Physics 524

Survey of Instrumentation & Laboratory Techniques: Unit 5: Cooling & Thermal management

Lecture 4 of 4

(13:1)

(5.7) Examples from cooling silicon tracking detectors in particle physics (ATLAS, CMS, LHCb)

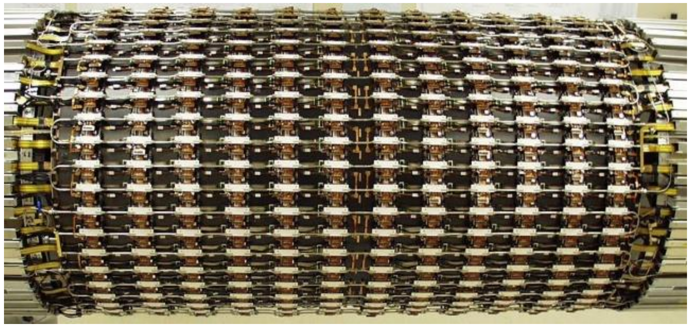
We've seen some examples from the present running of ATLAS:

- **Saturated Fluorocarbons of the form $C_nF_{(2n+2)}$ like C_6F_{14} (current use as liquid coolant in parts of the CMS Silicon tracker) and C_3F_8 (current use in most of the ATLAS Silicon tracker) which have respective GWP_{20} of around 6640 & 5890 x CO_2.**
- **New upgraded trackers are however being built for the High Luminosity phase of LHC to run from 2029-2041**
- **A core aim in these detectors is to use low Global Warming Potential coolants**
- **Any coolant must be non-flammable, non-toxic, non-oxone depleting, (electrically) non-conductive, radiation resistant and have low or zero GWP**
- **CO_2 cooling is being pushed hard at CERN but has problems of high operating pressure and a limiting evaporating temperature of -56 °C (triple point temperature where 3 phases of CO_2 co-exist (liquid, vapor, solid CO_2 'snow')**

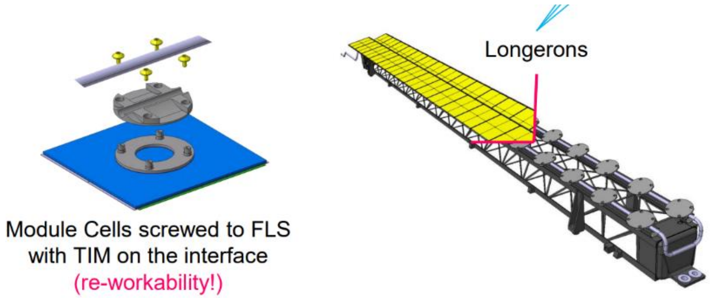
(5.7) Examples from cooling particle physics Si trackers (ATLAS, CMS, LHCb)

Two distinct types of detector cooling geometry:

(1) Tube and block 'DNA'



ATLAS barrel SCT (present)

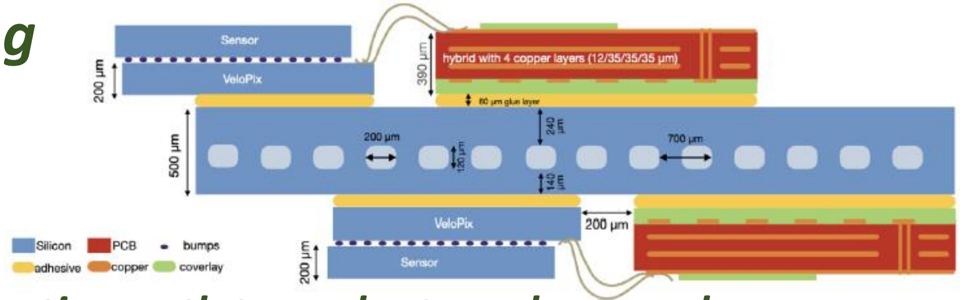


ATLAS ITK Barrel longerons and Si module block attachment (future HL-LHC)

Disadvantages: longer heat conduction path (more interfaces) Si➔ (colder) coolant

(2) Micro-channel cooling

LHCb VELO upgrade



Advantages: shortest heat conduction path to coolant: coolant can be warmer:

Disadvantages: fraglity issues: channels etched in silicon and cover plate attached

(5.7) Examples from cooling particle physics Si trackers (ATLAS, CMS, LHCb)

Micro-channel cooling: more on the LHCb VELO upgrade

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Microchannel cooling for the LHCb VELO Upgrade I

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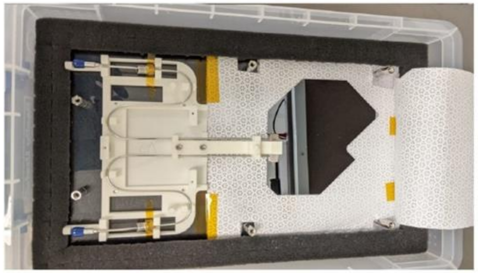
O.A. de Aguiar Francisco, W. Byczynski, K. Akiba et al.



O.A. de Aguiar Francisco, W. Byczynski, K. Akiba et al.

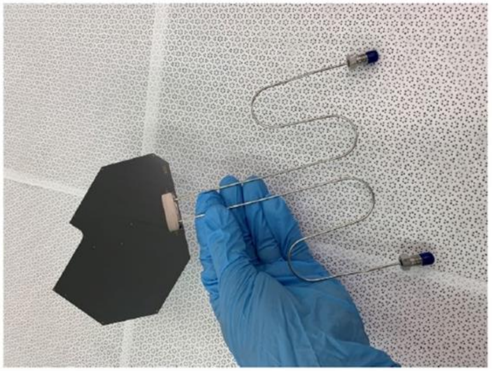


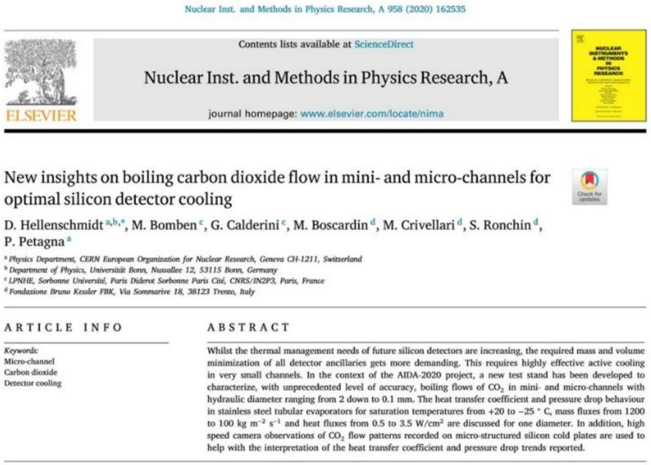
Fig. 20. Microchannel assembly, consisting of a microchannel cooler soldered to a fluidic connector, ready to be equipped with VELO module components.

https://www.youtube.com/watch?v=RmlQwLdfFZg

(5.7) Examples from cooling particle physics Si trackers (ATLAS, CMS, LHCb)

Micro-channel cooling: more on the LHCb VELO upgrade

Recent mastery of evaporative CO_2 cooling in microchannels



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New insights on boiling carbon dioxide flow in mini- and micro-channels for optimal silicon detector cooling

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ABSTRACT

Whilst the thermal management needs of future silicon detectors are increasing, the required mass and volume minimization of all detector ancillaries gets more demanding. This requires highly effective active cooling in very small channels. In the context of the AIDA-2020 project, a new test stand has been developed to characterize, with unprecedented level of accuracy, boiling flows of CO_2 in mini- and micro-channels with hydraulic diameter ranging from 2 down to 0.1 mm. The heat transfer coefficient and pressure drop behaviour in stainless steel tubular evaporators for saturation temperatures from +20 to −25 ° C, mass fluxes from 1200 to 100 kg m^{-2} s^{-1} and heat fluxes from 0.5 to 3.5 W/cm^2 are discussed for one diameter. In addition, high speed camera observations of CO_2 flow patterns recorded on micro-structured silicon cold plates are used to help with the interpretation of the heat transfer coefficient and pressure drop trends reported.

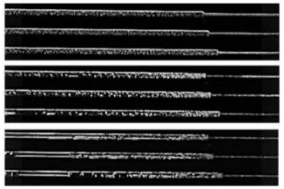


Fig. 7. Boiling CO_2 in micro-channels: upper to lower: 15 °C, 5 °C, −25 °C.

Fig. 8. Boiling CO_2 in micro-channels: left to right: 15 °C, 5 °C, −25 °C.

Fig. 9. Boiling CO_2 in micro-channels at 5 °C: boiling enhancement at inlet restrictions.

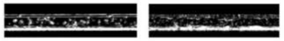
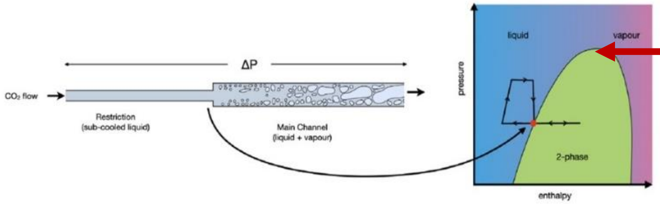


Fig. 10. Boiling CO_2 in micro-channels at 10 °C: film behaviour in the channels: homogeneous and smooth (left), inhomogeneous and wavy (right).



High CO_2 evaporation pressure

(~70 bar at room temp.)

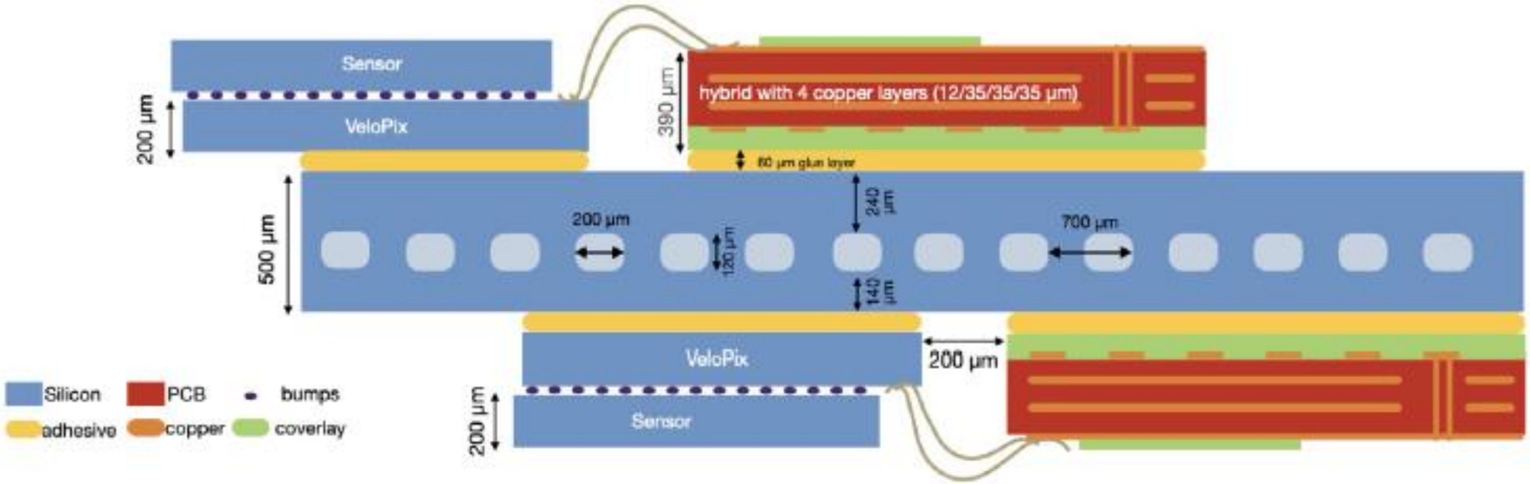
Fig. 2. The left side of the figures shows the typical channel shape for the bi-phase CO_2 microchannel cooling implementation. The pressure drop at the point where the channel expands should bring the coolant to the saturation point as it enters the region of the detector to be cooled. The diagram on the right illustrates the principle of the Two-Phase Accumulator Controlled Loop (2PACL) cooling concept used in LHCb [6].

https://www.youtube.com/watch?v=hsLXi9QTxUo

A film narrated by LHCb physicist Paula Collins

(5.7) Examples from cooling particle physics Si trackers (ATLAS, CMS, LHCb)

Despite these evident successes, the coolant is not directly passing through the detector chips, just through a heat collector plates onto which they are bonded which contain 200 x 120 micron etched microchannels .



So the silicon pixel detectors and their readout electronics are *almost directly* cooled by fluid evaporating in microchannels.

We can therefore ask:

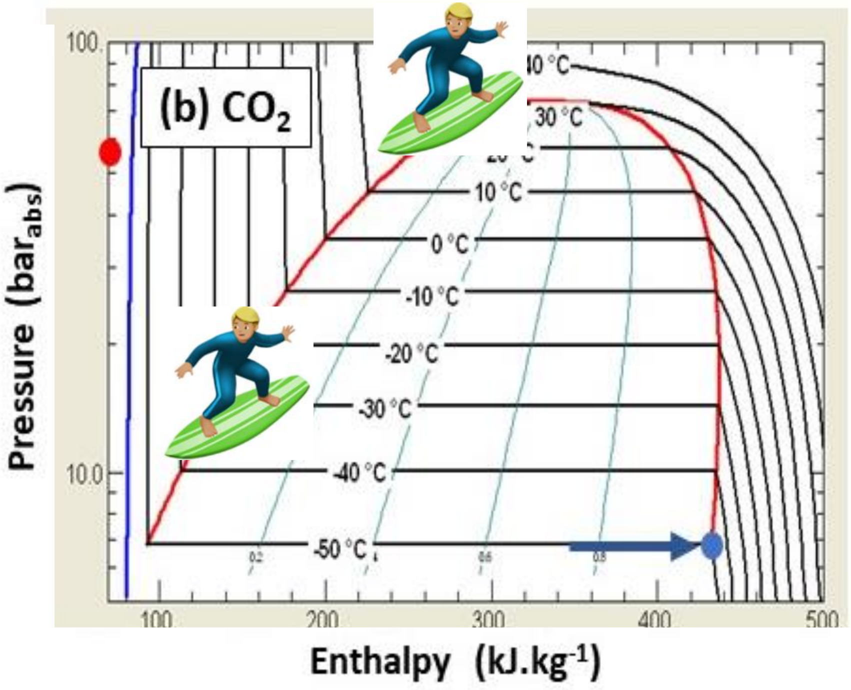
- **will processor chips ever have microchannels etched into them for direct coolant flow?**
- **will this coolant be liquid, or evaporative for reduced mass flow?**
- **how would the cooling pipes be connected?**
- **what would the (necessarily electrically non-conductive) fluid be: a fluorocarbon, CO_2 or a new low GWP fluid, for example from the 3M “NOVEC” range?**

(5.7) Examples from cooling particle physics Si trackers (ATLAS, CMS, LHCb)

The CO_2 problems:

(1) High evaporation pressure at room temperature (60-70 bar)
the detector has to ‘surf ‘ down the saturated vapor line to the operating evaporation temperature of -30 ➔ -40 °C (pressure around 12 - 18 bars):
fatigue cycling an issue in microchannels..?

(2) The high triple point temperature of -56 °C
limits the lowest temperature attainable in the tubes of a tube & block cooling system:
may not be cold enough for operation of Si detectors after years of irradiation in the LHC High Luminosity program (2019-41)



(5.7) Examples from cooling particle physics Si trackers (ATLAS, CMS, LHCb)

Low GWP Alternatives to CO_2:

(1)Noble gases like Xenon and Krypton

- *Very expensive and in very short supply, particularly since the war in Ukraine.*
- *Complex transcritical circulation for Krypton (outside the scope of this unit);*
- *Xenon probably just squeaks in (~50 bar @ 15 C) but still has relatively high pressure evaporation at room temp, but no triple point problem (-112 ˚C)*

(2) Fluoroketone ($C_nF_{2n}O$) replacements for saturated fluorocarbons ($C_nF_{(2n+2)}$)

- *The substitution of two fluorine atoms with an oxygen atom can reduce the GWP to zero: if the oxygen atom is on the end or on a side-arm of the molecule (see next slide);*
- *Ultraviolet scission of the molecules in the upper atmosphere des not created long-lived debris molecules (references given in unit support notes);*
- *($C_nF_{2n}O$) molecules with the same number of carbons as their ($C_nF_{(2n+2)}$) partners will hve similar thermodynamics (molecular weight difference = 22 units);*
- *3M NOVEC 649 ($C_6F_{12}O$) authorised for use as a C_6F_{14} replacement at CERN (liquid cooling)*

(5.7) Examples from cooling particle physics Si trackers (ATLAS, CMS, LHCb)

A Fluoroketone ($C_nF_{2n}O$) replacement for a saturated flurorcarbon ($C_nF_{(2n+2)}$)

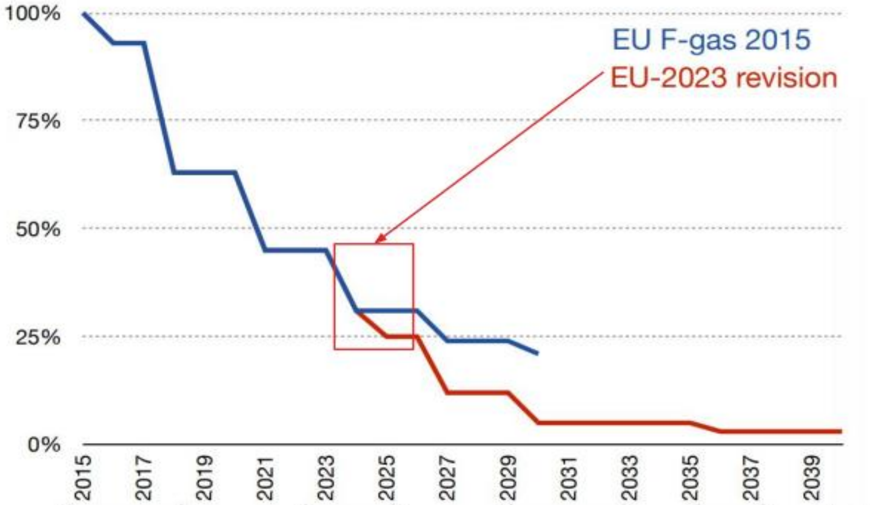
Thermophysical Properties of NOVEC 649 ($C_6F_{12}O$) & C_6F_{14} (at 25ºC except where noted: after [7.15])

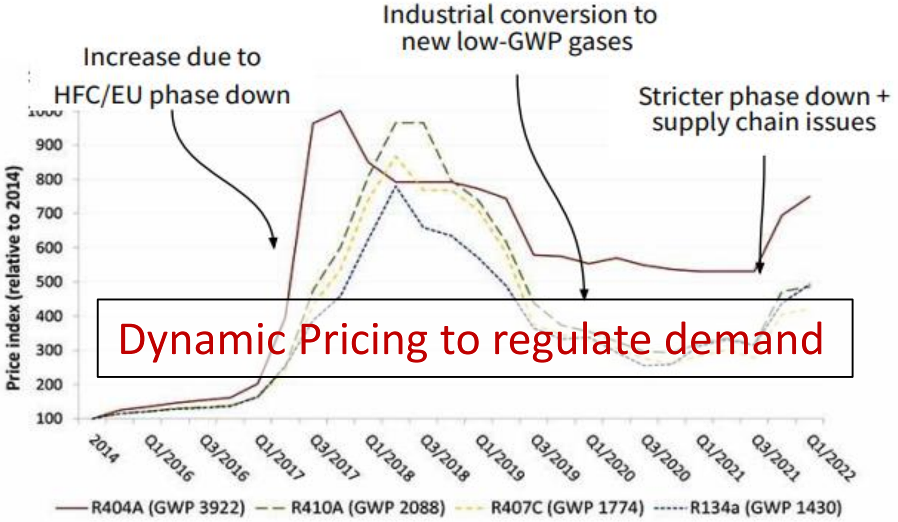
Fluid thermophysical property	NOVEC 649: $C_2F_5C(O)CF(CF_3)_2$ Perfluoro-2-methyl-3-pentanone ($C_6F_{12}O$ fluoro-ketone)	C_6F_{14} (Perfluorohexane, Saturated fluorocarbon)
Boiling temp @ 1 atm (˚C)	49	56
Critical Temp (˚C)	169	178
Critical Pressure (MPa)	1.87	1.89
Freezing temperatre (˚C)	< -100	< -100
Specific heat ($J.kg^{-1}K^{-1}$)	1103	1050
Density ($kg.m^{-3}$)	1610	1680
Kinematic viscosity (cSt)	0.42	0.4
Latent Heat ($J.kg^{-1}$)	88	88
Vapour Pressure @ 25 ˚C (kPa)	40.4	30.9
Vapour Pressure @ 100 ˚C (kPa)	441	350
Water solubility (ppm_w)	21	10

On the turning away…

Example: The uncertain ECHA (European Chemicals Agency) route to fluorocarbon (PFC, PFAS…) prohibition

(A path paved with impracticalities..?)



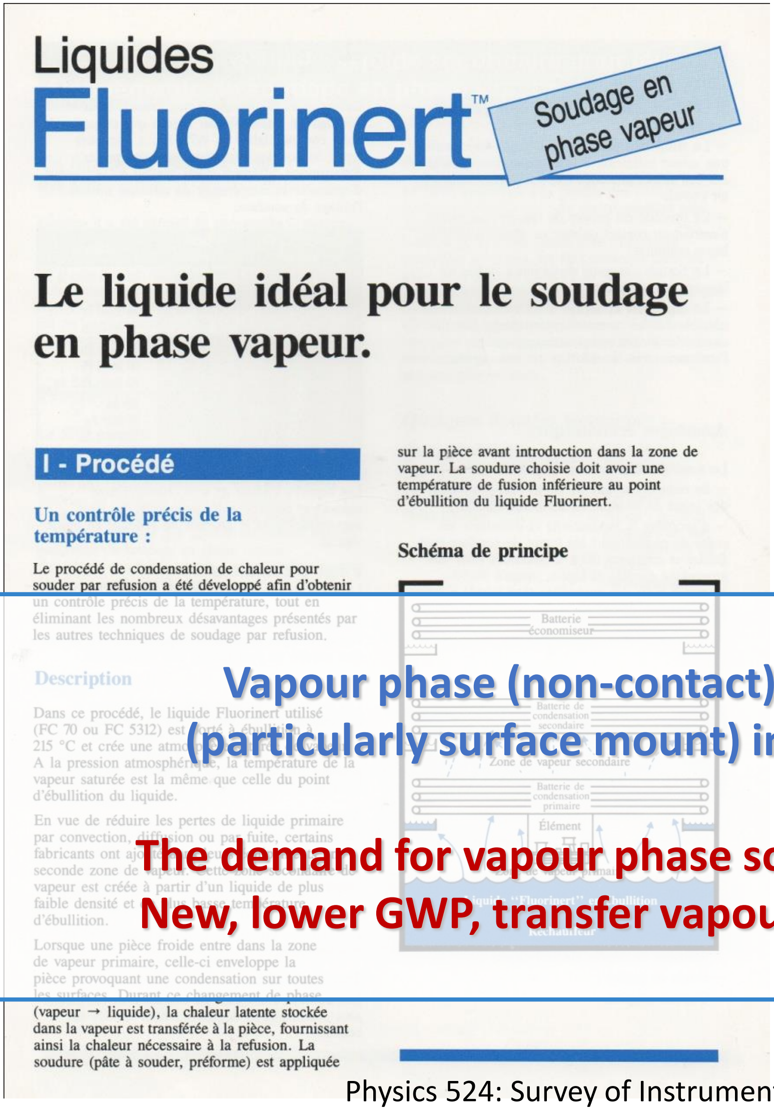


Dynamic Pricing to regulate demand

Au revoir 3M… need to clarify manufacturers' attitudes (Dehon Co. (Fr), Synquest (USA), F2 (UK), various companies in China)… on future *lin*-fluoroketone ($C_nF_{2n}O$) production

Electronics industry is the driver: physics just rides the coat-tails!

Massive use of fluorocarbons in electronics industry for semiconductor manufacture and soldering complex computer mother boards with SMD components



Liquides

Fluorinert™

Soudage en phase vapeur

Le liquide idéal pour le soudage en phase vapeur.

I - Procédé

Un contrôle précis de la température :

Le procédé de condensation de chaleur pour souder par refusion a été développé afin d'obtenir un contrôle précis de la température, tout en éliminant les nombreux désavantages présentés par les autres techniques de soudage par refusion.

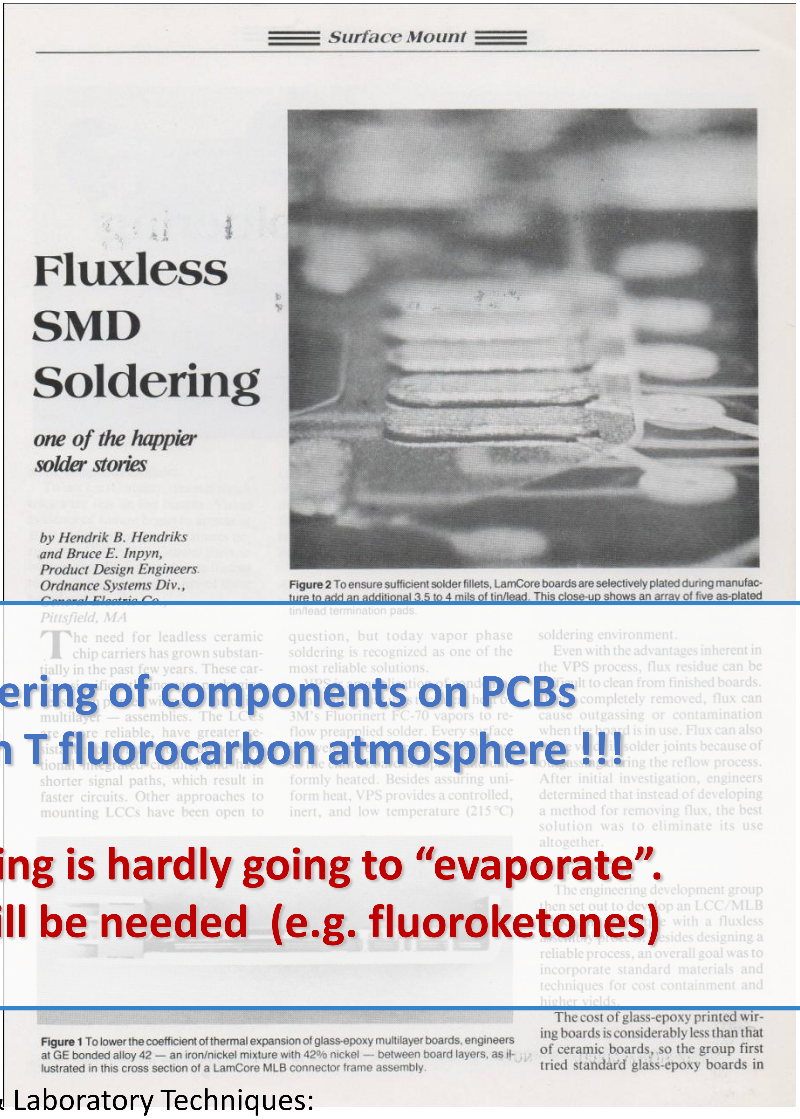
Description

Dans ce procédé, le liquide Fluorinert utilisé (FC 70 ou FC 5312) est porté à ébullition à 215 °C et crée une atmosphère [illegible] vapeur. A la pression atmosphérique, la température de la vapeur saturée est la même que celle du point d'ébullition du liquide.

En vue de réduire les pertes de liquide primaire par convection, diffusion ou par fuite, certains fabricants ont ajouté [illegible] seconde zone de vapeur. Cette zone secondaire de vapeur est créée à partir d'un liquide de plus faible densité et [illegible] plus basse température d'ébullition.

Lorsque une pièce froide entre dans la zone de vapeur primaire, celle-ci enveloppe la pièce provoquant une condensation sur toutes les surfaces. Durant ce changement de phase (vapeur → liquide), la chaleur latente stockée dans la vapeur est transférée à la pièce, fournissant ainsi la chaleur nécessaire à la refusion. La soudure (pâte à souder, préforme) est appliquée sur la pièce avant introduction dans la zone de vapeur. La soudure choisie doit avoir une température de fusion inférieure au point d'ébullition du liquide Fluorinert.

Schéma de principe



Surface Mount

Fluxless SMD Soldering

one of the happier solder stories

by Hendrik B. Hendriks and Bruce E. Inpyn, Product Design Engineers Ordnance Systems Div., General Electric Co., Pittsfield, MA

Figure 2 To ensure sufficient solder fillets, LamCore boards are selectively plated during manufacture to add an additional 3.5 to 4 mils of tin/lead. This close-up shows an array of five as-plated tin/lead termination pads.

The need for leadless ceramic chip carriers has grown substantially in the past few years. These carriers significantly increase packaging [illegible] printed wiring [illegible] multilayer — assemblies. The LCCs are more reliable, have greater resistance [illegible] tional integrated circuits, and have shorter signal paths, which result in faster circuits. Other approaches to mounting LCCs have been open to question, but today vapor phase soldering is recognized as one of the most reliable solutions.

VPS is an application of condensation [illegible] heat [illegible] 3M's Fluorinert FC-70 vapors to reflow preapplied solder. Every surface [illegible] so the entire board is rapidly and uniformly heated. Besides assuring uniform heat, VPS provides a controlled, inert, and low temperature (215 °C) soldering environment.

Even with the advantages inherent in the VPS process, flux residue can be difficult to clean from finished boards. If not completely removed, flux can cause outgassing or contamination when the board is in use. Flux can also cause voids in solder joints because of outgassing during the reflow process. After initial investigation, engineers determined that instead of developing a method for removing flux, the best solution was to eliminate its use altogether.

The engineering development group then set out to develop an LCC/MLB [illegible] with a fluxless assembly process. Besides designing a reliable process, an overall goal was to incorporate standard materials and techniques for cost containment and higher yields.

The cost of glass-epoxy printed wiring boards is considerably less than that of ceramic boards, so the group first tried standard glass-epoxy boards in

Figure 1 To lower the coefficient of thermal expansion of glass-epoxy multilayer boards, engineers at GE bonded alloy 42 — an iron/nickel mixture with 42% nickel — between board layers, as illustrated in this cross section of a LamCore MLB connector frame assembly.

Vapour phase (non-contact) soldering of components on PCBs (particularly surface mount) in high T fluorocarbon atmosphere !!!

The demand for vapour phase soldering is hardly going to "evaporate".
New, lower GWP, transfer vapours will be needed (e.g. fluoroketones)

(5.7) Examples from cooling particle physics Si trackers (ATLAS, CMS, LHCb)

https://link.springer.com/article/10.1140/epjp/s13360-023-04703-w

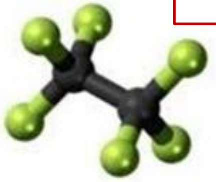
Saturated fluorocarbons ($C_nF_{(2n+2)}$) and their Spurred fluoroketone ($C_nF_{2n}O$) analogs (with 20 year Global Warming Potentials, where measured)

Si COOLING (Evap.)

COOLING (Liq.)

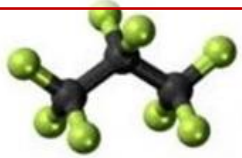
CF_4
(GWP_{20} = 4880)

Ih.T. H335



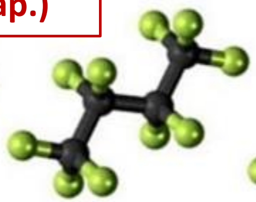
C_2F_6
(GWP_{20} = 8210)

Ih.T. H335



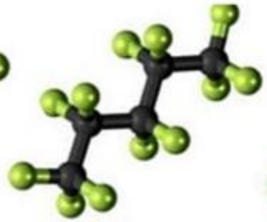
C_3F_8
(GWP_{20} = 6640)

Ih.T. H335



C_4F_{10}
(GWP_{20} = 6870)

Ih.T. H335

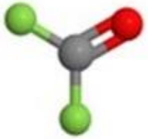


C_5F_{12}
(GWP_{20} = 6350)

Ih.T. H335

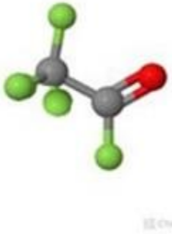
C_6F_{14}
(GWP_{20} = 5890)

Ih.T. H335



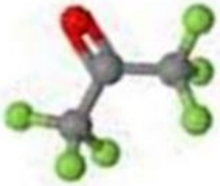
CF_2O
(GWP_{20} = ?)

Ih.T H330, reactive



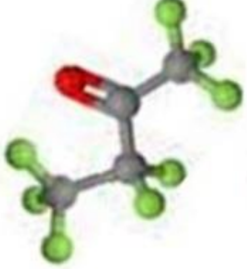
C_2F_2O
(GWP_{20} = ?)
$CF_3C(O)F$

Ih.T H331, reactive



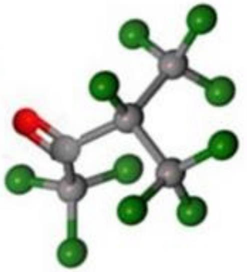
C_3F_6O
(GWP_{20} = ?)
$CF_3C(O)CF_3$

Ih.T H331, reactive



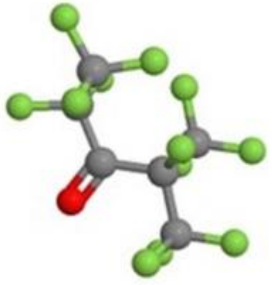
C_4F_8O
(GWP_{20} = ?)
$CF_3CF_2C(O)CF_3$

Ih.T. H335



NOVEC 5110 $C_5F_{10}O$
(GWP_{20} = ≤ 1)
$CF_3C(O)CF(CF_3)_2$

Ih.T. H335



NOVEC 649 $C_6F_{12}O$
(GWP_{20} = ≤ 1)
$CF_3CF_2C(O)CF(CF_3)_2$

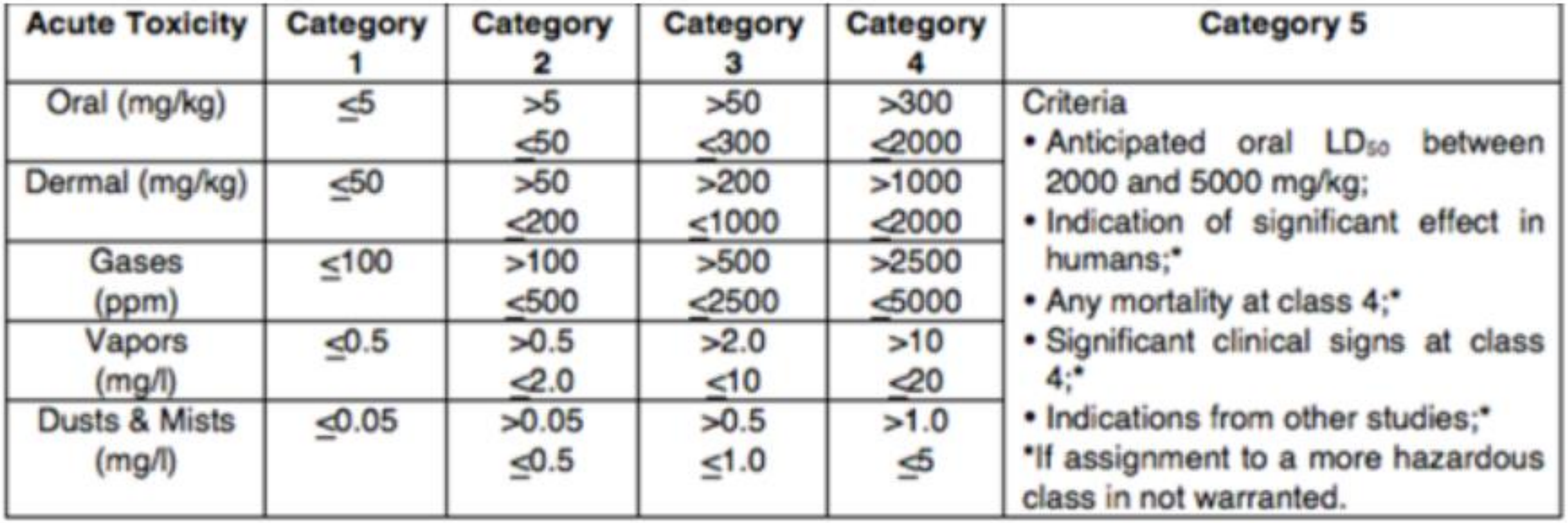
COOLING (Liq.)

Ih.T. H335

GHS Classification Criteria for Inhalation Toxicity

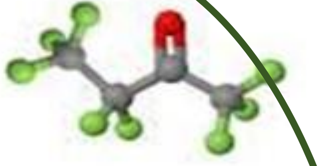
H330	**Fatal if inhaled**
H331	Toxic if inhaled
H332	Harmful if inhaled
H333	May be harmful if inhaled
H334	May cause allergy or asthma symptoms or breathing difficulties if inhaled
H335	May cause respiratory irritation
H336	May cause drowsiness or dizziness

H310	**Fatal in contact with skin**
H311	Toxic in contact with skin
H312	Harmful in contact with skin
H313	May be harmful in contact with skin
H314	Causes severe skin burns and eye damage
H315	Causes skin irritation



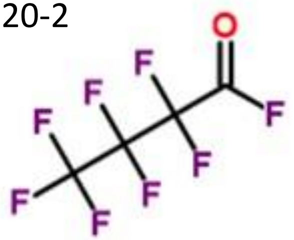
Acute Toxicity	Category 1	Category 2	Category 3	Category 4	Category 5
Oral (mg/kg)	≤5	>5 ≤50	>50 ≤300	>300 ≤2000	Criteria • Anticipated oral LD_{50} between 2000 and 5000 mg/kg; • Indication of significant effect in humans;* • Any mortality at class 4;* • Significant clinical signs at class 4;* • Indications from other studies;* *If assignment to a more hazardous class in not warranted.
Dermal (mg/kg)	≤50	>50 ≤200	>200 ≤1000	>1000 ≤2000	
Gases (ppm)	≤100	>100 ≤500	>500 ≤2500	>2500 ≤5000	
Vapors (mg/l)	≤0.5	>0.5 ≤2.0	>2.0 ≤10	>10 ≤20	
Dusts & Mists (mg/l)	≤0.05	>0.05 ≤0.5	>0.5 ≤1.0	>1.0 ≤5	

Molecular shapes is important for GWP and toxicity



☺

CAS: 337-20-2
H335



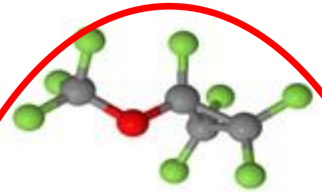
CAS 335-42-2
H331, H335

GWP ?

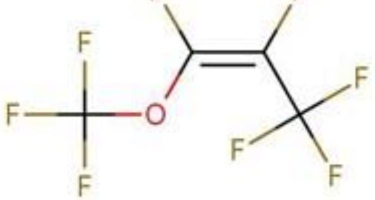
CAS: 677-84-9
H335

GWP ?

C_4F_8O
Linear & branched with Oxygen atom on external spur
(GWP_{20}= ?)



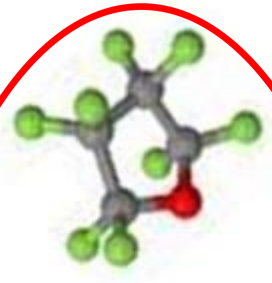
CAS: 67641-44-5
H332, H335, H336



GWP ?

CAS:10493-43-3
H332, H335, H336

C_4F_8O
Linear with Oxygen atom as internal link and double carbon bonded link
(GWP_{20}= ?)



Ih.T. H335

CAS 773-14-8
Unlisted

High GWP!!

C_4F_8O
Cyclic
Perfluorotetrahydrofuran,
Octofluorotetrahydrofuran
(GWP_{20}= 8975) [10]

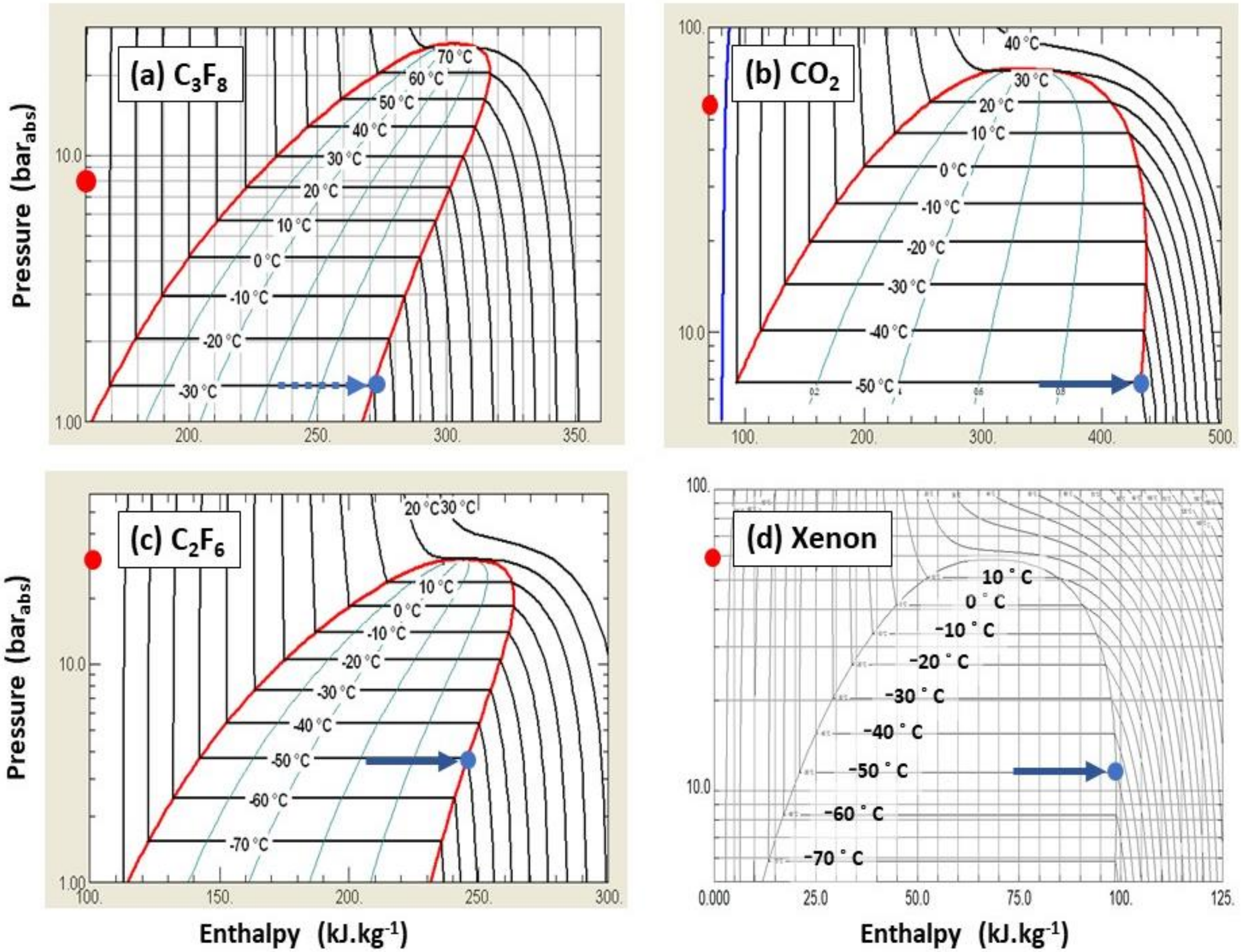
Cyclic, non-cyclic & non-cyclic double carbon-bonded C_4F_8O isomers: refs at end.

Placement of oxygen atom can also determine chemi-potential, flammability & toxicity

(5.7) Examples from cooling particle physics Si trackers (ATLAS, CMS, LHCb)

Some Thermodynamic comparisons two convenient SFCs, CO_2, Xe

(F-K thermodynamics should be similar to same carbon order SFCs)



(5.7) SWOT analysis of cooling fluids HL-LHC

Strengths CO_2

Non-flammable, non-toxic, electrical insulator, non-ozone-depleting, radiation resistant, GWP=1

Weaknesses CO_2

High pressure circulation (60 bar) at ambient temp before cooldown to operating temp

High triple point (-56°C)

Threats CO_2

High triple point may make Si tracker operation problematic: less thermal 'headroom' after heavy irradiaton ('thermal runaway' phenomenton)

Opportunities CO_2

Extensive R&D program at CERN

Evaporative coolant of choice for ATLAS, CMS for start of HL-LHC program

Strengths xenon

Non-flammable, non-toxic, electrical insulator, non-ozone-depleting, radiation resistant, GWP=0

Weaknesses xenon

High pressure circulation (50 bar) at ambient temp before cooldown to operating temp (amost transcritical)

Extremely expensive

Threats xenon

Very difficult future procurement

(war in Ukraine)

(10^{-8} atmospheric content.)

Opportunities xenon

Could find expertise

In particle physics community for fabrication of circulators: already used in dark matter experiments

Strengths C_2F_6

Non-flammable, non-toxic, electrical insulator, non-ozone-depleting, radiation resistant

Weaknesses C_2F_6

Very high GWP

(around 6000 x CO)

Threats C_2F_6

Production will be phased out unless a strong motivation from semiconductor manufacture industry

Opportunities C_2F_6

Proved to decrease the operating temp of an ATLAS SCT thermal model in blend with 75% C_3F_8

Strengths $C_nF_{2n}O$

Non-flammable, non-toxic, electrical insulator, non-ozone-depleting, radiation resistant, GWP=0

Weaknesses $C_nF_{2n}O$

Threats $C_nF_{2n}O$

Large scale industrial production may depend on the phasing-out of SFCs, needs of semiconductor manufacture industry:

Toxicity, material compatibility need further study.

Opportunities $C_nF_{2n}O$

Expertise in particle physics community for

3M NOVEC 649 ($C_6F_{12}O$)

- ***Last problem (6): See separate sheet – really one for the sleuth***:
- while a new C_3F_6O isomer might have similar thermodynamics to C_3F_8, at low to zero GWP, (C_3F_8 & C_3F_6O differ in mol. wt. by 22 units) it is not perfect for cooling a processor chip at room temperature. An evaporation pressure nearer 1 bar_{abs} would be better). What fluid (or even blend of fluids) in the $C_nF_{2n}O$ spectrum might be better, and why?
- **Hint:** the figures below may help in this.


CF_4 (GWP_{20}= 4880) [H 335]


C_2F_6 (GWP_{20}= 8210) [H 335]

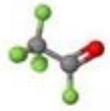

C_3F_8 (GWP_{20}= 6640) [H 335]

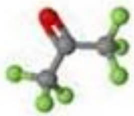

C_4F_{10} (GWP_{20}= 6870) [H 335]

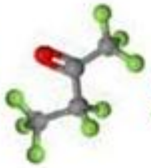

C_5F_{12} (GWP_{20}= 6350) [H 335]

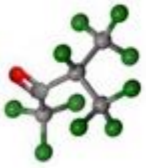

C_6F_{14} (GWP_{20}= 5890) [H 335]

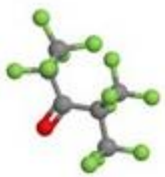

CF_2O (GWP_{20}= ?) [H 330]

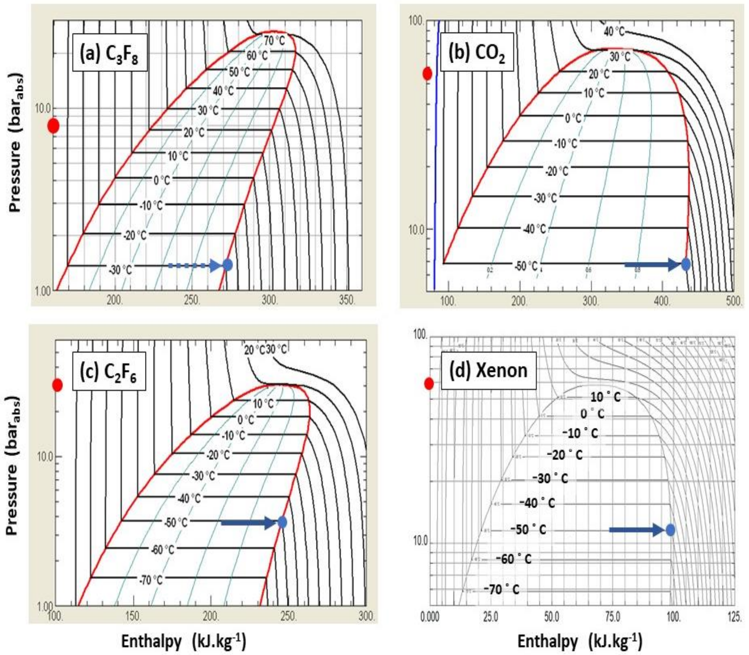

C_4F_2O (GWP_{20}= ?) $CF_3C(O)F$ [H 331]


C_3F_6O (GWP_{20}= ?) $CF_3C(O)CF_3$ [H 330]

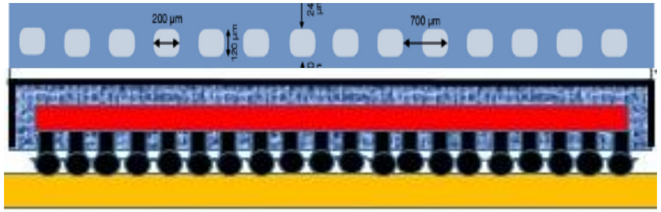

C_4F_8O (GWP_{20}= ?) $CF_3CF_2C(O)CF_3$ [H 335]


NOVEC 5110 $C_5F_{10}O$ (GWP_{20}= ≤ 1) [13] $CF_3C(O)CF(CF_3)_2$ [H 335]


NOVEC 649 $C_6F_{12}O$ (GWP_{20}= ≤ 1) [12] $CF_3CF_2C(O)CF(CF_3)_2$ [H 335]

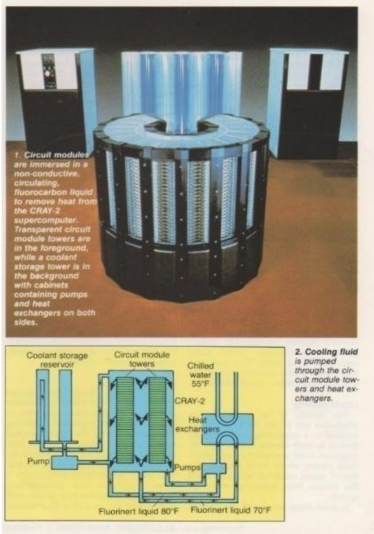


So where does this leave the option of immersion cooling of processors, or the direct liquid cooling of processor ships themselves thru microchannels?



Electrical connections
to computer mother board

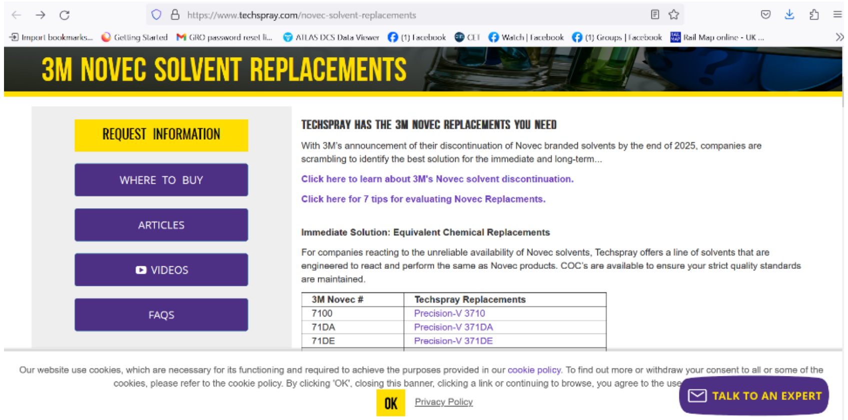
Will processor chips ever look like this?
Can semiconductor lithography, implantation, microchannel etch & sealing be achievable in one final device?



1. Circuit modules are immersed in a non-conductive, circulating, fluorocarbon liquid to remove heat from the CRAY-2 supercomputer. Transparent circuit module towers are in the foreground, while a coolant storage tower is in the background with cabinets containing pumps and heat exchangers on both sides.

2. Cooling fluid is pumped through the circuit module towers and heat exchangers.

3M seem to have lost enthusiasm to produce any more fluorinated fluids after 2025, but companies like F2 Chemicals (Preston, UK), Astor (Ru), Synquest (FL), Techspray (GA) continue (probably many others: e.g.China)



3M NOVEC SOLVENT REPLACEMENTS

TECHSPRAY HAS THE 3M NOVEC REPLACEMENTS YOU NEED

With 3M's announcement of their discontinuation of Novec branded solvents by the end of 2025, companies are scrambling to identify the best solution for the immediate and long-term...

Click here to learn about 3M's Novec solvent discontinuation.

Click here for 7 tips for evaluating Novec Replacments.

Immediate Solution: Equivalent Chemical Replacements

For companies reacting to the unreliable availability of Novec solvents, Techspray offers a line of solvents that are engineered to react and perform the same as Novec products. COC's are available to ensure your strict quality standards are maintained.

3M Novec #	Techspray Replacements
7100	Precision-V 3710
71DA	Precision-V 371DA
71DE	Precision-V 371DE

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Some 3M NOVEC fluids are HFCs with GWPs in the ranges of hundreds:
Better to concentrate on $C_nF_{2n}O$ molecules over the full carbon spectrum with GWP = 0.
But the needs of the semiconductor & electronics industries will be determinant…