Requirements and Specifications for metal cooling tubes for evaporative CO2 cooling

Richard Bates, Richard French, Robert Gabrielczyk, Martin Gibson, Tim Jones, John Noviss, Hector Marin-Reyes, John Mathieson, Ian Mercer, Steve Snow, Peter Sutcliffe, Georg Viehhauser, Ian Wilmut

Introduction

- This talk discusses part of the R&D on metal internal cooling tubes for the strip system of the ATLAS ITk (ATLAS phase II upgrade)
  - Our R&D includes material and dimension choices, manufacture, bending, joining (incl. electrically insulating breaks)
  - Here focus on requirements and specifications
  - Currently writing reports on all aspects
    - Report on requirements and specification is part I
    - Current draft attached to this agenda – not yet complete
    - Will be placed on CERN EDMS → publicly available
- Developed in the context of our specific project, but should be useful for wider field of applications
  - It has taken us an astonishing amount of effort to collect the information presented here – this presentation and the report might help others embarking on similar project

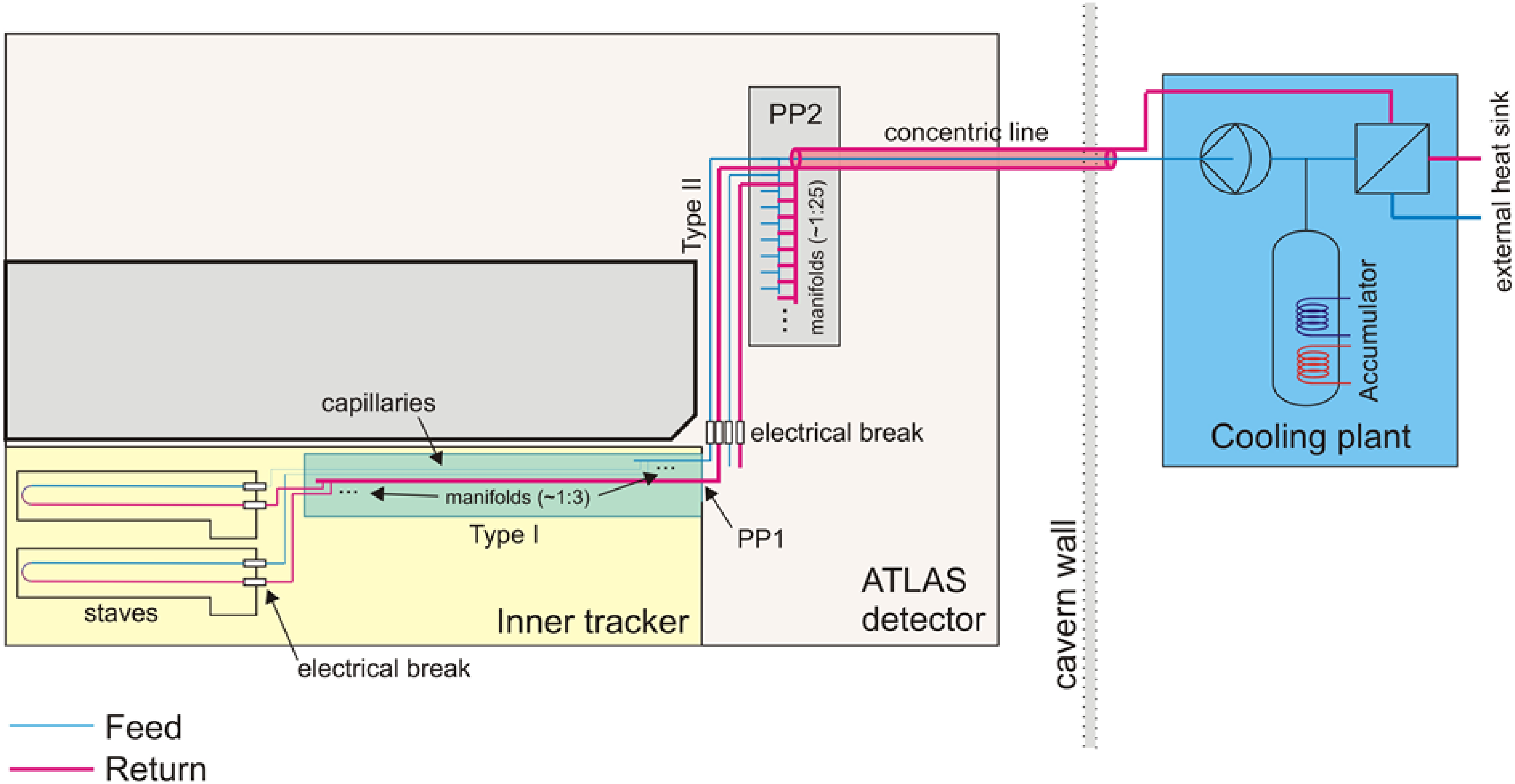
Internal cooling tubes of the ATLAS IK strip tracker

A short introduction to explain the context

Cooling system

- The ATLAS phase II tracker upgrade (ITk) will be cooled by an **evaporative CO_2** cooling system following the 2-phase accumulator controlled loop (**2PACL**) principle
- The target maximum evaporation temperature is currently specified as $\boldsymbol{T_{evap} = -35°C}$
  - The allowable temperature drop of the evaporation still needs to be fixed, but is currently set to $\boldsymbol{\Delta T = 3°C}$
    - To limit temperature differences on local structures and
    - To limit pressure difference between evaporator and pressure control point (accumulator)
- This corresponds to a saturation pressure of about $\boldsymbol{p_{sat} = 12 \text{ to } 11 \text{ bar}_a}$
- Further pressure drop in the return pipes to the pressure control point (accumulator) is specified to be below an equivalent of 7°C

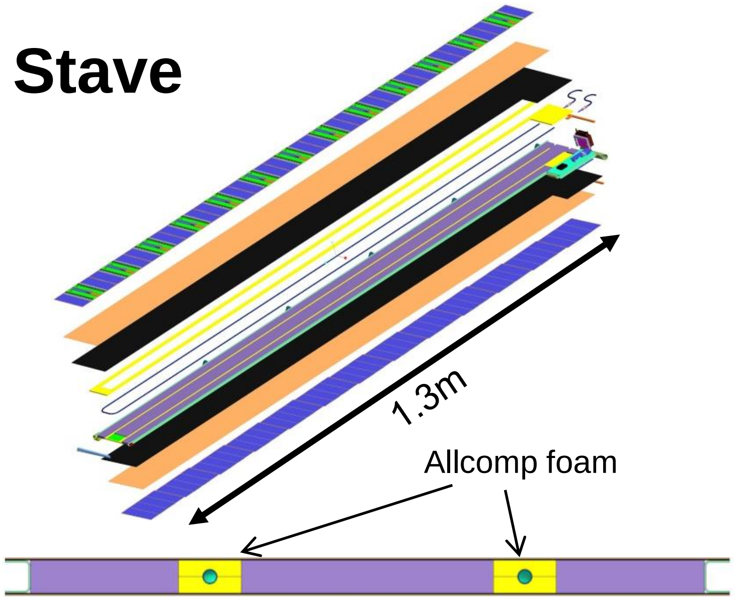
Schematics



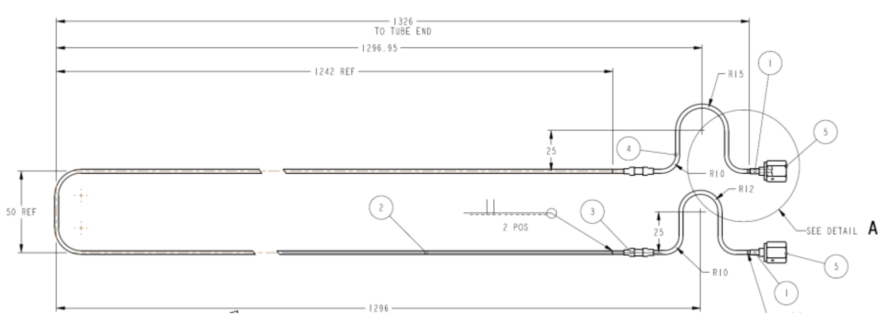
Details of the cooling system and distribution still need to be defined

Internal components

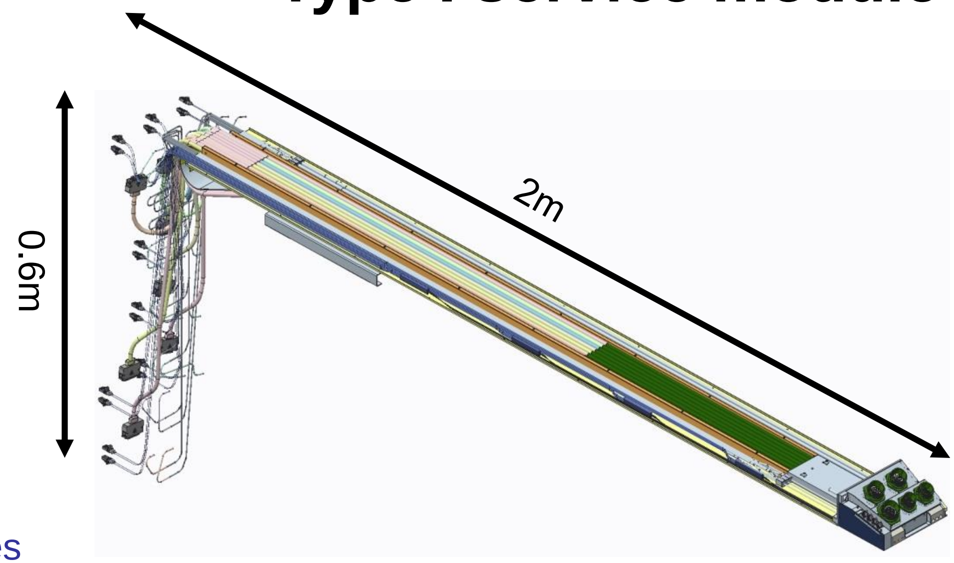
Stave



- Local support holding 2×13 silicon detector modules (100×100mm^2)
- Sandwich of carbonized materials
- Cooling pipe embedded (glued) into high-thermal conductivity carbon foam (Allcomp)
- Power per stave ~140W → **mf = 1g/s**



Type I service module



- Contains all services (cooling, electrical and optical) for 1/32 φ-slice of the barrel strip system (8 staves)
- Ends in PP1, which is part of the ITk barrier system (humidity, thermal, Faraday cage)
- Optimized for fast integration and connection
- Cooling pipework includes capillaries and small (up to 1:4) internal manifolds

Requirements

Standards and Certification

- Our approach builds strongly on the **use of international standards**
- These summarize many years of tried and tested methods built upon a theoretical basis
- On their own they are not legally binding
  - However, in many applications it would be usual to design directly to these standards and then have the system certified to conform to them
  - Conformity with international standard will make it easier to demonstrate diligent engineering
- Standards **include (prudent) factors of safety**
  - It is important to understand these safety factors, so that they are not employed redundantly, when different complimentary standards are used

Our use of standards

- European standards used
  - **Pressure Equipment Directive 97/23/EC (PED)**
  - EN norms
    - **EN 13445** for pressure vessels
    - **EN 13480** for metallic piping
    - Currently we are investigating which of the two applies for our tubes
  - British standard **PD5500** (ex-BS5500)
- US standard used
  - **ASME Boiler and Pressure Vessel (BPV) code**
- Limitations:
  - As these standards are written for a wide range of applications they do – despite their considerable size – not cover all aspects we are interested in
    - Example: EN13445 and EN13480 both focus on Steel and its derivatives with additions for aluminium and copper, but do not provide for the use of other materials like Titanium
      - Titanium is covered by the ASME BPVC and PD5500
  - There are aspects which in which our application falls outside of the direct application of these standards
    - Examples:
      - Standards are for free (clamped) tubes - our evaporators are glued into stave core
        - » But the standards (EN 13445) provide guidance on how to design systems for which the simple calculations are not applicable
        - » We have backed up the simple calculations with FEA studies
      - In the ASME code there is a minimum wall thickness requirement of 1.5mm

Design pressure

- Definitions:
  - PED: ***maximum allowable pressure P_s***,
    - Defined as "*Maximum allowable pressure means the maximum pressure for which the equipment is designed, as specified by the manufacturer.*"
    - We use this pressure to calculate the wall thickness of tubes in the system using the subsequent standard EN 13480
  - ASME BPVC:
    - ***Maximum allowable working pressure (MAWP)*** - equivalent to *maximum allowable pressure* in the EN
    - *Maximum operating pressure (MOP)* - Should be less or equal to the MAWP, but it does not prescribe their ratio
  - This is the **pressure used to dimension the cooling system components**
- Pressure test limits (to which all components of a pressure system need to be tested hydraulically)
  - **EN 13445** specifies the **test pressure to be 1.43×P_s**
  - **ASME BPVC** prescribes hydraulic test to **1.5×MAWP**
  - The safety factors required by these standards for the wall thickness dimensioning put this test pressure **well within the designed pressure containment capabilities** of the system

Our design pressure

- Follow same arguments as used in specification of ATLAS IBL cooling tubes
- Accumulator will be designed to contain all liquid in the system, as well as allowing control of the temperature up to 35°C
  - For an appropriately dimensioned accumulator volume this would result in an operating pressure of 110 bar_a. Any higher pressures will be limited by pressure safety valves
- Within the rest of the system
  - Operating pressure given by the maximum discharge pressure of the pumps: maximum saturation pressure 65 bar_a (during start-up system is flooded with warm liquid at up to 25°C) + pump head required to drive fluid through the system (expected to be ~25 bar_a)
    - Pump discharge pressure will be limited to similar values as the pressure limit for the accumulator
  - The pressure in each section which can be closed off needs to be limited by a burst disc
    - The burst limit for these discs should be higher than the regular operating pressures
    - Convenient **pressure limit is 130 bar_g, for which commercial standard burst discs do exist**
    - Although we do not plan that this limit will be reached during operation we do allow for such a condition
    - **Defines maximum allowable pressure P_s** to be 130 bar_a

→ **All components need to be tested hydraulically to 186 bar_a**

Leak rate

- No **standard prescribing leak rates** throughout a system
- No other strong requirements like cost or environmental concerns or a concern of contamination of the tracker volume
- We therefore derive a **leak rate limit from a target overall allowable leak rate of the whole system**, which we set to 5% of the coolant per year
  - Assuming that total amount of coolant is 1000 kg, total leak rate of the system would be 0.5 mbarl/s at regular operation (-35°C, 12 bar_a)
  - Assuming 10^3 internal circuits this translates into a leak rate of **5×10^{-4} mbarl/s per circuit**
  - Assuming 10^4 joints, a leak rate of 5×10^{-5} mbarl/s per joint. The component leak rate has to be achieved under standard operating conditions (-35°C and 12 bar_a).
- *General comment: We have the suspicion that people get too much hung up on very small leak rates, where instead the real issue is reliability*

Failure rate

- Large number of joints within the tracker
  - On average about 20 per circuit
  - Of the **order of 10^4 internal joints for the whole tracker**
  - Inaccessible with any reasonable effort
- **Require 10% probability of a failure somewhere in the system**
  - **This is achieved for a failure rate of 1 in 10^5 per joint**
- Failure: development of a **leak rate which would require disconnection of the circuit** and its associated manifolds
  - We define this leak rate to be above 100 kg/y or 1 mbarl/s at the regular operating point
  - Significantly above leak rate specification per joint as outlined in previous section
  - This failure rate needs to be achieved over the full lifetime of the phase II upgrade, including handling during assembly and integration, and all thermal cycling
- NB: such a failure rate is almost impossible to demonstrate beforehand
  - If one restricts the analysis to the final connection of staves to the type I services (order of 10^3 connections) the failure rate needs to be 1 in 10^4 for a 10% probability of a failure in the system.
  - To demonstrate such a failure rate with 90% confidence 2.3×10^4 joints without failure would need to be demonstrated – this is practically impossible
  -

Environment

- Temperature
  - No part inside the tracker will be below -45°C during normal operation
  - Without detailed failure analysis assume the possibility that in the case of a catastrophic failure anywhere in the system the pressure will drop to atmospheric pressure → T at freezing point of CO_2 at -56°C
    - All components must withstand **short-time exposure to -56°C at the maximum allowable pressure**
  - Temperature will **not exceed 40°C**
- Temperature cycling
  - Expect average of about 15 cooling system stoppages per year during routine operation (based on current experience)
    - 30 cold-warm cycles per year, or 300 cycles over the anticipated lifetime of the experiment (including safety factor of 2)
  - T change rate during start-ups of the 2PACL system can be fully controlled (different than current C_3F_8)
  - Shocks only occur as result of fault conditions, in particular a large sudden leak to atmospheric pressure would reduce the temperature to -55°C

  → Require all components to **withstand 300 cycles between 25 and -45°C at a rate of 1°C/s, and 30 cycles instantly from -35°C to -55°C**
- Radiation
  - Based on integrated luminosity for phase II times safety factor of 2, for innermost barrel
  - **400 kGray, 10^{16} n/cm^2 1 MeV neutron equivalent fluence**

Other material properties

- Galvanic properties
  - We are working on this – input would be welcome
- Magnetic properties
  - Should **not be significantly magnetic**, therefore preventing significant forces on the sub-detector or affecting the path of the particles in the magnetic field
  - Consider two aspects
    - Change to average magnetic field if this magnetic material is distributed uniformly
      - $\mu_{eff} = 1 + f\chi < 1+10^4$, with fraction f of the space occupied and μ permeability of material
    - Difference in the integrated curvature of a track which passes through pipe wall compared with a track which just misses the same pipe
      - Difference of $\int B\,dl$ is $(1-\mu)\times$wall thickness/lever arm $\approx (1-\mu)\times10^{-3}$, require this to be below 10^{-3} (small against momentum resolution)
- Joinability
  - **Require a material which is compatible with reliable orbital TIG welding and vacuum brazing**

Section-specific requirements

- On-detector cooling tube
  - Multiple scattering material
    - Badly defined
    - Material of the stave core (incl. tapes) ~0.66% X_0, of which 0.088% X_0 (13.3% of the stave core)
  - Pressure drop
    - Equivalent to ΔT~3°C (~1.27 bar at -35°C)
  - Geometrical constraints
    - Length: 2.5m to 3.1m, depending on geometry and location of electrical break
    - Bend radii: 15mm
- Type I tubes
  - Multiple scattering material
    - Still needs to be defined
  - Pressure drop
    - Feed: Capillary, design to have 10× evaporator pressure drop (to maintain flow in all branches of manifold)
    - Return: Equivalent ΔT from stave end to PP2 again 3°C or less (1.17 bar at -38°C). Material-critical section is the individual pipe from the stave to the internal manifold, which is in front of the ECs.
  - Geometrical constraints
    - Bend radii: currently down to 8mm, but can be increased
    - Length:
      - Feed: capillaries up to 2.2 m
      - Return: 0.85m (individual), 1.54 m (common)

Other requirements

- Bend deformation requirements
  - All bends to have **no visible local deformations** (ripples etc.).
  - Reasonably limited local changes in the cross-section will only have minor effects on pressure drops
    - Therefore **maximum reduction of the cross-section in the bend to 5%** (achieved for a reduction of one diameter by about 20%)
- Electrical break
  - To satisfy the grounding and shielding requirements each on-detector cooling pipe needs to be electrically isolated from the others.
    - → There needs to be an **electrical break in each type I pipe** (feed and return) between the end of the stave and the internal manifolds.
    - → Pipes between the stave end and the break need to be electrically insulated.
  - A further break is required outside the tracker close to PP1, but is not the subject of this document.
  - These electrical breaks will need to satisfy the same requirements as outlined throughout this talk for all components

Specifications

Based on our preference for Ti CP2 (first choice) and stainless steel 316L (back-up)

Material specifications

- Temper
  - Term usually associated with carbon steel to describe the crystalline structure of the steel and its associated properties.
    - In the context of this document use it to discuss the available yield and ultimate tensile strength properties available in a material through heat treatment
  - Use **properties of fully annealed material**
    - This is because of the effects of joining techniques like welding or brazing, which raise the temperature of the tubes
    - This is also the approach suggested by standards
  - Tempting to push for lower material by assuming higher temper, but
    - Tendency for the Ultimate Tensile Strength (UTS) to end very close to the yield
    - All the standards that describe best practice support using the fully annealed yield values

- Magnetic properties
  - No issues for Ti
  - Stainless steel:
    - Assume µ of 1.005 for annealed 316L
      $\rightarrow \mu_{eff} = 1 + 7\times10^{-7}$ and $\Delta(\int B dl)/\int B dl \sim 5\times10^{-6}$
    - Both are well within requirements (the amount of steel in the small thin-walled tubes is negligible)

Tube diameter choice

- Based on calculated predictions of pressure drops
  - So far have used only my code (FLUDY)
  - Only recently go access to COBRA – will compare the two
  - Have run the Thome and Friedel correlations to calculate pressure drop
  - All predictions need to be verified experimentally
- Evaporator:
  - Target: ΔT = 3°C (mf = 1 g/s, L = 2.5m, T_{max} = -35°C, x from 0 to 0.5)
  - **2mm ID is plenty**, 1.77mm would be possible, but doesn't get us a lot in material
    - Predicted HTC ranges from ~4-5 kW/Km (start) to about 10-15 kW/Km
- Type I tube:
  - Material critical part is the individual section (in front of ECs)
    - Pressure drop also includes gravitational pressure drop
    - L = 1.4 m, x = 0.5, $T_{stave,out}$ = -38°C
    - ID 2.1mm probably sufficient (model dependent)
  - Common section for now chosen by standard OD (1/4")
  - Capillary currently ID 500µm
    - Given by easy availability
    - Adequate pressure drop (about 10×evaporator) needs to be verified

Wall thickness choices – Design by formula (DBF)

- Following procedures outlined in standards
- For **stainless steel follow EN 13480**
  - Assumes that tubes can be treated as piping and not pressure vessel
- There is no EN which covers **titanium** piping
  - **Use ASME BPV** code, which uses similar approach
- Note:
  - To calculate wall thickness **use maximum allowable pressure** (not proof pressure or similar)
    - Safety is taken care of by catalogued yield strengths, which are significantly below real values (~40% of real values)
  - DBF is strictly speaking not applicable for stave evaporator, as formulas are for clamped, but otherwise free pipe
    - Requires Design by Analysis (DBA) – see later

Wall thickness evaporator (DBF – stainless steel)

$$e = \frac{P_S D_0}{2f \cdot z - P_S}$$

Maximum allowable stress Joint allowance

- Maximum allowable stress and safety factors
  - From BS EN 10216-5:2013 “Material properties for pressure handling materials”

Steel grade		Proof strength [MPa]		Tensile strength R_m [MPa]	Elongation at failure A [%]	
Steel name	Steel number	0.2% $R_{p0.2t}$	1% $R_{p1.0t}$		longitudinal	transverse
X2CrNiMo17-12-2	1.4404	190	225	490 to 690	40	30

  - Time-independent maximum stress $f = \frac{R_{p1.0t}}{1.5}$
  - Time dependent stress
    - Captures degradations principally relating to creep
      - Due to low temperature this is not a concern for us
    - Safety factor for welded joints not required as they are all orbital so implicitly have an additional 100% safety factor compared with the hoop direction yield

  → Maximum allowable stress is 150MPa

- Joint allowance: no joint considerations needed for butt welds → z = 1
- Corrosion allowance: not needed (non-corrosive environment)
- Bend allowance: $e_{bend} = e\frac{(R/D_0)+0.5}{(R/D_0)+0.25}$
- Final results:

D_o [mm]	e [mm]	e_{bend} [mm]
2.275	0.103	0.107
3.175	0.144	0.151

Wall thickness evaporator (DBF – Titanium)

$$w_{min} = \frac{pR_i}{SE - 0.6p}$$

Maximum allowable stress   Joint efficiency

- Joint efficiency
  - Seamless pipe has longitudinal joint efficiency of 1
  - If circumferential welds have too low a joint efficiency (<0.5) the axial load could dominate
    - Butt weld from one side made without backing (type 3 weld), has a E=0.6 regardless of inspection regime

  → Use E = 1
- Maximum allowable stress

Material form and Spec no.	ASTM grade	Specified Tensile strength [MPa]	Min Yield 0.2% Offset [MPa]	Maximum allowable stress [MPa] for metal temperature not exceeding			
				38°C	66°C	93°C	121°C
Pipe SB-337 Seamless	2	345	276	86.1	82.6	75.1	68.1

- No corrosion allowance required
- Still investigating bend allowance (expect it to be similar to EN)
- Results:

OD [mm]	Wall thickness [mm]
2.275	0.162
3.175	0.226

- We will **use 160 µm wall thickness in the ITk for 2.275 mm OD**
- The ASME BPV code specifies minimum material thickness in any material section for any shells exclusive of corrosion allowance to be 1.5mm. We are always in breach of this code.
  - However, there is no fundamental reason why this equation should not apply for smaller wall thicknesses other than weakening due to finite grain size

Design by analysis - DBA

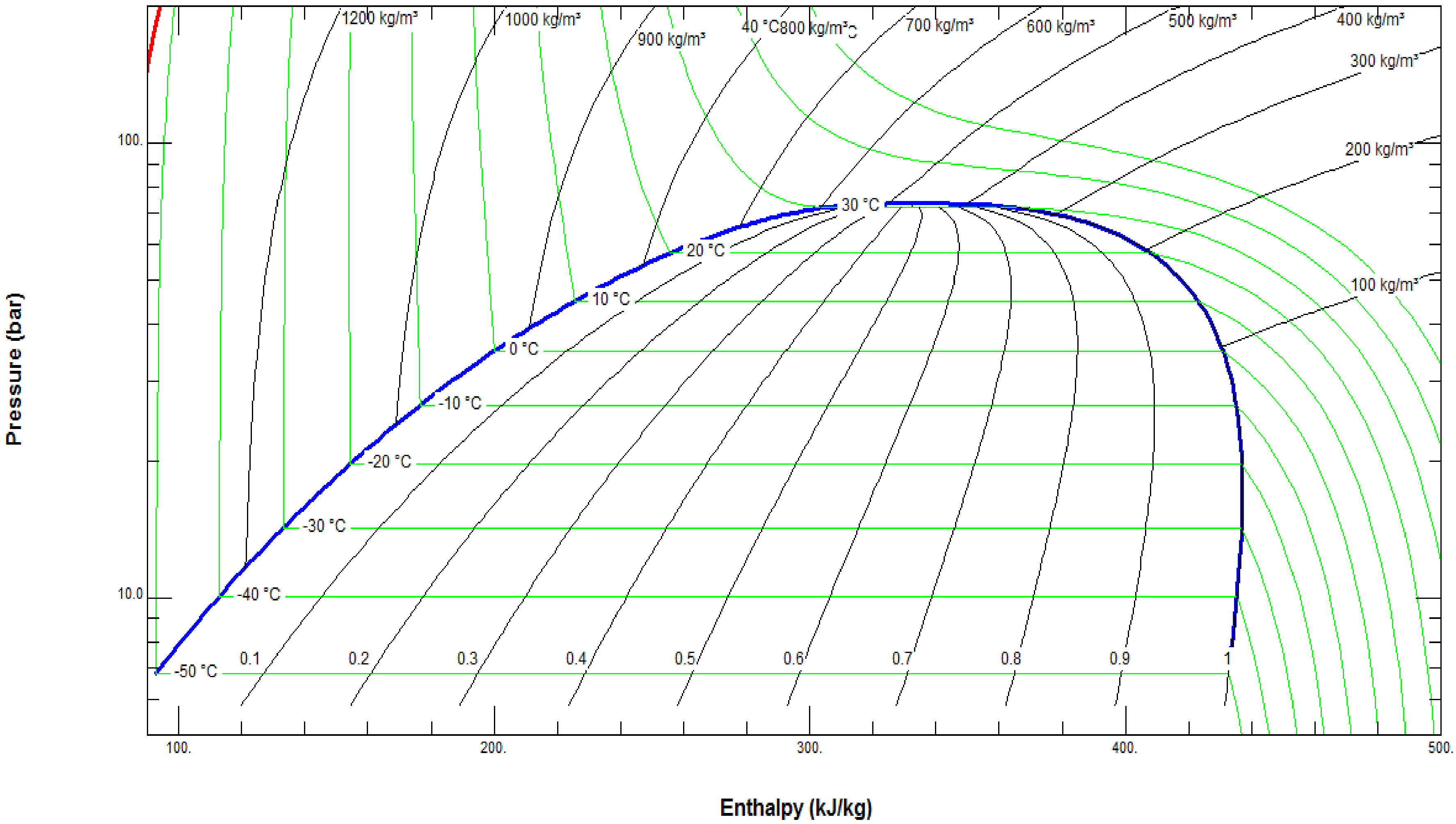
- EN13445 gives guidelines on how to deal with cases which fall outside the standard equations
  - In particular this applies for systems with additional constraints and the combined effects of pressure and thermal loads
- Calculate stress in tube walls from FEA
- For our application three issues studied
  - Tube stress in encapsulated pipe within the stave (glued into carbon foam)
  - Tube stress in wiggle at stave end as a result of thermal expansion/contraction (constrained at far end)
  - Tube stress as radial type I services expand and contract (constrained at outer radius)
- Calculations for all cases have been made, but need to be written up
  - In any case too specific for discussion here
  - No radically different conclusions than DBF

Conclusions

- We have carefully tried to collate the requirements for the tubes of the ATLAS ITk strip tracker
- The requirements build on international standards
  - In particular for pressure rating and wall dimensioning
  - Different standards differ in detail but common spirit
    - Specify maximum working pressure
    - Calculate wall thickness from this (using reduced yield strength for safety)
    - Test to maximum working pressure + 43-50%
- Large number of joints makes reliability a critical system parameter
  - Required failure rates cannot be practically demonstrated
- Our choice for the evaporator tube at a maximum allowable pressure of 130bar_g is a 2.275 mm OD Titanium CP2 tube with 160 µm wall thickness
  - More aggressive approach probably possible, but the gain in terms of material would have been marginal (cooling tube is less than 0.1% X_0, compared to 2.8% X_0 per layer)
  - Handling and joining of such a tube is manageable with reasonable effort
- Efforts are being documented and will be available on EDMS

Further material

Properties of CO_2



Standards

- **EU Pressure Equipment Directive 97/23/EC (PED)**
  - Sets out standards for design and fabrication of pressure equipment generally over one litre in volume and having a maximum pressure more than 0.5 bar_g. It also sets administrative procedure requirements for the "conformity assessment" of pressure equipment, for the free placing on the European market without local legislative barriers. However, as detector cooling system is not produced for commercial resale we can safely ignore these administrative procedures requirements.
- **ASME Boiler and Pressure Vessel Code**
  - an American Society of Mechanical Engineers (ASME) standard that provides rules for the design, fabrication, and inspection of boilers and pressure vessels
- **EN13445 “Unfired Pressure Vessels”**
  - Requirements for design, construction, inspection and testing of unfired pressure vessels.
  - Defines terms, definitions and symbols applicable to unfired pressure vessels.
  - Introduced in 2002 as a replacement for national pressure vessel design and construction codes and standards in the European Union and is harmonized with the Pressure Equipment Directive (97/23/EC or "PED").
- **EN13480 “Metallic industrial piping”**
  - 8 sections in total covering most aspects of metal industrial piping, but only for stainless steel pipes with a limited discussion of aluminium tubes.
- **PD 5500 "Specification for unfired, fusion welded pressure vessels“**
  - Code of practice that provides rules for the design, fabrication, and inspection of pressure vessels
  - PD 5500 formerly a widely used British Standard known as **BS 5500**, but withdrawn from the list of British Standards because not harmonized with PED. Now replaced by EN 13445 in the UK
  - Currently published as a "Published Document" (PD) by the British Standards Institution.

Typical tube material properties

	Stainless steel	Titanium	Aluminium	Cu/Ni	Carbon fibre
Alloy/grade	316L[(1)]	CP2	5251	70/30	n/a
UNS[(2)]	S316xx	R50400	A95251	C71500	n/a
Density [g/cm^3]	8[(3)]	4.51[(4)]	2.69[(5)]	8.94[(6)]	1.6-1.9 (typ.)
Radiation length (X_0) [mm]	18	36	89	14	230-280 (typ.)
Heat conductivity [W/Km]	14.6[(7)]	21.0[(8)]	134	29	1 (typ.)[(9)]
CTE [10^{-6} m/m]	16.5[(7)]	8.4[(8)]	25	16	~0
Modulus [GPa]	193	103	70	150	High
Yield strength (fully annealed)[(10)] [MPa]	290	276	80	88	n/a
Yield strength typical (1/3 hard)[(10)] [MPa]	758	352	190	124	High
Ultimate tensile strength [MPa]	560	345	180	372	High
Figure of merit (Yield)[(11)] × X_0) [10^6 kg/s^2]	5.2	10.0	7.1	1.2	n/a

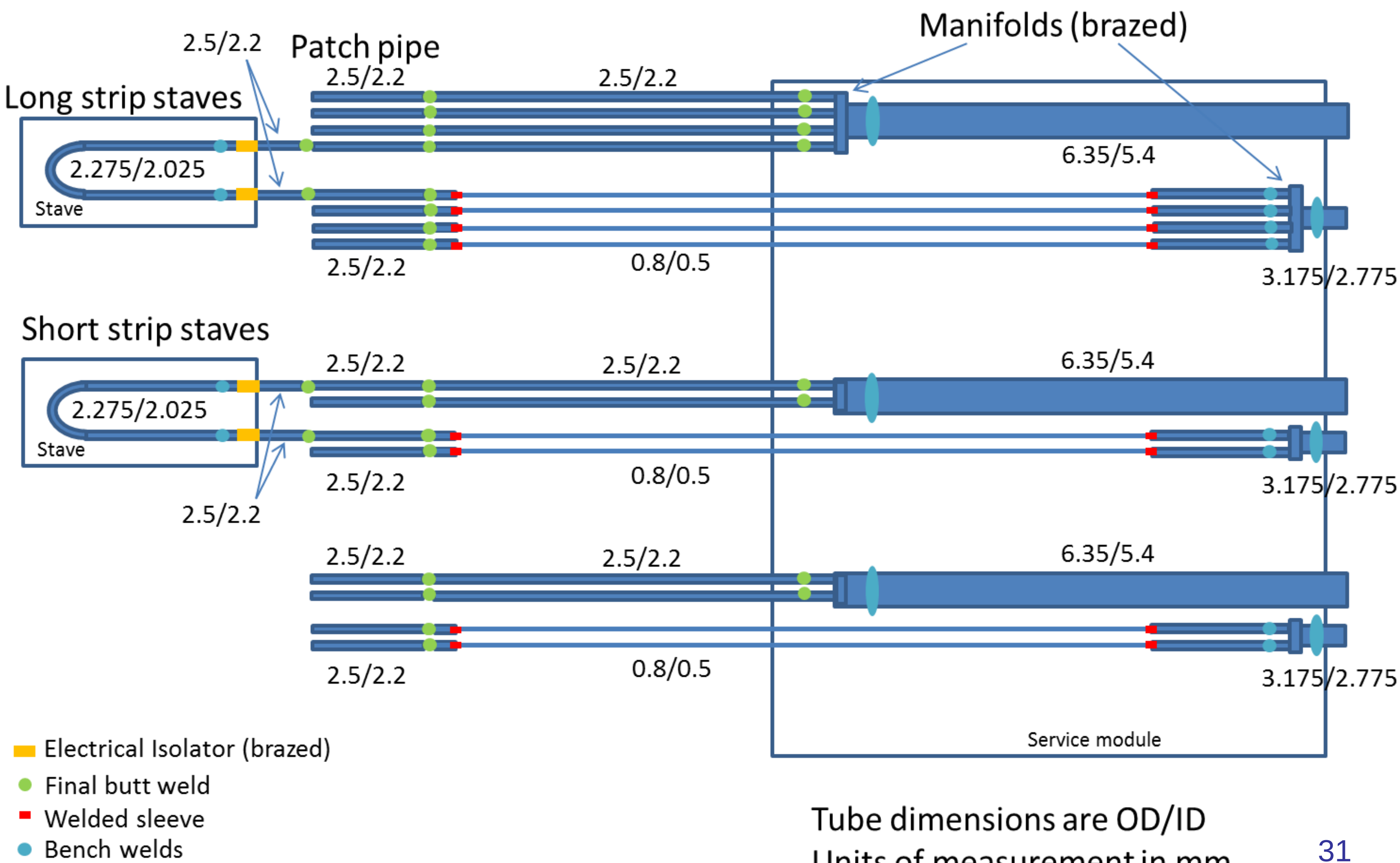
(1) Including derived alloys (316LV, 316LN, etc.)
(2) Unified Numbering System for Metals and Alloys
(3) http://www.matweb.com/search/DataSheet.aspx?MatGUID=1336be6d0c594b55afb5ca8bf1f3e042&ckck=1 using annealed sheet data. Very close to 316LV or 316LN properties
(4) http://www.smithmetal.com/downloads/CPGrade2_SMC.pdf
(5) http://www.matweb.com/search/DataSheet.aspx?MatGUID=16bb703f31d6429a95216564dbf857d5
(6) http://www.matweb.com/search/DataSheet.aspx?MatGUID=1de470e1f95c442990e87658c7b6eb36
(7) between 20°C and 100°C
(8) average between -100°C and 0°C
(9) perpendicular to fibres
(10) 0.2% proof stress
(11) using fully annealed yield

Wall thickness type I tubes (DBF)

OD [mm]	Minimum wall thickness [mm] For stainless steel 316L (according to EN 13480)	For titanium (according to ASME BPV)
2.5	0.117	0.178
3.175	0.151	0.234
6.35	0.313	0.452

- Stainless steel includes bend allowance, Ti does not (yet)
- Plan to use titanium tubes with
  - 2.5 mm OD and 200 µm wall thickness (individual return lines)
  - 6.35 mm OD and 450 µm wall thickness (common return)
  - 3.175 mm OD and 250 µm wall thickness (common feed)
  - Capillaries are 500 µm ID, 800 µm OD (from manufacturing constraints)
    - No issues with pressure handling capabilities

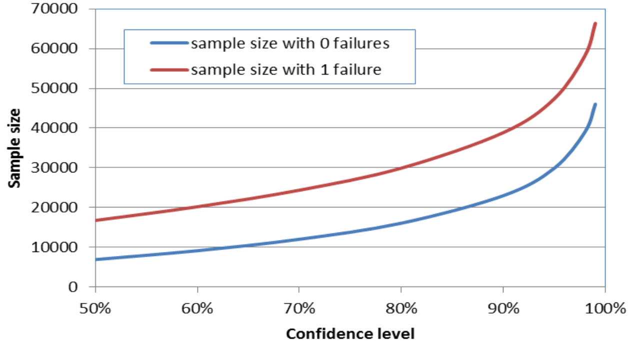
Connection topology



Tube dimensions are OD/ID
Units of measurement in mm

Sample size for pass/fail estimates

- Sample size n, failure rate per component 1 in m
- Probability for at least one failure $p = 1 - \left(1 - \frac{1}{m}\right)^n$
  - For m=n p =63%
  - To get p=10% m≈10n
  - So for example if n = 10^3 need 1 failure in 10^4 for each component for 10% probability of one failure
- Sample size needed to demonstrate failure rate 1/m with confidence level c
  - If no failures found $n = \dfrac{\ln(1-c)}{\ln\left(1 - \frac{1}{m}\right)}$
  - If one failure found: solution to $\dfrac{1-c}{1+\frac{n-1}{m}} = \left(1 - \frac{1}{m}\right)^{n-1}$



  - Example: Sample size of about *n* = 23,000 without failure has to be demonstrated for 90% confidence that the failure rate is 1 in 10,000 or below.
    - Similar confidence can be achieved if one failure is found in about 39,000 pass/fail tests