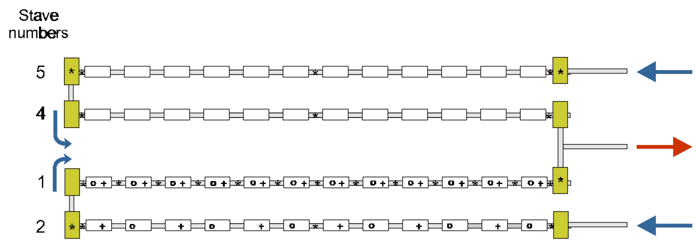


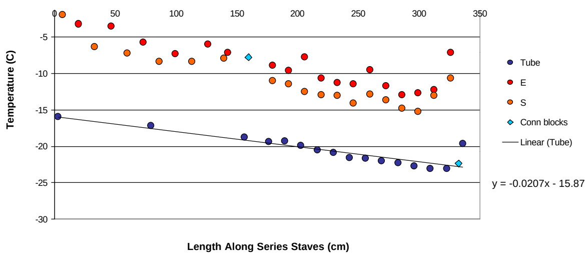
Figure 6: SCT Barrel Stave 4-fold Manifold

In the present thermo-structure, each stave carries 12 heater plates attached with thermally conductive glue to one 7.2mm side of a flat-walled oval tube having an equivalent I.D. of 2.7mm. A total of 64 temperature sensors are attached to the plates and on the tubes between them. Plates are laminated from two (60 x 20 mm) pieces of aluminum with thermally conductive glue, to investigate the layering of the detector module, in which the hybrid supporting the readout electronics ("E") is mounted on top of the silicon substrate ("S"), which has closer attachment to the cooling tube. Temperature sensors are mounted on the E and S sides of the blocks.

Figure 7 shows sample data taken with C_3F_8 at 10W/block. The temperature (pressure) gradient between the input of the first series stave and the output of the second is ~7°C (1.1 bar). Block temperatures vary between -2°C and -13°C, and the target (S) temperature of -7°C is not met at the beginning of the first stave. The (60 x 7mm) film of thermal glue fastening the blocks to the tube causes an average temperature difference of ~ 7°C between the tube and the S sides of the blocks. The E sides are ~2°C warmer. It was concluded that the 2.7 mm ID of the cooling tubes in the present thermo-structure was insufficient to evacuate the vapour produced from ~240 Watts dissipation of two staves in series. Figure 8 is an example of test data with

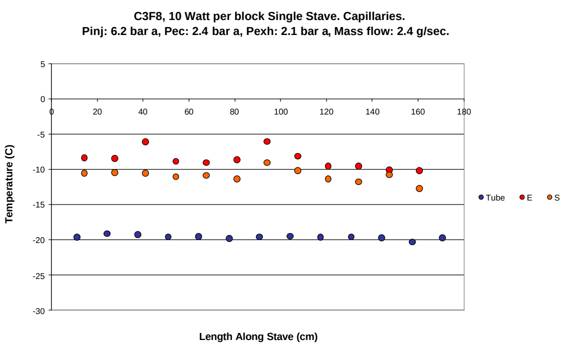
Figure 7: Barrel SCT Series Stave Test with C_3F_8

the manifold rebuilt for "single pass" of refrigerant. The temperature (pressure) profile along the single 1.6m



stave with the 2.7 mm ID tube is ~7°C (0.3 bar). Block temperatures (E) vary between -8°C and -11°C, and the target (S) temperature of -7°C was met everywhere along the stave.

Figure 8: Forward SCT Manifold Test with C_3F_8:
10 Watts per block, single stave



2.3 Tests on Pixel Forward Structures

Thermal measurements have been made on a developmental series of forward pixel disk sector thermo-structures (ref Pixel TDR), in which cooling tubes bent in 'W' or 'WV' shapes are sandwiched between skins of Carbon-Carbon (C-C). In some structures, an aluminium tube with slightly flattened faces was used, while in others, a glassy carbon tube, "flocked" with grown-on carbon fibres is bonded to the C-C plates (ref). Figure 9 shows the thermal profile on a
prototype sector with a 3.6mm ID carbon tube and C_4F_{10} coolant at a boiling pressure of 345mbar. This sector carried 10 pixel modules dissipating a total of 55W. More recent structures have fewer modules and a shorter cooling tube. The temperature profile on the sector was found to be invariant with orientation (ref Pixel TDR).

2.4 Tests on Pixel Barrel Structures

Thermal measurements have been made on an 80cm pixel barrel stave thermo-structure with a 2.9 mm equivalent ID cooling channel made from a carbon fibre U channel glued to a sealed C-C support plate, onto which 13 dummy pixel modules are glued. In the pixel cooling layout, pairs of staves in the 2 outer (r = 10, 13 cm) pixel layers dissipate ~100W and share a common exhaust tube. In the B-layer the higher occupancy closer to the beams, stave dissipation is ~143W.

Figure XXXa,b shows the temperature profile along the stave for CF_3I and C_4F_{10} for power loads varying between 78W and 143W, for C_3F_8 at a power of 100W and for a 50/50 (molar) C_4F_{10}/C_3F_8 mixture at 55W. The average silicon temperatures at the different boiling pressures are given in table (2). It was found that the hydraulic ID of the present pixel stave is insufficient to maintain the -7°C silicon temperature with C_4F_{10} at dissipations exceeding ~80W, and with the 50/50 C_4F_{10}/C_3F_8 mixture at dissipations exceeding ~60W, but that cooling to the target temperature was possible, both with CF_3I and C_3F_8 at the highest envisaged dissipation.

Two-phase flow pressure drop calculations have suggested that satisfactory cooling at the highest power should be possible with a hydraulic ID of 3.x mm (ref Derek Cragg): the next iteration of the pixel stave will use a tube of this dimension.

Table 2: Temperature Profile Summary for different fluids: pixel stave thermo-structure

Fluid	**Power on pixel stave (W)**	**Boiling Pressure (bar abs)**	**Average Silicon Temp**
CF_3I	78 143		-8.0 -7.0
C_4F_{10}	78 100		-7.0 -3.5
C_3F_8	100	1.67	-15.0
C_3F_8/ C_4F_{10} (50/50)	55	0.83	-11.0

3. MEASUREMENT OF HEAT TRANSFER COEFFICIENT

A second refrigerant recirculator (ref Tapio) was constructed to allow simultaneous measurements of heat transfer coefficient while full size thermo-structure prototypes were measured in the main circulator. Heat transfer coefficients were measured on a 1.6m long simplified SCT stave with 12 copper blocks soft-soldered onto a 1.6 m long cupro-nickel tube with 3.6mm ID. On each block were a ceramic heater and a PT100 sensor. PT100's were fitted to the coolant tube in 13 positions between the blocks and at each end. Another sensor measured the liquid temperature upstream of the capillary or injector. In this tube, heat transfer coefficients (H.T.C: Wm^{-2} K^{-1}) were measured at 12 points along the tube from the (block-tube) temperature difference, and knowledge of the dissipation at each block and its contact area with the tube. Typical HTC measurements for the different fluids in this tube are shown in figure ZZ, and varied in the range $2\text{-}4.10^3$ depending on power dissipation. The highest HTCs were seen in the case of C_3F_8, and the lowest for with the 50/50 C_4F_{10}/C_3F_8. The reason for this difference is not presently known, and measurements are continuing.

4 IRRADIATION STUDIES OF FLUOROCARBONS

Samples of saturated ($C_nF_{(2n+2)}$) fluorocarbons and CF_3I have been subjected to high dose rates of ionizing and neutron irradiation.

4.1 Neutron Irradiation

Perfluoro-n-pentane (C_6F_{14}) and CF_3I were subjected to neutron irradiations simulating the total dose over 10 years of operation at LHC. Studies showed the main longest lived radioisotopes to be ^{18}F (106 min 511 KeV γ emitter) and ^{128}I (25 min: 433 KeV γ emitter).

(2.1) Neutron Irradiations

(2.1.1) Results of neutron activations of iodine (I2) at SINQ, PSI

Irradiation Time: 20 sec

Fluences: n(thermal): 2.2*10^13 cm^-2; n(epithermal): 5.7*10^10cm^-2 n(fast): 3.9*10^11 cm^-2

Measured 3 samples (each of mass 41.7 microgram) of solid iodine

The only radioisotope found was 128I (T/2 = 25 min, 443, 526 KeV gammas)
Measure activity after 20 sec: (232 +/- 3)Bq/gm

(2.1.2) Results of neutron activations of Teflon, C6F14 liquid, CF3I gas and solid iodine at the TAPIRO reactor, ENEA Casaccia.

Characteristics
Radial channel 1:
Irradiation time; 8 min at 1 Watt power.
Cumulative neutron flux; 4.2 *10^10

Results for Teflon: no activity above background (285 Hz)

Results for C6F14 liquid: no activity above background (285 Hz)

Results for CF3I gas (in pure Al tube):
28 Al and 27 Mg were recorded;
after 3 hours cooling time background was reached

Results for solid iodine (in polypropylene tube):
128I recorded. Initial activity 1.7*10^5 Bq/gm
after 2.45 hours cooling time background was reached

(2.1.3) Maximum Expected Neutron Fluences and Activities

(Sorin did not specify the radii to which these fluences correspond)

CMS Tracker TDR: E < 100 KeV 4.10*4 n/cm^2s^-1
CMS Tracker TDR: E > 100 KeV 5.10*5 n/cm^2s^-1

ATLAS Tracker TDR: E < 100 KeV 7.10*4 n/cm^2s^-1
ATLAS Tracker TDR: E < 100 KeV 1.10*6 n/cm^2s^-1

Expected specific activity for 2.10*7 n/cm^2 and 20 s irradiation
for pure iodine: 120000 Bq/gm

Expected activity per gram for 2.10*7 n/cm^2 and 20 s irradiation of CF3I

From 12C (0.069 grams): negligible
From 19F (0.29 grams): 6000 Bq (1.63 MeV gamma)
From 127I (0.65 grams): 8000 Bq (0.443MeV gamma)

(4.2) Radiochemical Studies

Radiochemical studies on C_6F_{14} and CF_3I were carried out with doses up to ~ 6Mrad of ^{60}Co γ's. In some studies, samples of materials from which a cooling circuit might be built were immersed in the liquid.

Experience with RICH detectors has shown that molecules of the form $C_nF_{(2n+2)}$, made by F ➔ H substitution from the corresponding hydrocarbons, can sometimes be incompletely fluorinated, giving a source of H for radiolytic formation of chemically aggressive HF.

The high irradiation doses (> 2 MRad/yr) in the inner detector cavity of ATLAS might cause the disintegration of these molecules into chemically aggressive HF. 0.2% of circulating around expected to cause the break-up of about (2.2.1) Products of Radiolysis and their Radiochemical yields (literature data)

(G value = no. Molecules produced per 100 eV absorbed energy:
(G =1 corresponds to 0.1036 micromoles/Joule))

FLUID	PHASE PRODUCT	
RADIOCHEMICAL YIELD		
McAlpine	Shah	Hsieh
(760 Torr)	(300 Torr)	(25 Torr)
CF3I	Gas	I2
0.13	4.08	0.5
		CF4
1.08	0.03	0.55
	(0.6 in 5% O2)	
		C2F4
-	0.89	0.0056
		C2F6
-	3.0	0.11
		C2F2I2
0.82	-	0.01
		C3F8
-	-	0.012
		C2F5I
-	-	0.0014
CF3I	Liquid	I2
1.36		
		CF4
0.37		
		C2F6
1.03		
CF3I	Liquid	I2
4.27		
	(+ 0.1% O2)	CF4
0.06		
		C2F6

5.72 (+COF2 and white deposit on trace)

(2.2.2) Irradiated CF3I Cooling Fluid – Radiation-induced by-products
(comparison of liquid GC analysis with some yields given in the literature data)

(i) Recapitulation of ionizing radiation fluxes:

Max expected dose /yr: 4 x 10^4 Gy (4 Mrad)
Absorbed Energy /year 4 x 10^4 J/kg

(ii) CF3I Liquid G values (for comparison with liquid GC analysis:

CF3I molecular weight = 196

In liquid phase, G (I2) value of 4 (x 0.1036 micromoles/Joule) would mean 4 gm I2 evolved per kg CF3I /yr

In liquid phase, G (C2F6) value of 5.7 (x 0.1036 micromoles/Joule) would mean 3 gm C2F6 evolved per kg CF3I /yr

A liquid chromatography analysis was made on un-irradiated and irradiated CF3I samples. The purity of the unirradiated fluid was 95.8% CF3I. After irradiation of two liquid samples to 6Mrad, the measured CF3I concentrations were essentially unchanged at 96.1% in one sample, and slightly degraded to 94.9% (around a 1% loss) in the second sample.

5 Properties of Custom Fluorocarbon Mixtures

For custom fluorocarbon mixtures, thermo-physical properties including enthalpy-pressure relations vapour pressure, viscosity and speed of sound have been calculated with NIST/NBS software, and a sonar mixture analyser has been constructed to aid in mixing. Results on mixture analysis and performance will be presented.

Finally, aspects of full scale evaporative cooling circulator design for the ATLAS experiment will be discussed, together with plans for future development.

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